Measurements of the hadronic cross sections with the CMD-3 and SND detectors at the VEPP-2000 e+e- collider

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Measurement of the cross section $e^+e^- \rightarrow \text{hadrons}$ in the low energy range is interesting for:

- measurement of parameters of light vector mesons $\rho, \omega, \phi, \rho', \rho'', \omega', \omega''$
- Test of QCD sum rules, ChPT, VDM, ... etc, search of exotics (light hybrids and glueballs)
- CVC test in comparison with spectral functions of tau decays
- measurement of $R(s)$:

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

it is essential for the interpretation of precision measurements of:
- muon $(g-2)$ - good test of SM
- for calculation of:
- $\alpha_{\text{QED}}(M_Z)$ - used in precise prediction of EW physics,

(better precision in case of ILC physics needed)
SM prediction for muon $g-2$

$$a_{\mu}^{\text{experimental}} = (g-2)/2$$

11 659 208.9 $\pm 6.3 \times 10^{-10}$

$\mu$ world average

$$a_{\mu}^{\text{theory}} = a_{\mu}^{\text{QED}} + a_{\mu}^{\text{EW}} + a_{\mu}^{\text{hadron}}$$

QED contribution

$11 658 471.808 \pm 0.015$ Kinoshita & Nio, Aoyama et al

EW contribution

$15.4 \pm 0.2$ Czarnecki et al

NLO hadronic

$-9.8 \pm 0.1$ HLMNT11

Hadronic contributions

LO hadronic $694.1 \pm 4.3 \times 10^{-10}$ HLMNT11

main channels contribution to precision at $\sqrt{s} < 1.8$ GeV

$\pi^+\pi^-$ $505.65 \pm 3.09$

$\pi^+\pi^-2\pi^0$ $18.62 \pm 1.15$

$\pi^+\pi^-\pi^0$ $47.38 \pm 0.99$ (mostly from omega region)

$2\pi^+2\pi^-$ $13.64 \pm 0.36$ (BaBar)

$K^+K^-$ $22.95 \pm 0.26$ (BaBar)

from Isospin relations $5.98 \pm 0.42$ for not measured $KK\pi, KK2\pi, 2\pi4\pi0, 2\pi3\pi0$

(or $12.46 \pm 0.76$ for $\sqrt{s} < 2$ GeV) (1.5-3σ of total error - crucial in case of isospin violation)

$R_{\text{qcd}}[2-11.09\text{GeV}]$ $41.19 \pm 0.82$

Light-by-light $10.5 \pm 2.6$ Prades, de Rafael & Vainshtein

Theory TOTAL $\pm 4.9$

$\Delta_{\text{Exp - Theory}} \approx 3.3-3.6\sigma$


New $g-2$ experiments at FNAL and J-PARC have plans to reduce error to $1.5 \times 10^{-10}$
The value and the error of the hadronic contribution to muon \((g-2)\) are dominated by low energy \(R(s)\) (<2GeV give 92%).

\[ \alpha_{\text{QED}}(M_Z) \text{ - half of error comes from } 2E < 4 \text{ GeV} \]
• Up to 2 GeV c.m. Energy
• VEPP-2000 uses special optics providing “round beams”
give additional gain in luminosity
and will provide:

\[ L = 10^{31} \text{ cm}^{-2}\text{c}^{-1}, \sqrt{s} = 1.0 \text{ GeV} \]
\[ L = 10^{32} \text{ cm}^{-2}\text{c}^{-1}, \sqrt{s} = 2.0 \text{ GeV} \]

Status:
2010 - start of experiments
Plans:
\( \approx 100 \text{ pb}^{-1} \text{ per detector per year} \)
Advantages compared to previous CMD-2:

- new drift chamber with $x2$
  - better resolution, higher B field
  - better tracking
  - better momentum resolution
- thicker barrel calorimeter
  - $(8X_0 \rightarrow 15X_0)$
  - better particle separation
- LXe calorimeter
  - measurement of conversion point for $\gamma$'s
  - shower profile
- TOF system
  - time separation for $p$

1 - vacuum tube, 2 - drift chamber, 3 - calorimeter BGO (680 crystals), 4 - Z-chamber, 5 - CMD-3 superconducting solenoid, 6 - calorimeter LXe (400 liters), 7 - calorimeter CsI (1152 crystals), 8 - magnet yoke, 9 - solenoids of VEPP-2000, (not shown) muon range system and TOF system
SND Detector – new version

1 - beam pipe
2 - tracking system
3 - aerogel
4 - NaI(Tl) crystals
5 - phototriodes
6 - muon absorber
7 - muon detector
8 - muon detector
9 - muon detector
10 - focusing solenoid

Advantages compared to previous SND:
- new system - Cherenkov counter (n=1.05, 1.13)
  - $e/\pi$ separation $E<450$ MeV
  - $\pi/K$ separation $E<1$ GeV
- new drift chamber
  - better tracking
  - better determination of solid angle

NIM A449 (2000) 125-139
The \(10^{31} \text{ cm}^{-2} \text{c}^{-1}\) luminosity at \(\sqrt{s}=2.0\) GeV was reached. Currently the luminosity at high energy is limited by a deficit of positrons and maximum energy of the booster (825 MeV now), after upgrade it will gain factor x10.
Clean collinear events (mostly without background).
Overall corrections at the level of a few percent.

