6th International Symposium on Radiative Corrections - RADCOR 2002
6th Zeuthen Workshop on Elementary Particle Theory - Loops and Legs

Recent results on low energy R measurements in Novosibirsk

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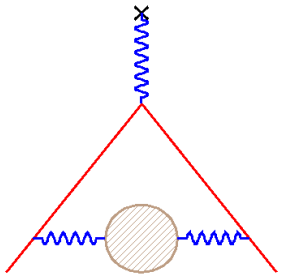
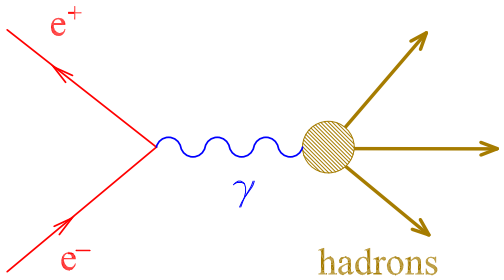
Why R at low energies is so interesting?

$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

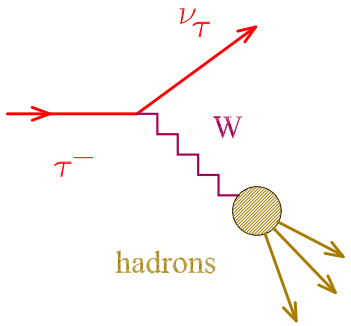


Necessary to calculate hadronic contribution to muon (g-2)

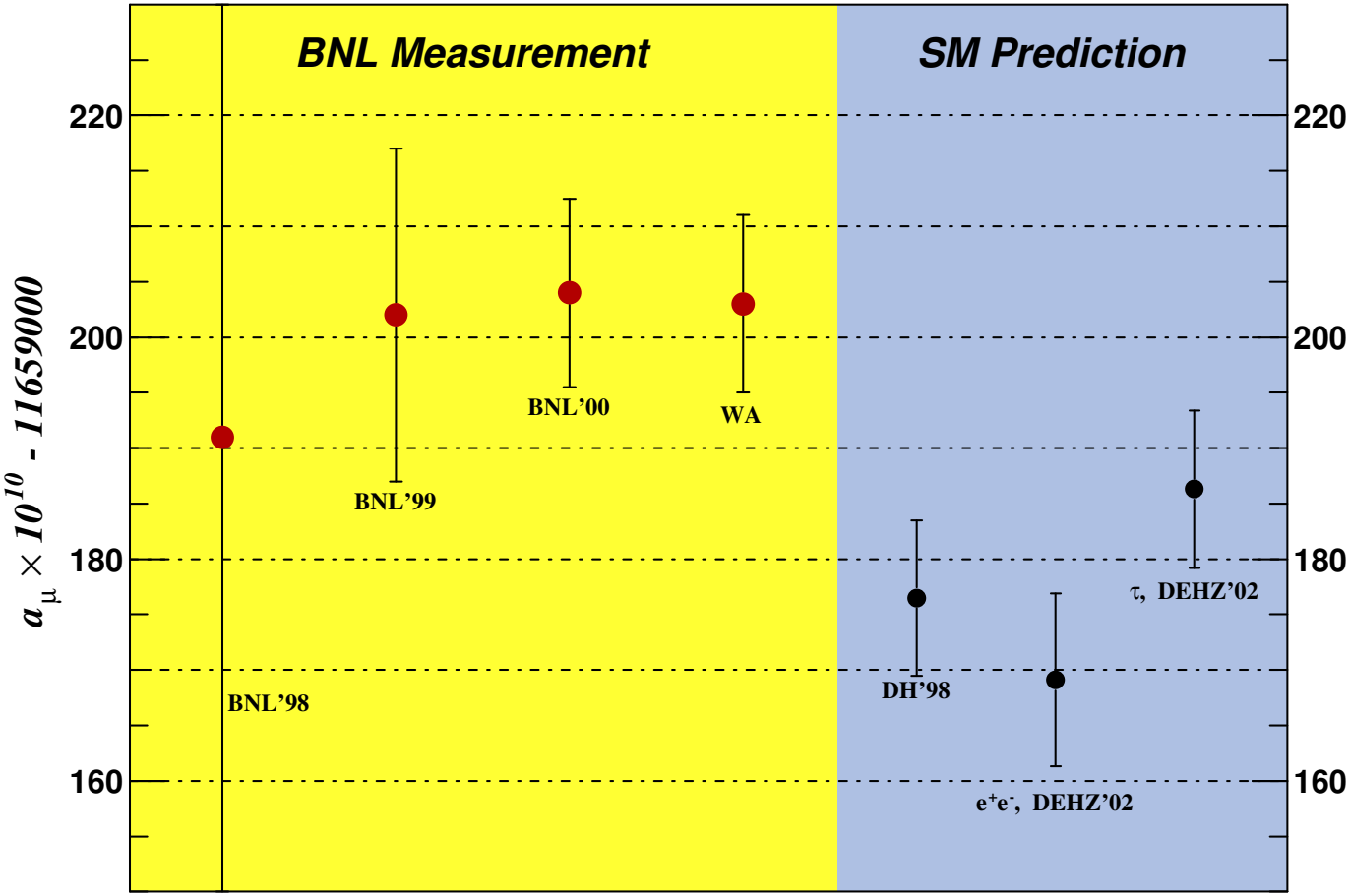
$$a_\mu(had;1) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s} K(s) R(s)$$



- R(s) at low energies provides dominant contribution to both value and uncertainty
- Cannot be calculated from the first principles
- Can be related to hadronic τ decays



