CMD-3 EXPERIMENT OVERVIEW

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on behalf of CMD-3 collaboration

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\( \sigma(e^+e^- \rightarrow \text{hadrons}) \) and the hadronic contribution to \(a_\mu\)

So far, the hadronic contribution to \(a_\mu\) is calculated by integrating experimental cross-section \(\sigma(e^+e^- \rightarrow \text{hadrons})\).

Weighting function \(\sim 1/s\), therefore lower energies contribute the most.

Many sources of data:

- Novosibirsk: CMD-2 and SND (VEPP-2M), CMD-3 and SND (VEPP-2000)
- Factories: Babar, KLOE
- BES-III, KEDR

\[ R(s) = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \]

\[ \Delta a_\mu(\text{exp} - \text{th}) = (287 \pm 80) \cdot 10^{-11} \text{ (DHMZ'12)} \]

\( \Delta a_\mu(\text{exp} - \text{th}) \) corresponds to

\( (4.15 \pm 1.15)\% \cdot a_\mu^{\text{had,LO}} \)

FNAL expected precision of 140 ppb

\( 0.25\% \cdot a_\mu^{\text{had,LO}} \)
VEPP-2000 (2010-2013)

ILU
3 MeV Linac

B-3M
250 MeV synchro-
betatron

BEP
$e^+, e^-$
booster
825 MeV

e$^- \rightarrow e^+$
converter

CMD-3

SND

Beam energy
by Compton
backscattering

2 m

C.m. energy range is 0.32-2.0 GeV; unique optics – “round beams”

Design luminosity is $L = 10^{32} \text{1/cm}^2\text{s}$ @ $\sqrt{s} = 2 \text{ GeV}$

Experiments with two detectors, CMD-3 and SND, started by the end of 2010
Detector CMD-3
Collected luminosity in 2011-2013

The luminosity was limited by a deficit of positrons and limited energy of the booster.

The VEPP-2000 upgrade has started in 2013.

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Collected Luminosity (pb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ω(782)</td>
<td>8.3</td>
</tr>
<tr>
<td>2E &lt; 1 GeV</td>
<td>9.4</td>
</tr>
<tr>
<td>φ(1019)</td>
<td>8.4</td>
</tr>
<tr>
<td>2E &gt; 1.04 GeV</td>
<td>34.5</td>
</tr>
</tbody>
</table>
Exclusive channels $e^+e^- \rightarrow \text{hadrons}$

- At VEPP-2000 we do exclusive measurement of $\sigma(e^+e^- \rightarrow \text{hadrons})$.

- 2 charged

$$e^+e^- \rightarrow \pi^+\pi^-, K^+K^-, K_SK_L, p\bar{p}$$

- 2 charged + $\gamma$'s

$$e^+e^- \rightarrow \pi^+\pi^-\pi^0, \pi^+\pi^-\eta, K^+K^-\pi^0, K^+K^-\eta, K_SK_L\pi^0, \pi^+\pi^-\pi^0\eta,$$
$$\pi^+\pi^-\pi^0\pi^0, \pi^+\pi^-\pi^0\pi^0\pi^0, \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$$

- 4 charged

$$e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-, K^+K^-\pi^+\pi^-, K_SK^*$$

- 4 charged + $\gamma$'s

$$e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0, \pi^+\pi^-\eta, \pi^+\pi^-\omega, \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0, K^+K^-\eta, K^+K^-\omega$$

- 6 charged

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

- $\gamma$'s only

$$e^+e^- \rightarrow \pi^0\gamma, \eta\gamma, \pi^0\pi^0\gamma, \pi^0\eta\gamma, \pi^0\pi^0\pi^0\gamma, \pi^0\pi^0\pi^0\eta\gamma$$

- other

$$e^+e^- \rightarrow n\bar{n}, \pi^0e^+e^-, \eta e^+e^-$$
Published results from 2011-2013: CMD-3

- $K_SK_L$
- $\sigma(e^+e^+ \rightarrow 3(\pi^+\pi^-))$
- $\sigma(e^+e^+ \rightarrow K^+K^-\pi^+\pi^-)$
Dominant channel: $e^+e^- \rightarrow \pi^+\pi^-$

$|F_\pi|^2$

$\chi^2 / \text{ndf}$: 16.78 / 16

Prob: 0.4003

p0: 0.9961 ± 0.004429

Some corrections are not applied (result is “blinded”)
Dominant channel: $e^+ e^- \rightarrow \pi^+ \pi^-$

- Energy range below $\varphi$ was scanned in 2013. Data analysis is in progress.

- Energy range above $\varphi$ was scanned in 2011-2012. Data analysis for $\pi^+ \pi^-$ hasn’t started yet. There are known problems with data, which will limit precision, e.g. the beam energy was measured only for subset of energy points.

