Measurements of $e^+e^- \rightarrow$ hadrons cross sections with CMD-3 at VEPP-2000

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Introduction

Measurement of the cross section $e^+e^- \rightarrow \text{hadrons}$ in the low energy range up to 2 GeV is interesting for:

- measurement of parameters of light vector mesons $\rho$, $\omega$, $\varphi$, $\varphi'$, $\rho''$, $\omega'$, $\omega''$
- search of exotics (light hybrids and glueballs)
- CVC test in comparison with spectral functions of tau decays

- measurement of $R(s)$:

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

It is essential for the interpretation of precision measurements of the $(g-2)$ of muon - good test of SM
The value and the error of the hadronic contribution to muon $(g-2)$ are dominated by low energy $R(s)$ ($<2\text{GeV}$ give 92%).
SM prediction for muon g-2

\[ a_\mu^{\text{exp}} = \frac{(g-2)_\mu}{2} = (11 \,659 \,208.9 \pm 6.3) \times 10^{-10} \]

\[ a_\mu^{\text{th}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{had}} \]

\[ \Delta(\text{Exp. - Theor.}) \sim 3 - 3.6 \sigma \]

Main channels which contribute 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)

Isospin relations:
- 5.98 \( \pm \) 0.42 for not measured \( KK\pi, KK2\pi, 2\pi4\pi0, 2\pi3\pi0 \)
  - (12.46 \( \pm \) 0.76 for \( \sqrt{s} < 2 \) GeV HLMNT 11, J. Phys. G 38, 085003 (2011))

- \( R_{\text{QCD}[2\text{-}11\text{GeV}]} \)
  - 41.19 \( \pm \) 0.82

- LBL
  - 10.5 \( \pm \) 2.6

- Th. TOTAL
  - 11 659 180.2 \( \pm \) 4.9

New g-2 experiments at FNAL and J-PARC have plans to reduce error to 1.5\( \times \)10\(^{-10} \)
Exclusive cross-sections

CMD-2 and SND data

BaBar data
**VEPP-2000 e⁺e⁻ collider**

Main idea: Round Beams

\[
L = \frac{\pi \gamma^2 \tilde{e}^2 \tilde{e}^2 \gamma \xi f}{r_e \beta_y} \left(1 + \frac{\sigma_y}{\sigma_x}\right)^2
\]

\[
L = \frac{4 \pi \gamma^2 \tilde{e}^2 \gamma \xi f}{r_e \beta^*}
\]
CMD-3 Detector

1 – beam pipe, 2 – drift chamber, 3 – BGO calorimeter (680 crystals), 4 – Z-chamber, 5 – CMD-3 superconducting solenoid, 6 – calorimeter LXe (400 liters), 7 – calorimeter CsI (1152 crystals), 8 – iron yoke, 9 – solenoids of VEPP-2000, (not shown) muon range system (scintillation counters) and TOF system.
Collinear Events @ CMD-3
($E_{c.m.} = 1.95$ GeV)
The maximum luminosity is $2 \cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ at 1.7-1.8 GeV, falling much slower with decreasing energy than before the round beams.

At high energies luminosity is limited by a deficit of positrons and maximum energy of the booster (800 MeV now)

In 2013 we reached $2 \times 160 \text{ MeV}$, the smallest energy ever measured at ee colliders.
Energy measurement by Compton back scattering

\[ e^+ e^- \rightarrow \pi^+ \pi^- \] by CMD3

Clean collinear events (mostly without background)

Plans to reduce systematic error from 0.6% \(-\) 0.3%:
- Event separation will be checked by different methods 0.2%
- Better test of Radiative corrections 0.2% \(-\) 0.1%
- Determination of fiducial volume controlled independently by LXe and ZC subsystems (0.1%)

Statistical precision of cross section measurement

Collected L \sim 60 \text{ pb}^{-1} \text{ per detector}

- 8.3 pb\(^{-1}\) \(\omega\) - region
- 9.4 pb\(^{-1}\) < 1 GeV (except \(\omega\))
- 8.4 pb\(^{-1}\) \(\phi\) - region
- 34.5 pb\(^{-1}\) > 1.04 GeV
\[ e^+e^- \rightarrow \pi^+\pi^- \text{ by CMD3} \]

\[ |F_{\pi}|^2 \]

Preliminary, not all corrections taken into account

e/\mu/\pi \text{ separation using energy deposition in calorimeter}

e/\mu/\pi \text{ separation using particles momentum}
We have very clean selection of 6 and 5 pions

Other data for $e^+e^- \rightarrow 3(\pi^+\pi^-)$

The best description is with one $\rho(770)$ and 4 pions in $S$-wave
Process $e^+e^- \rightarrow 2(\pi^+\pi^-\pi^0)$

We have relatively clean selection of 2 and 1 $\pi^0$ in addition to four charged tracks.

many intermediate states are seen, systematic errors are under study.
Look at the Process $e^+ e^- \rightarrow 2(\pi^+ \pi^-)\pi^0$

Example of $\omega f_0(980)$ signal in $\omega \pi^+ \pi^-$ final state.

Detailed analysis is coming...
We confirm $a_1(1260)\pi$ dominance. Some other states ($\rho(770)f_0(600)$, $\rho(770)f_0(980)$) are seen. Statistical errors are at the level of 1-2% per point. Analysis of systematic errors is in progress.
Study of $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$

In addition to dominant $\omega\pi^0$ and $a_1\pi$ we see $\rho^+\rho^-, \rho(770)f^0(600)\pi$, $\rho(770)f^0(980)$

We have statistical errors at the level of 1-2% per point. Systematic errors are under study.
Preliminary results on $e^+e^- \rightarrow pp$

Cross section

Ratio $G_E/G_M$ from analysis of angular distributions
Process \( e^+e^- \rightarrow K^+K^-\pi^+\pi^- \)

Rich dynamics seen, many intermediate states:

\( K_1(1270)K \rightarrow K^*(892)K\pi \)
\( K_1(1400)K \rightarrow K^*(892)K\pi \)
\( K_1(1270)K \rightarrow \rho KK \)
\( K^*(892)K^*(892), \phi\pi\pi \)
Processes $e^+e^- \rightarrow K^+K^-\eta$

$K^+K^-$ invariant mass and missing mass

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

Number of events vs. Missing mass of $(K^+,K^-)$, MeV

BABAR

CMD3

$\sigma(e^+e^-\rightarrow K^+K^-\eta)$, nb

$E_{c.m.}$, GeV

Preliminary
Processes $e^+e^- \rightarrow K^+K^-, K_SK_L$
Conclusion

- New accelerator concepts used at the VEPP-2000 collider were successfully proved. First three experimental runs generated considerable amount of data which analysis is in progress now. The second detector, SND, with very good photon detection collected similar statistics and has a lot of various results on hadronic cross sections, particularly on channels with neutrals.

- The last experimental run ended in the middle of July 2013. Then a long shutdown for ~1.5 years to increase the booster energy to 1 GeV and commission the new injection complex to reach $10^{32}$ cm$^{-2}$s$^{-1}$

- Hopefully, in the next 5-10 years the VEPP-2000 will produce the integrated luminosity ~ 1 fb$^{-1}$ which should provide new precise interesting results on the hadron production in $e^+e^-$ annihilation.

Thank You