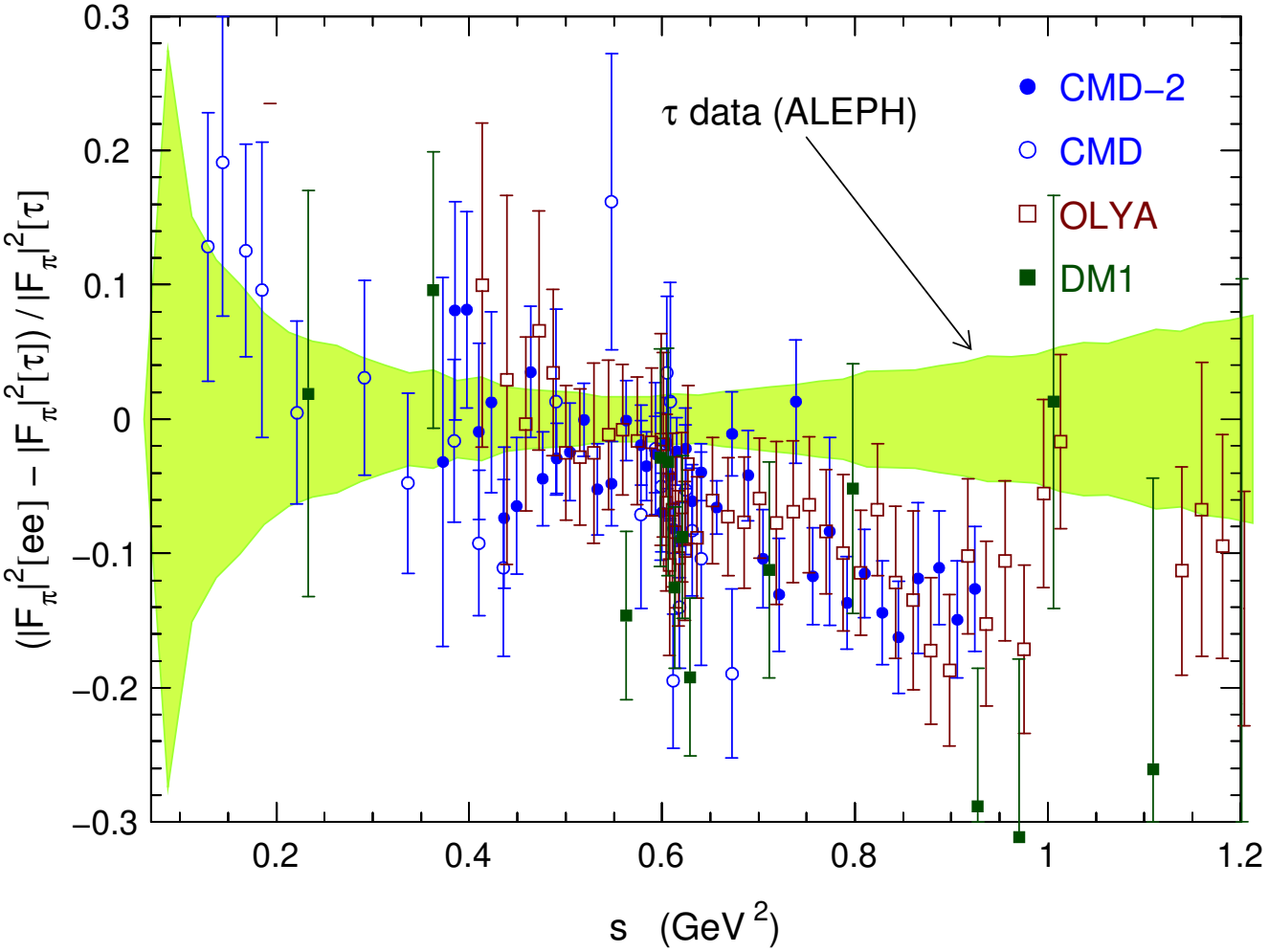
Measurement of a_μ at BNL



$$a_\mu(exp) - a_\mu(SM; e^+e^-) = (33.9 \pm 11.2)\cdot 10^{-10} \quad (3.0\sigma)$$

$$a_\mu(exp) - a_\mu(SM; \tau) = (16.7 \pm 10.7)\cdot 10^{-10} \quad (1.6\sigma)$$