Current estimate of the systematic error:

~< 1% for momentum separation
~1.5-2% for energy deposition

Open the box when both methods <1%
Hopefully later this year
Recent result from CMD-3:

- $K_S K_L$ at $\varphi$, systematic precision 1.8%
- $K^+ K^-$ at $\varphi$, systematic precision 2.5% (under internal review)
$K^+ K^-$: comparison with other measurements

$K_S K_L$ at $\varphi$ is consistent between different experiments, but there is discrepancy in $K^+ K^-$ channel.

New CMD-3 $K^+ K^-$ cross-section is above CMD-2 and BaBar, but is consistent with isospin symmetry:

$$R = \frac{g_{\varphi K^+ K^-}}{g_{\varphi K_S K_L} \sqrt{Z(m_{\varphi})}} = 0.990 \pm 0.017$$

- $R_{SND} = 0.92 \pm 0.03 (2.6\sigma)$
- $R_{CMD-2} = 0.943 \pm 0.013 (4.4\sigma)$
- $R_{BaBar} = 0.972 \pm 0.017 (1.5\sigma)$
\[ K_S K_L \text{ and } K^+ K^-: \rho - \phi \text{ interference} \]

\[ R_{c/n} = \sigma(e^+ e^- \rightarrow K^+ K^-) \times \frac{p_{K^0}^3(s)}{p_{K^\pm}^3(s)} \times \frac{1}{Z(s)} - \delta \times \sigma(e^+ e^- \rightarrow K_S K_L) \]

- \( r_{\rho,\omega} = 0.91 \pm 0.04 \)

  deviation of SU(3) relations

  \( g_{\omega K^+ K^-} = g_{\rho K^+ K^-} = -g_{\phi K^+ K^-}/\sqrt{2} \)

- \( \delta = 0.989 \pm 0.003 \)

  test of systematic errors
$e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^- \mathbf{\oplus} \varphi(1020)$

PLB 768 (2017) 345-350

2011-2013 data, 10 $1$/pb
systematic error 3.5%

$B(\varphi \rightarrow 2(\pi^+\pi^-)) = (6.5 \pm 2.7 \pm 1.6) \times 10^{-6}$
$e^+ e^- \rightarrow \pi^+ \pi^- \pi^0 \eta$

First measurement of total $e^+ e^- \rightarrow \pi^+ \pi^- \pi^0 \eta$ cross section. Systematic error is 15%.

https://arxiv.org/abs/1706.06267v1

2011

2012
Dynamics of $e^+e^- \rightarrow \pi^+\pi^-\pi^0\eta$

At “low” energies dominated by $e^+e^- \rightarrow \omega\eta, \varphi\eta$

At “high” energies dominated by $e^+e^- \rightarrow a_0(980)\rho$

We see non-$\omega, \varphi, a_0$ contribution

Possible mechanism:

$e^+e^- \rightarrow \omega(1650) \rightarrow \rho(1450,1700)\pi \rightarrow \rho(770)\eta\pi$
CMD-3 preliminary: $\pi^+\pi^-(\omega, \eta), K^+K^-(\omega, \eta)$
\[ \omega \rightarrow \pi^0 e^+ e^- \]

- Motivation: study of the internal structure of the vector mesons (transition form factor).
- \( \pi^0 \rightarrow \gamma \gamma \).
- \( \pi^+ \pi^- \pi^0 \): opening angle between tracks, kinematic of the decay, recoil mass of photon pairs.
- \( \pi^0 \gamma \): The method for \( \pi^0 e^+ e^- \) and \( \pi^0 \gamma \) (with conversion \( \gamma \) on material of the detector) separation is based on information from drift chamber and uses a neural network.

- 1339 events of decay were selected (The amount of statistic \( 8.1/\text{pb} \));
- Current value: \( \text{Br}(\omega \rightarrow \pi^0 e^+ e^-) = (8.15 \pm 0.18) \times 10^{-4} \) (stat.) (the contributions of \( \omega \rightarrow \pi^+ \pi^- \pi^0 , \omega \rightarrow \pi^0 \gamma \) were not taken into account).
VEPP-2000 upgrade (2013-2016)

Collider upgrades:
- x10 more intense positron source
- booster up to 1 GeV (match VEPP-2000)

CMD-3 upgrades:
- New electronics for Lxe calorimeter
- New TOF system
- DAQ and electronics upgrades

Detectors resumed data taking by the end of 2016
2017 data taking

In 2017: big improvement in luminosity at high energy, still way to go

Collected data at “high” energies

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>1 pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.007 GeV</td>
<td>4</td>
</tr>
<tr>
<td>p\bar{p} and n\bar{n} threshold</td>
<td>14</td>
</tr>
<tr>
<td>Overall</td>
<td>50</td>
</tr>
</tbody>
</table>