**Plans to reduce systematic error from 0.6-08% → 0.35%:**
- Event Separation will be checked by different methods (0.2%)
- More proof of Radiative corrections 0.3% → 0.1%
- Determination of fiducial volume controlled independently by LXe and ZC subsystems (0.1%)
- Beam Energy measured by method of Compton back scattering of the laser photons($\sigma_E < 50$ keV)(0.1%)

**Statistical precision of cross section measurement**

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

**e/µ/π separation using energy deposition in calorimeter**

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**e+e- -> K+K-π+π- by CMD3**

**K** particle identification by dEdX in DC (colors by likelihood separation for KKππ events)

Seen rich dynamics, many intermediate states:
- $K^*(1270)K \rightarrow K^*(892)K\pi$
- $K^*(1400)K \rightarrow K^*(892)K\pi$
- $K^*(1270)K \rightarrow \rho KK$
- $K^*(892)K^*(892), \phi\pi\pi$

For $(g-2)_\mu$, $a_{QED}(M_Z)$ need to be measured also all possible KKπ KKππ, with K – also neutral

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e+e- -> multi pions with CMD3

One of the dominated systematic source is model uncertainty.
High statistic will allow much better dynamics study.

3(π+π-) main production channel by ρ(770) + 4π in phase space or f₀.

Seen change of dynamics in 1.7-1.9 GeV range.
Interesting feature: sharp dip at pp threshold (dip in sum of 6π roughly as pp+nn cross section).

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With many neutral pions by SND

SND have advantages in neutral modes

\[ e^+e^- \rightarrow \omega \pi^0 \rightarrow \pi^0\pi^0\gamma \]

First published data by new SND

\[ e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0\pi^0 \rightarrow \pi^+\pi^- 8\gamma \]

Not measured before (in R(s) taken by Isospin relations)

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CMD3 Collaboration
3π, 4π by SND

\[ e^+e^- \rightarrow \pi^+\pi^-\pi^0 \]

Need to be measured also in \( \omega \)-region, now we have plenty of statistics for it.
CMD2 has publication (2000) with good systematic (1.3%), but low statistics,
SND have good statistics but lower systematics (3.4%).

Worse known cross-section above phi
For >1.4 GeV a this moment the only published data from >30 year old experiments from Orsay DCI and ADONE.
2 nucleons at threshold

We are able to measure nucleon formfactor at threshold.
With more statistics we want to distinguish electrical and magnetic part by $|G_e/G_m|$.
Conclusion

- VEPP-2000 accelerator successfully operates with a goal to get ~1fb-1 in 5-10 years which should provide new precise results on the hadron production

- We have upgraded detectors CMD-3 and SND, with much better performance and monitoring of different detector subsystems

- Data analysis is in progress, the already collected data have same or better statistical precision on cross sections than previous experiments.

- First publications on data analysis appeared (6π, ωπ0)

- During upcoming shutdown for about 1.5 year new positron injection complex to increase luminosity by factor x10 up to $10^{32}$ cm$^{-2}$s$^{-1}$ on $2E=2$ GeV will be commissioned
Pion formfactor : Event separation (CMD-2)

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

\[
\mathcal{L} = -\sum_{\text{events}} \ln \left( \sum_{\text{type}} N_{\text{type}} \cdot f_{\text{type}}(E^+, E^-) \right) + \sum_{\text{type}} N_{\text{type}}
\]

\[\text{type} = e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \text{cosmic}\]
Inclusive Hadronic Cross-Sections with CMD2&SND

The uncertainty in $\mu_{(had)}$ was improved by factor 3 as the result of VEPP-2M measurements.
Pion formfactor

\[ \frac{O^{\text{measured}}_{\mu^+\mu^-}}{O^{QED}_{\mu^+\mu^-}} - 1 = -2 \pm 1.3 \pm 0.7\% \]

\[ \chi^2 / \text{ndf} = 6.942 / 9 \]