Comparison between e^+e^- and τ data

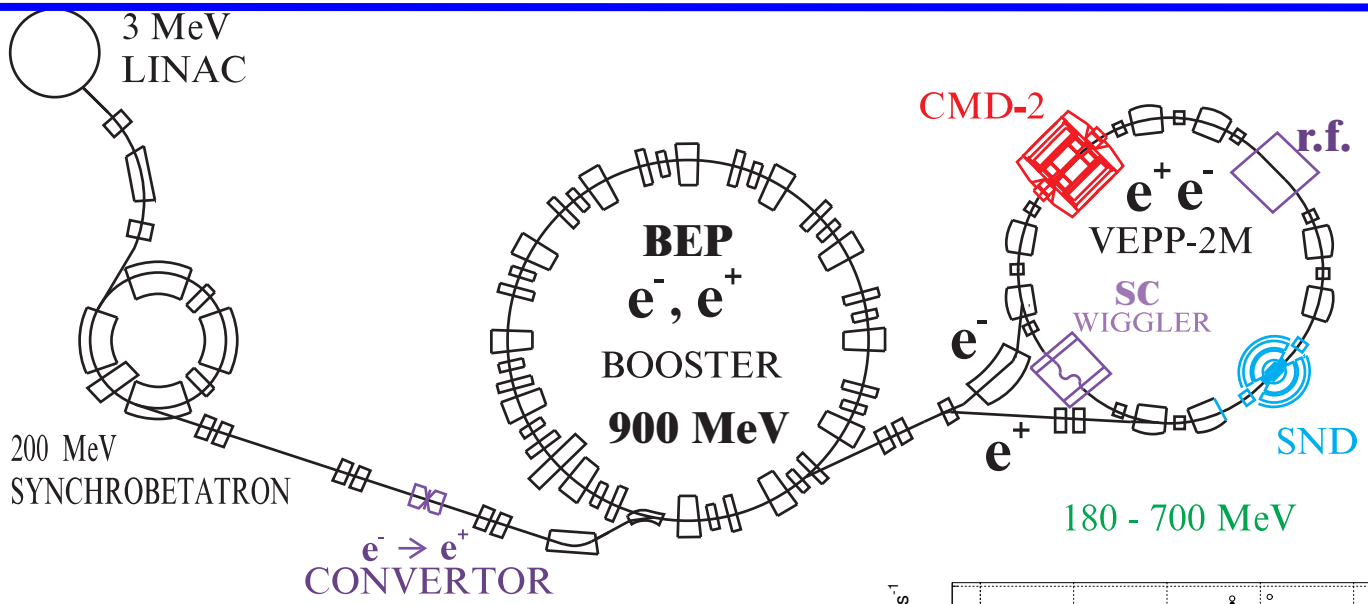


M. Davier, S.Eidelman, A.Hocker and Z.Zhang, hep-ph/0208177

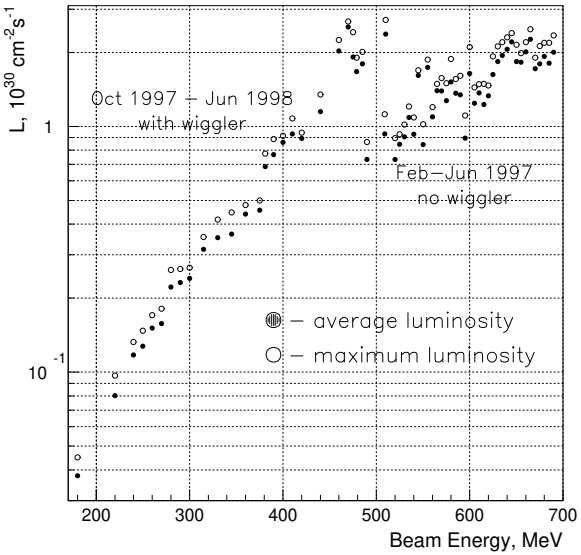
Hadronic contribution to a_μ

Modes	Energy [GeV]	$a_\mu^{\rm had,LO}$ (10^{-10}) e^+e^-	τ ()	$\Delta(e^+e^- - \tau)$
Low s exp. $\pi^+\pi^-$	$[2m_{\pi^\pm} - 0.500]$	$58.04 \pm 1.70 \pm 1.14$	$53.99 \pm 1.67 \pm 0.29$	$+4.1 \pm 2.7$
$\pi^+\pi^-$	$[0.500 - 1.800]$	$440.81 \pm 4.65 \pm 1.54$	$459.03 \pm 2.94 \pm 2.51$	-18.2 ± 6.2
$\pi^0\gamma$, $\eta\gamma$	$[0.500 - 1.800]$	$0.93 \pm 0.15 \pm 0.01$	-	-
ω	$[0.420 - 0.810]$	$36.94 \pm 0.84 \pm 0.80$	-	-
$\pi^+\pi^-\pi^0$ [below ϕ]	$[0.810 - 1.000]$	$4.20 \pm 0.40 \pm 0.05$	-	-
ϕ	$[1.000 - 1.055]$	$34.80 \pm 0.92 \pm 0.64$	-	-
$\pi^+\pi^-\pi^0$ [above ϕ]	$[1.055 - 1.800]$	$2.45 \pm 0.26 \pm 0.03$	-	-
$\pi^+\pi^-2\pi^0$	$[1.020 - 1.800]$	$16.73 \pm 1.32 \pm 0.20$	$21.38 \pm 1.08 \pm 0.60$	-4.7 ± 1.2
$2\pi^+2\pi^-$	$[0.800 - 1.800]$	$13.95 \pm 0.90 \pm 0.23$	$12.31 \pm 0.96 \pm 0.40$	$+1.6 \pm 1.1$
$2\pi^+2\pi^-\pi^0$	$[1.019 - 1.800]$	$2.09 \pm 0.43 \pm 0.04$	-	-
$\pi^+\pi^-3\pi^0$	$[1.019 - 1.800]$	$1.29 \pm 0.22 \pm 0.02$	-	-
$3\pi^+3\pi^-$	$[1.350 - 1.800]$	$0.10 \pm 0.10 \pm 0.00$	-	-
$2\pi^+2\pi^-2\pi^0$	$[1.350 - 1.800]$	$1.41 \pm 0.30 \pm 0.03$	-	-
$\pi^+\pi^-4\pi^0$	$[1.350 - 1.800]$	$0.06 \pm 0.06 \pm 0.00$	-	-
$\eta(\to \pi^+\pi^-\gamma,\ 2\gamma)\pi^+\pi^-$	$[1.075 - 1.800]$	$0.54 \pm 0.07 \pm 0.01$	-	-
$\omega(\to \pi^0\gamma)\pi^0$	$[0.975 - 1.800]$	$0.63 \pm 0.10 \pm 0.01$	-	-
$\omega(\to \pi^0\gamma)(\pi\pi)^0$	$[1.340 - 1.800]$	$0.08 \pm 0.01 \pm 0.00$	-	-
K^+K^-	$[1.055 - 1.800]$	$4.63 \pm 0.40 \pm 0.06$	-	-
$K_S^0K_L^0$	$[1.097 - 1.800]$	$0.94 \pm 0.10 \pm 0.01$	-	-
$K^0K^\pm\pi^\mp$	$[1.340 - 1.800]$	$1.84 \pm 0.24 \pm 0.02$	-	-
$K\overline{K}\pi^0$	$[1.440 - 1.800]$	$0.60 \pm 0.20 \pm 0.01$	-	-
$K\overline{K}\pi\pi$	$[1.441 - 1.800]$	$2.22 \pm 1.02 \pm 0.03$	-	-
$R = \sum$ excl. modes	$[1.800 - 2.000]$	$8.20 \pm 0.66 \pm 0.10$	-	-
R [Data]	$[2.000 - 3.700]$	$26.70 \pm 1.70 \pm 0.00$	-	-
J/ψ	$[3.088 - 3.106]$	$5.94 \pm 0.35 \pm 0.03$	-	-
$\psi(2S)$	$[3.658 - 3.714]$	$1.50 \pm 0.14 \pm 0.00$	-	-
R [Data]	$[3.700 - 5.000]$	$7.22 \pm 0.28 \pm 0.00$	-	-
R_{udsc} [QCD]	$[5.000 - 9.300]$	$6.87 \pm 0.10 \pm 0.00$	-	-
R_{udscb} [QCD]	$[9.300 - 12.00]$	$1.21 \pm 0.05 \pm 0.00$	-	-
R_{udscbt} [QCD]	$[12.0 - \infty]$	$1.80 \pm 0.01 \pm 0.00$	-	-
$\sum (e^+e^- \to \text{hadrons})$	$[2m_{\pi^\pm} - \infty]$	$684.7 \pm 6.0_{\rm exp} \pm 3.6_{\rm rad}$	$701.9 \pm 4.7_{\rm exp} \pm 1.2_{\rm rad} \pm 3.8_{\rm SU(2)}$	$-17.2 \pm 8.0_{\rm tot}$