About 50 pb\(^{-1}\) collected
Overview of CMD-3 data taking runs

CMD-3 Integrated Luminosity

![Graph showing CMD-3 Integrated Luminosity over time for different years: 2011, 2012, 2013, and 2017. The graph plots luminosity in units of 1/pb against days. Each year has a distinct line color and style.]
2017: $e^+e^- \rightarrow 3(\pi^+\pi^-)$ at $N\bar{N}$ threshold

In 2017, CMD-3 collected 13 1/pb in the narrow energy range around $N\bar{N}$ threshold. Very first look at the data:

- the sharp drop in cross section is confirmed
- can be described as single transition at $(m_p + m_n)/2$ with ~2.5 MeV width
- or as two narrow transitions at $m_p$ or $m_n$ (consistent with only beam energy spread, $\sigma_{2E} \approx 1.2$ MeV)
Conclusion

• In 2011-2013 CMD-3 has collected 60 1/pb in the whole energy range $0.32 \leq \sqrt{s} \leq 2.0$ GeV, available at VEPP-2000.

• Data analysis of exclusive modes of $e^+e^- \rightarrow \text{hadrons}$ is in progress. Many results have been published.

• In 2013-2016 the collider and the CMD-3 detector have been upgraded.

• The data taking was resumed in 2017. About 50 1/pb were collected over 5 months in the energy range above 1.28 GeV.
CMD-3 Performance (2011-2013)

- 1.0-1.3 T magnetic field
- Tracking: $\sigma_{R\phi} \sim 100 \mu$, $\sigma_z \sim 2 - 3$ mm
- Combined EM calorimeter (LXE, CsI, BGO), 13.5 $X_0$
  - $\sigma_E/E \sim 3\% - 10\%$
  - $\sigma_\Theta \sim 5$ mrad

$\Delta p/p$

$\Delta x$, mm calorimeters

Relative energy resolution $\sigma_E/E$

Beam energy, MeV
New TOF system

“Old” TOF
2012-2013

In 2013-2016 the TOF system was completely replaced
- More granulated (16 counters → 175 counters)
- 0.8 ns resolution per counter

“New” TOF (2017-)

Strip scintillation counters
LXe outer shell
$R(s)$ at $N\bar{N}$ threshold

One of first results from CMD-3:

- Sudden drop of $e^+e^- \to 3(\pi^+\pi^-)$ cross section at $N\bar{N}$ threshold
- Confirmed, that $p\bar{p}$ production cross section increases quickly at threshold
- Preliminary studies of dynamics of $e^+e^- \to 3(\pi^+\pi^-)$, hint of energy dependent dynamics in 1.7-1.9 GeV energy range
Search for $e^+e^- \rightarrow \eta'(958)$


C-even resonances can be produced via $2\gamma$

Theory: assuming real $\gamma$

$B(\eta' \rightarrow e^+e^-) = 3.7 \cdot 10^{-11}$

$\gamma$ virtuality and transition form factor can enhance it

New limit:

$B(\eta' \rightarrow e^+e^-) < 5.6 \times 10^{-9} \ (90\% \text{CL}) - \text{SND+CMD-3}$

Dedicated data taking at $\sqrt{s} = M_{\eta'}$

Continuous beam energy monitoring is crucial
Search for FCNC process: $e^+ e^- \rightarrow D^{*0}$

Talk by Alexey Petrov (WSU) at ICHEP’16 and JHEP 1511 (2015) 142

\[
\sigma(e^+e^- \rightarrow D\pi)_{\sqrt{s} \approx m_{D^*}} = \sigma_{D^*}(s) = \frac{12\pi}{m_{D^*}^2} B_{D^* \rightarrow e^+e^-} B_{D^* \rightarrow D\pi} \frac{m_{D^*}^2 \Gamma_0^2}{(s - m_{D^*}^2)^2 + m_{D^*}^2 \Gamma_0^2}
\]

Estimated sensitivity:

\[
B_{D^* \rightarrow e^+e^-} \geq \frac{4 \times 10^{-10}}{\varepsilon \int L dt [pb^{-1}] \times \frac{\sigma_{2E}}{\Gamma_{D^*} [60 \text{ keV}]}}
\]

Standard Model:

\[
B_{D^* \rightarrow e^+e^-} \approx (0.1 \div 7) \times 10^{-19}
\]

Example of New Physics contribution:

\[
B_{D^* \rightarrow e^+e^-}^{Z'} < 2.5 \times 10^{-11}
\]

In 2017 CMD-3 collected $4 \, pb^{-1}$ at 2007 MeV with $\sigma_{2E} \approx 2 \, \text{MeV}$