Prob = 0.6431

p0 = -1.999 \pm 1.295

Systematic error

CMD2

\[ 0.7\% \]

\[ 0.6\% (95) / 0.8\% (98) \]

\[ 1.2 - 4.2\% \]

SND

\[ 3.2\% \]

\[ 1.3\% \]

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CMD3 Collaboration
### R measurement: systematic errors

#### What systematic error can be achieved for R measurement at CMD-3?

<table>
<thead>
<tr>
<th>Source of error</th>
<th>CMD2, 2π $\sqrt{s}&lt;1$ GeV</th>
<th>SND, 2π $\sqrt{s}&lt;1$ GeV</th>
<th>CMD2,4π $\sqrt{s}&gt;1.1$ GeV</th>
<th>CMD3, 2π $\sqrt{s}&lt;1$ GeV</th>
<th>CMD3,4π $\sqrt{s}&gt;1.1$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event separation</td>
<td>0.2-0.4%</td>
<td>0.5%</td>
<td>2% (cuts)</td>
<td>0.2%</td>
<td>1% (cuts)</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>0.2%</td>
<td>0.8%</td>
<td>3% (model)</td>
<td>0.2%</td>
<td>2% (model)</td>
</tr>
<tr>
<td>Energy calibration</td>
<td>0.1-0.3%</td>
<td>0.3%</td>
<td>1%</td>
<td>0.1%</td>
<td></td>
</tr>
<tr>
<td>Efficiency correction</td>
<td>0.2%-0.5%</td>
<td>0.6%</td>
<td>2% (tr+bg)</td>
<td>0.1%</td>
<td>1% (tr+bg)</td>
</tr>
<tr>
<td>Pion losses (decay, NI)</td>
<td>0.2%</td>
<td>0.2%</td>
<td></td>
<td>0.1%</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td>0.5%</td>
<td>2%</td>
<td></td>
<td>0.3% (lum)</td>
</tr>
<tr>
<td>Radiative corrections</td>
<td>0.3-0.4%</td>
<td>0.2%</td>
<td>1%</td>
<td>0.1%</td>
<td>1%</td>
</tr>
<tr>
<td>Total syst.</td>
<td>0.6-0.8%</td>
<td>1.3%</td>
<td>5%</td>
<td>0.35%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Stat.+Syst.</td>
<td>0.7%</td>
<td>1.5%</td>
<td>7%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Energy measurement by Compton back scattering

Излучение из точек A и C под углом φ = 0 интерферирует

E = 993.662 ± 0.016 MeV

\[ e^+e^- \rightarrow \eta \gamma \]

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

\[ 2\pi^0 \rightarrow \eta \pi^0 \]

\[ 2\pi^0 \rightarrow \text{Non}\omega \pi^0 \]
L = 24.39 m
f_{acc}= 172 MHz
V_{acc}= 120 kV
E=0.2 - 1 GeV
B_{bend} = 2.4 T
B_{sol} = 13 T
β*=2 - 10 cm
σs = 3 cm
ε=1.4•10^{-7}\,\text{mrad}
v_{x,z} = 2.1; 4.1
α= 0.036
ξ = 0.15
N_{\pm} = 1011
L=1•10^{32}\,\text{cm}^{-2}\text{s}^{-1}
Produced luminosity, averaged over run

L, $10^{30}$ /cm$^2$/s

Top 10% of runs
Median value
Bottom 25% of runs

Energy, MeV

Beam energy, MeV

Luminosity, cm$^2$/s

Run 2010-2011,
Long solenoids, $\beta^*=7.0$ cm
Run 2009-2010,
Long solenoids, $\beta^*=8.5$ cm
Run 2008, $\beta^*=4.5$ cm,
Short solenoids
HIGH 2012
RHO 2013

80x60 mA, $\xi=0.13$

40x40 mA, $\xi=0.13$

Limited e$^+$ production rate

Energy ramping

$\beta^*=2$ cm

Beam-beam limit with variable $\beta^*$
π+π−π+π−π+π−
Δα_{had}(M^2_Z) 

Δα_{had}(−s_0)

Direct integration of energy points

Use of Adler function
(It allows to use safely pQCD down to 2.5 GeV)

FJ08

δα(MZ)/α(MZ)~2×10^{-4} → 5×10^{-5}

Requirement from ILC (4x improvement)!
2 nucleons on threshold

$e^+e^- \rightarrow p \bar{p}$

$p\bar{p} \rightarrow e^+e^-$

$p\bar{p} \rightarrow e^+e^-$

Radiative corrections of polarization technique

$G_{pE}(q^2)/G_{pM}(q^2)(|q^2| \rightarrow \infty ) \rightarrow 1$

pQCD prediction

Spacelike region

$e^-p \rightarrow p^{-}$