Collider VEPP-2M

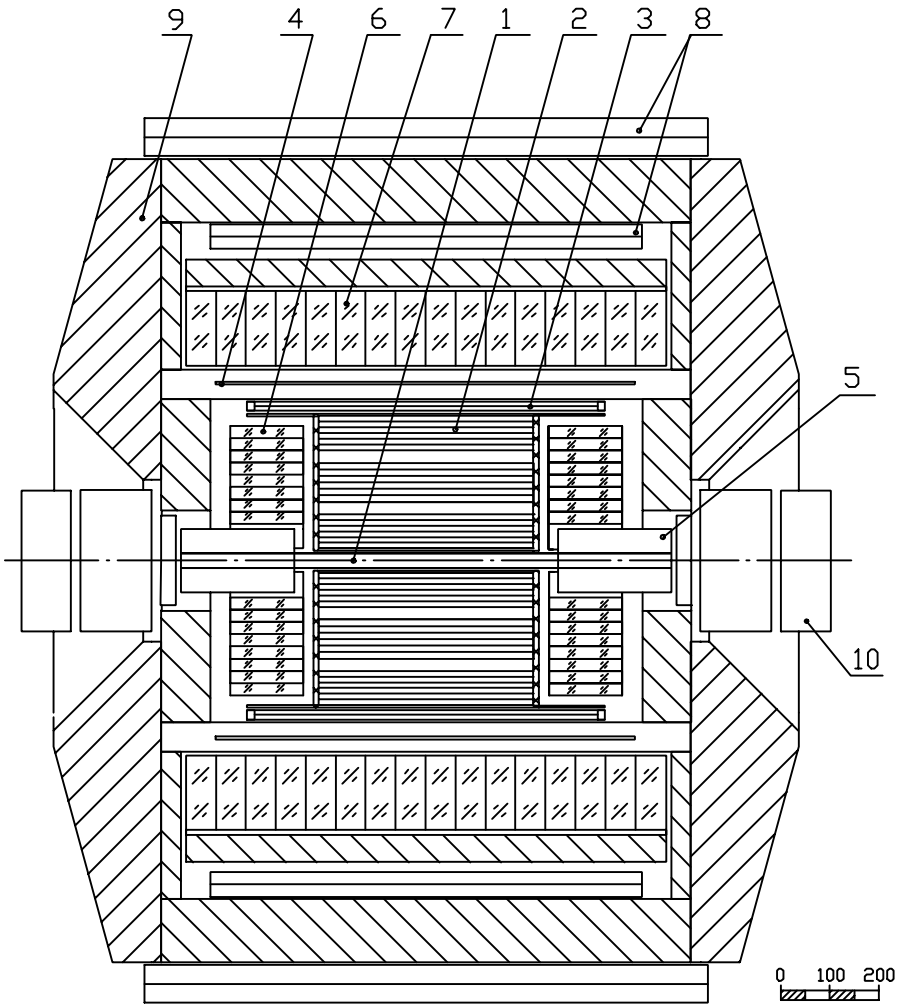


Beam energy	2*(180-700) MeV
Peak luminosity	$3 \cdot 10^{30}$ 1/cm^{2}s
Number of bunches	1
Interaction regions	2



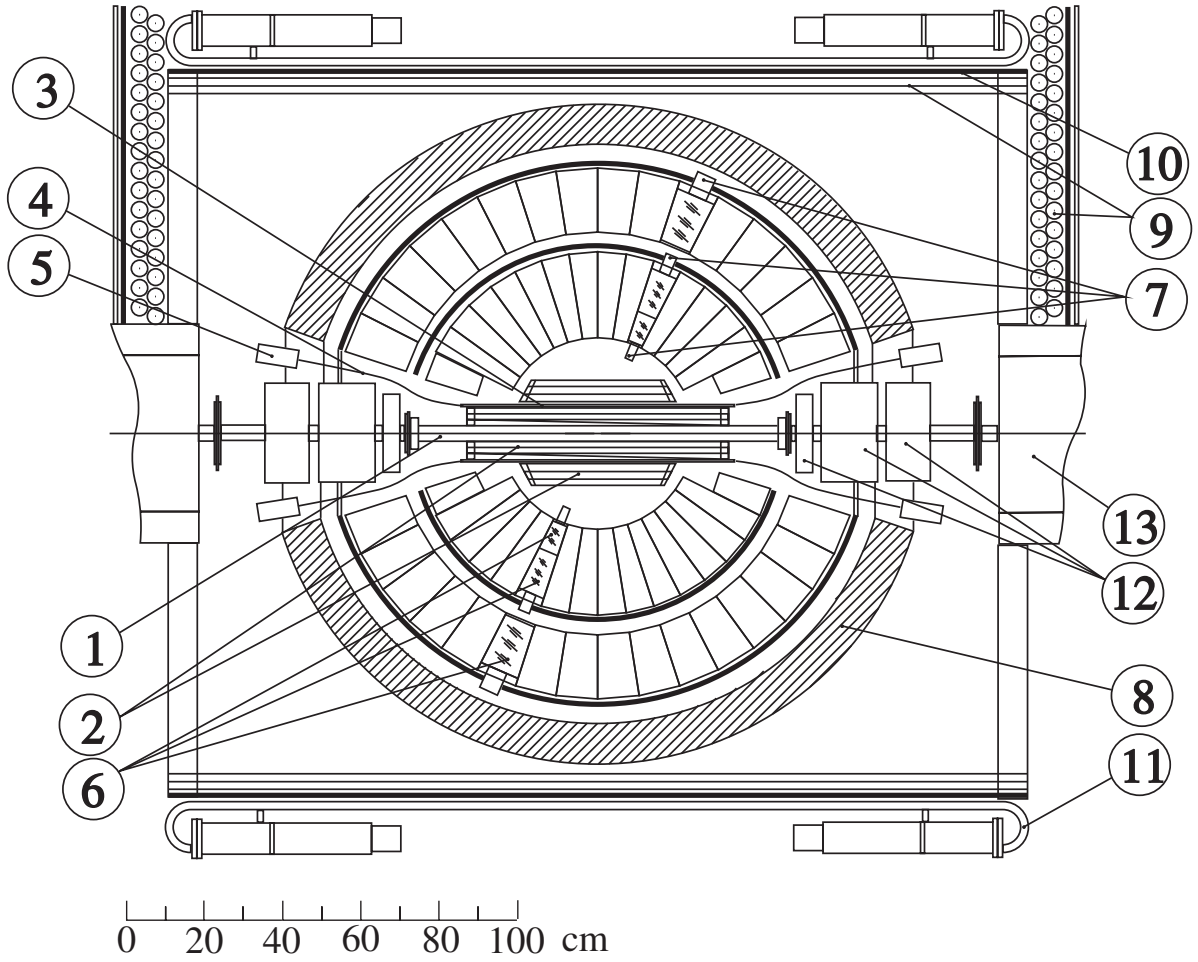
Detector CMD-2

1. Beam pipe
2. Drift chamber
3. Z-chamber
4. Superconductive solenoid
5. Compensating magnet
6. BGO calorimeter
7. CsI (Tl) calorimeter
8. Muon range system
9. Iron yoke
10. Quadrupole lenses



Detector SND

1. Beam pipe
2. Drift chamber
3. Coincidence counter
4. Fiber light guide
5. PMTs
6. NaI (Tl) crystals
7. Phototriodes
8. Iron absorber
9. Muon tubes
10. 1 cm iron plate
11. Muon counters
12. Magnetic lenses
13. Bending magnets



Data collected at CMD-2

Total collected:

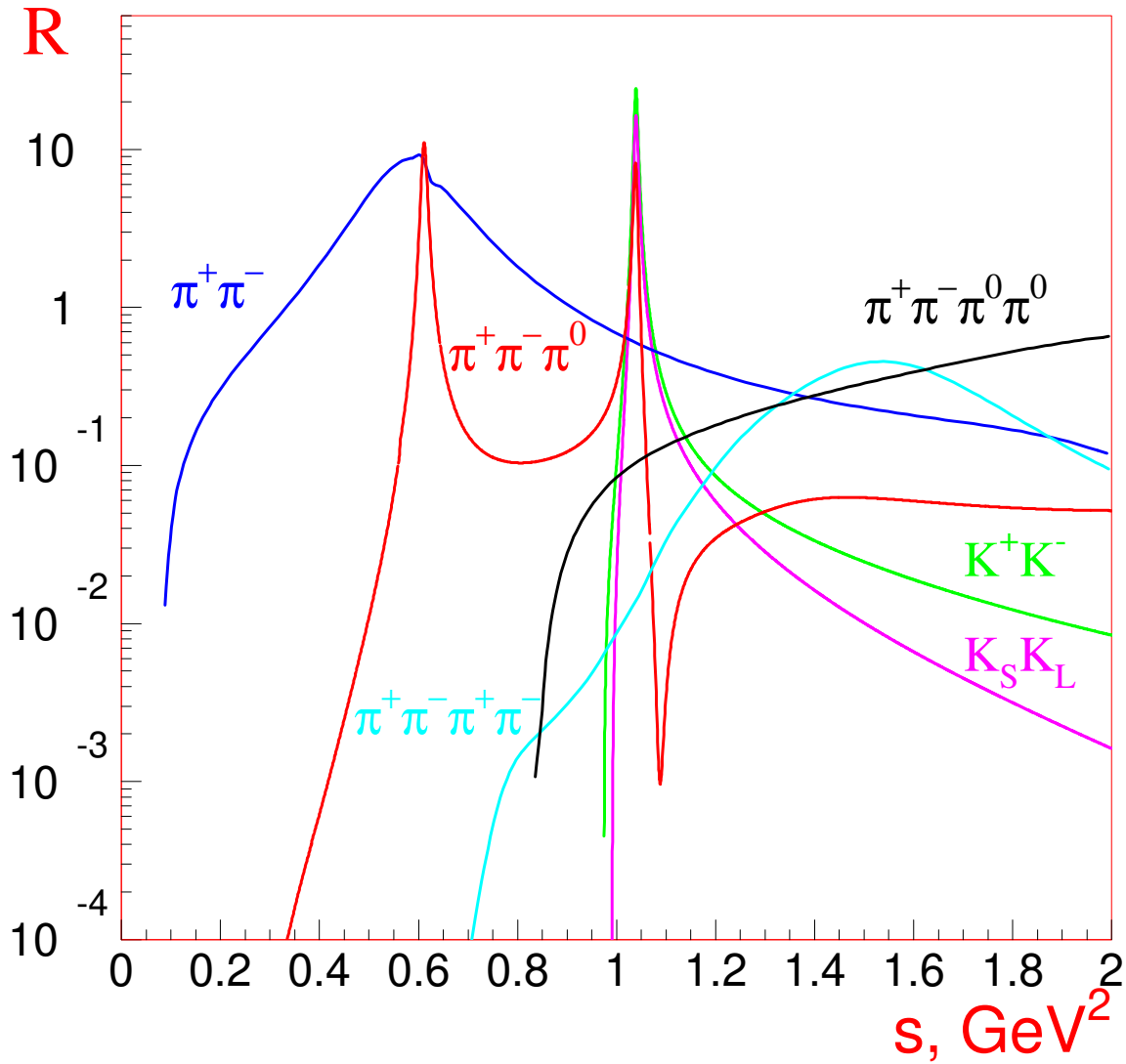
- ≈ 30 1/pb
- $2 \cdot 10^7$ φ decays
- $5 \cdot 10^6$ $\pi^+\pi^-$ decays
- $3 \cdot 10^6$ ω decays
- $2 \cdot 10^7$ multi-hadron events

ρ, ω mesons (2E=0.36–0.98 GeV)	
Feb 1994	0.15 1/pb
Dec 1994 – Jun 1995	0.16 1/pb
Sep 1996 – Oct 1996	0.10 1/pb
Mar 1998 – Jun 1998	3.5 1/pb
Dec 1999 – Jun 2000	4.5 1/pb

φ meson (2E=0.98–1.04 GeV)	
Feb 1993 – Jul 1993	1.43 1/pb
Jan 1994, Nov 1994	0.21 1/pb
Apr 1996 – Jul 1996	2.18 1/pb
Oct 1997 – Mar 1998	11.93 1/pb

Above φ (2E=1.04–1.37 GeV)	
Feb 1997 – Jun 1997	5.9 1/pb
Jan 1999 – Jun 1999	2.5 1/pb

Exclusive contributions to R at VEPP-2M energy



Cross-section $e^+e^- \to \pi^+\pi^-$ - data analysis

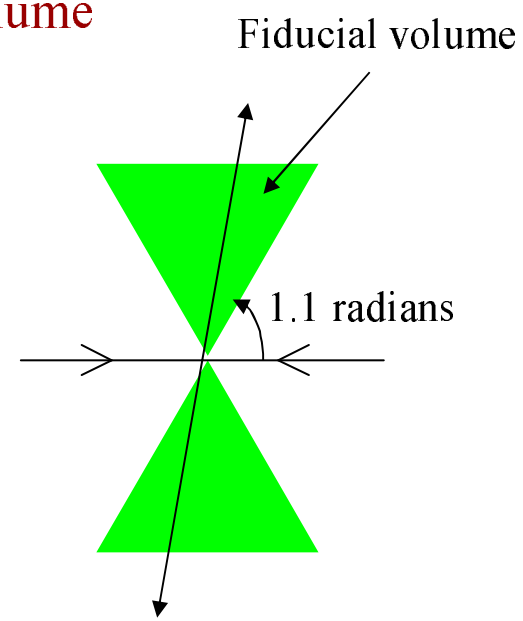
$$\sigma_{\pi\pi} = \frac{N_{\pi\pi}}{N_{ee} + N_{\mu\mu}} \cdot \frac{\sigma_{ee}(1+\delta_{ee})\varepsilon_{ee} + \sigma_{\mu\mu}(1+\delta_{\mu\mu})\varepsilon_{\mu\mu}}{(1+\delta_{\pi\pi})\varepsilon_{\pi\pi}(1-\Delta_{NI})(1-\Delta_D)}$$

1. Select collinear events inside the same fiducial volume
   $e^+e^- \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ and cosmic background

2. Reject cosmic background
   Spatial distribution of vertex

3. Separate e, μ, π

4. Calculate cross-section
   Radiative corrections, corrections for pion losses due to nuclear interactions and decays



How to achieve small systematic error

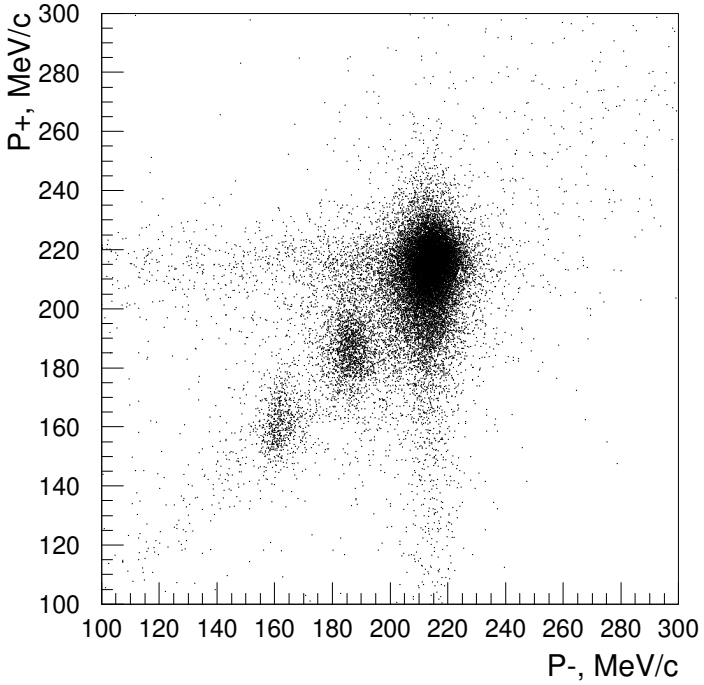
- Precise determination of fiducial volume
  Use Z-chamber to define fiducial volume
- Cancel detection efficiency
  Adjust cuts to minimize difference between e, μ, π
- e/μ/π separation with small systematic error

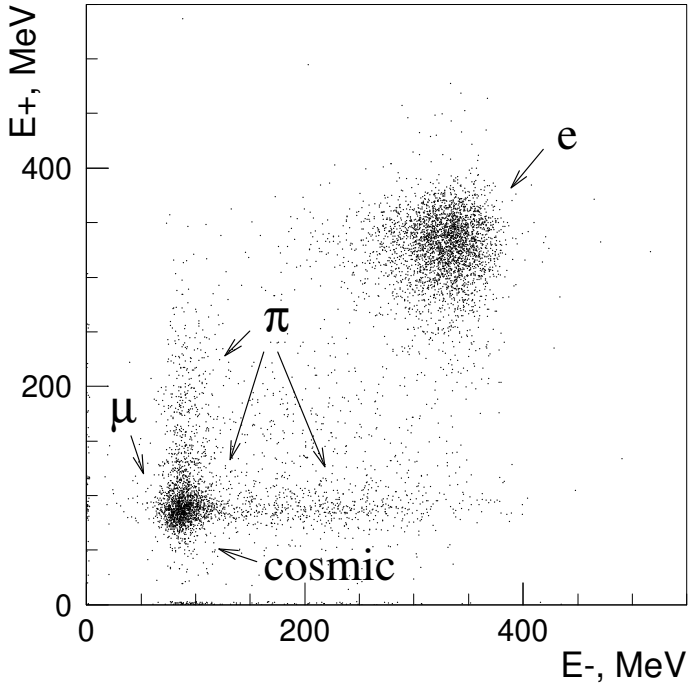
  Link $N_{\mu\mu}$ and N_{ee}: $N_{\mu\mu} = N_{ee} \cdot \frac{\sigma_{\mu\mu}(1+\delta_{\mu\mu})}{\sigma_{ee}(1+\delta_{ee})}$
- Minimize pion losses
  Thin beam pipe
- Improved calcuation of radiative corrections
- Measure beam energy with resonant depolarization technique

Cross-section $e^+e^- \to \pi^+\pi^-$ - event separation

Energies 2E<600 MeV: e, μ and π are separated by momentum

Energies 2E>600 MeV: e and μ /π are separated by energy deposition,
$N_{\mu\mu}/N_{ee}$ is fixed according to QED





Cross-section $e^+e^- \to \pi^+\pi^-$ - radiative corrections

Simple case

$$\sigma_{\pi\pi} = \frac{N_{\pi\pi}}{N_{ee}} \cdot \sigma_{ee}$$

With effects of FSR, ISR, VP

$$\sigma_{\pi\pi} = \frac{N_{\pi\pi}}{N_{ee}} \cdot \frac{\sigma_{ee}(1+\delta_{ee})}{(1+\delta_{\pi\pi})}$$

Radiative correction

- σ_{ee} and $\sigma_{\mu\mu}$ are "visible" cross-sections

  δ_{ee} and $\delta_{\mu\mu}$ include effects of ISR, FSR and VP
- By common agreement, effects of VP are absorbed by $\sigma_{\pi\pi}$

  $\delta_{\pi\pi}$ includes effects of ISR, FSR and does not include VP
- For calculation of R one needs "bare" cross-section $e^+e^- \to \pi^+\pi^-(\gamma)$

  we remove effects of VP from $\sigma_{\pi\pi}$ and add FSR to 4π

$$\sigma^0_{\pi\pi(\gamma)} = \sigma_{\pi\pi} \cdot |1-\Pi(s)|^2 \cdot \left(1+\frac{\alpha}{\pi}\Lambda(s)\right)$$

Cross-section $e^+e^- \to \pi^+\pi^-$ - radiative corrections

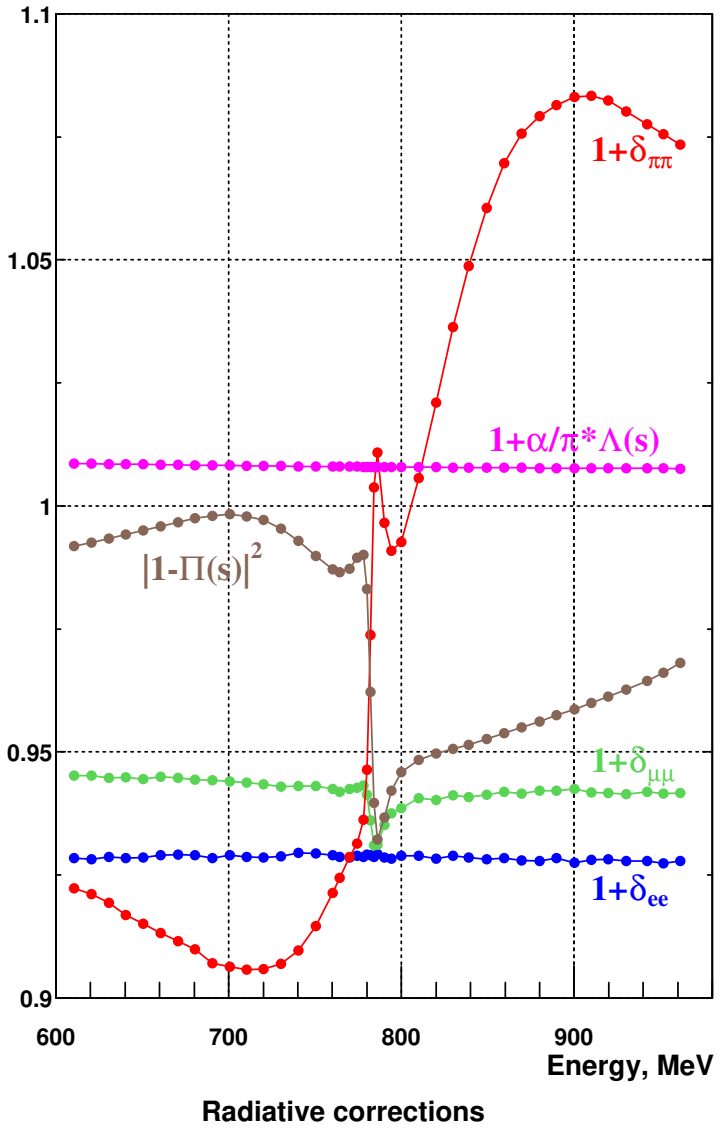
Differential cross-sections with radiative corrections is based on

A.B.Arbuzov et al., JHEP 10 (1997)

Taken into account:

- many photons in narrow cones around initial and final particles
- one photon outside narrow cones

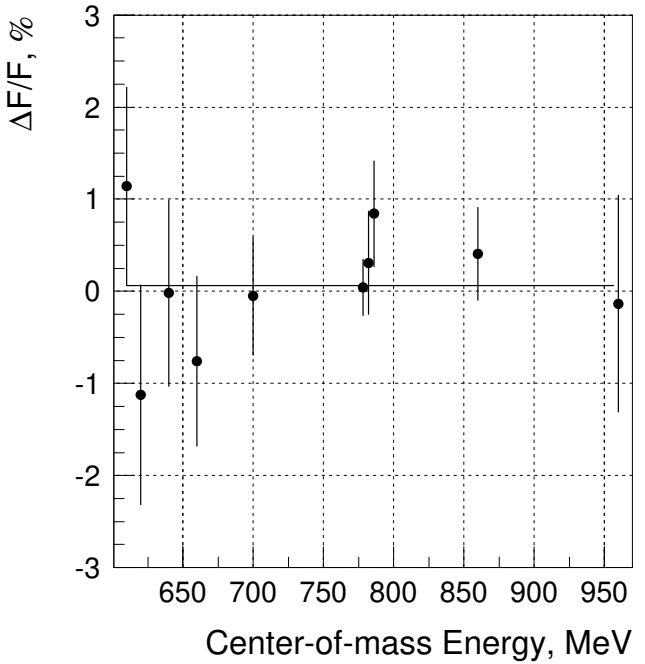
Radiative corrections are calculated via Monte Carlo simulation with all experimental selection criteria taken into account



Cross-section $e^+e^- \to \pi^+\pi^-$ - systematic error

Published data:

Source of error	Value
Beam energy	0.1%
Fiducial volume	0.2%
Detection efficiency	0.2%
Event separation	0.2%
Pion losses	0.2%
Radiative corrections	0.4%
Total systematic error	0.6%



Difference between simulated and reconstructed formfactor

Cross-section $e^+e^- \to \pi^+\pi^-$ - published data

Collected in 1994-1995

2E=610 – 960 MeV

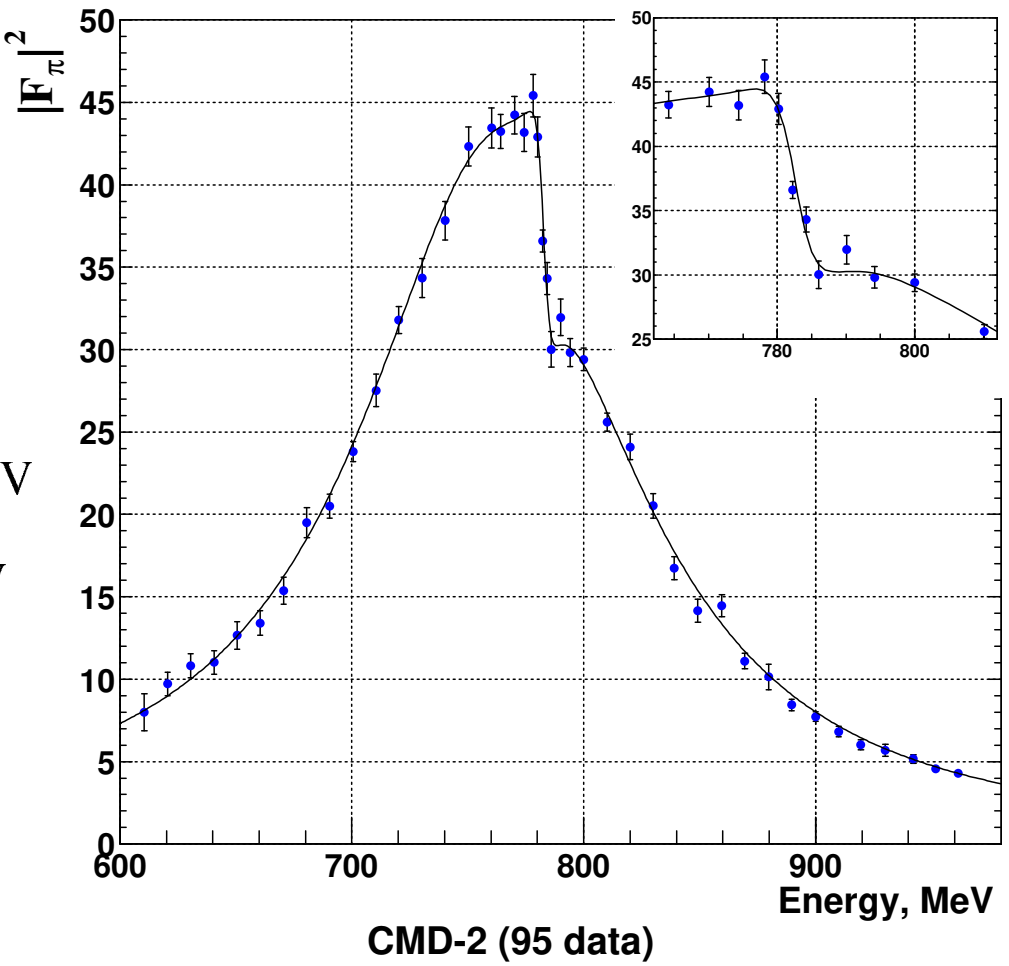
43 energy points

$$M_\rho = (776.09 \pm 0.64 \pm 0.50)\ \text{MeV}$$

$$\Gamma_\rho = (144.46 \pm 1.33 \pm 0.80)\ \text{MeV}$$

$$\Gamma_{\rho ee} = (6.86 \pm 0.11 \pm 0.05)\ \text{keV}$$

$$B_{\omega\pi\pi} = (1.33 \pm 0.24 \pm 0.05)\%$$



R.R.Akhmetshin et al., Phys. Lett. B527 (2002) 161.

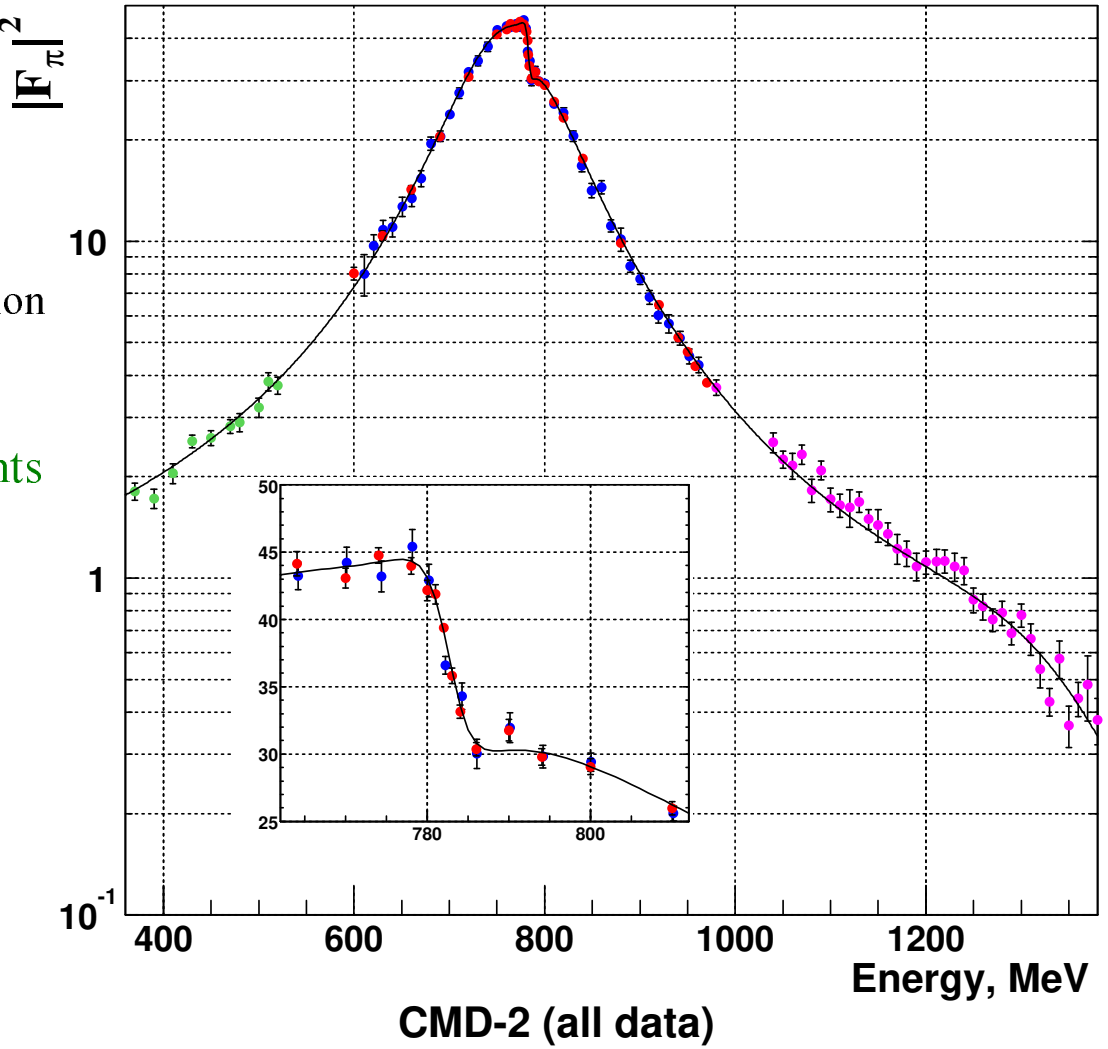
Cross-section $e^+e^- \to \pi^+\pi^-$ - preliminary data

Estimated Systematic Error

- 0.4-0.6 GeV
  5000 2π events
  1.5– 2.0 %
  more complicated event separation

- 0.6-1.0 GeV
  130k (95) + 1M (98) 2π events
  95 data: 0.6%
  98 data: 1.0 %
  drift chamber inefficiency in 98

- 1.0-1.4 GeV
  70k 2π events
  1.0 – 5.0 %
  small cross-section,
  higher background



Measurement of other hadronic channels

Select $e^+e^- \to$ hadrons

Selection efficiency
Background

Luminosity measurement

Large angle $e^+e^- \to e^+e^-$

$$L = \frac{N_{ee}}{\sigma_{ee}(1+\delta_{ee})\varepsilon_{ee}}$$

Radiative corrections

E.A.Kuraev, V.S.Fadin,
SJNP, 41 (1985) 466

$$\sigma(e^+e^- \to h) = \frac{N(e^+e^- \to h)}{L \cdot (1+\delta) \cdot \varepsilon}$$

Narrow resonances: ω(780) meson

1994-1995 data

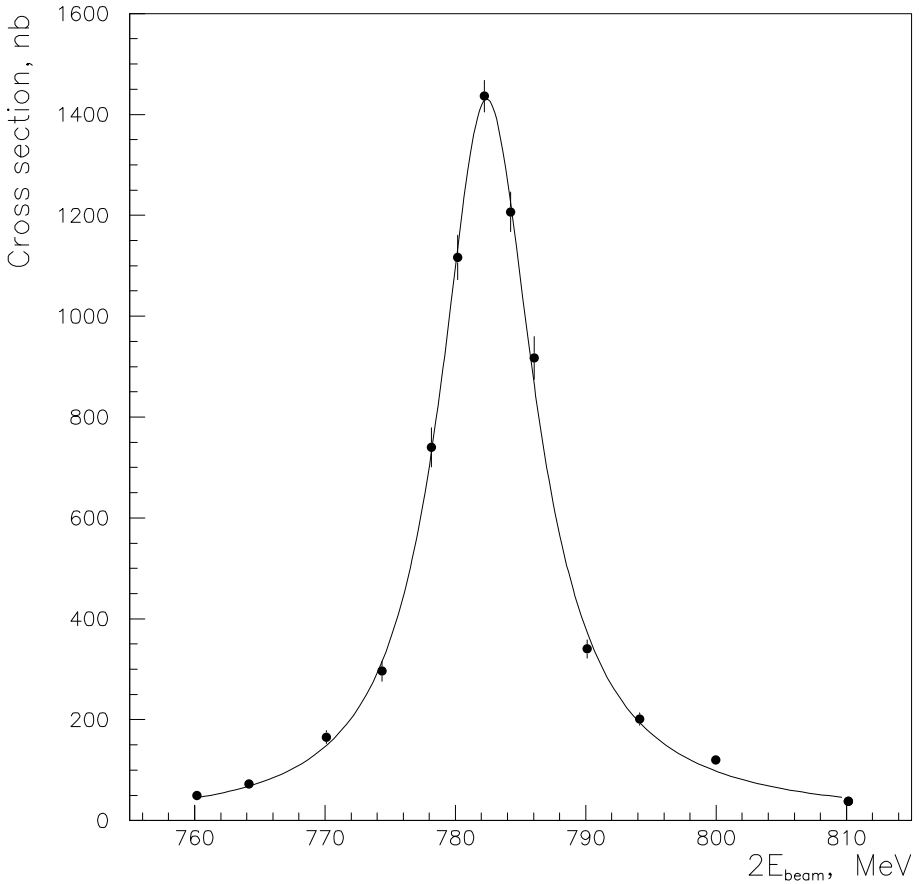
Syst.error 1.5%

$N_{\pi^+\pi^-\pi^0} = 11200$

$\sigma_0 = 1457 \pm 23 \pm 19$ nb

$M_\omega = 782.71 \pm 0.07 \pm 0.04$ MeV

$\Gamma_\omega = 8.68 \pm 0.23 \pm 0.10$ MeV

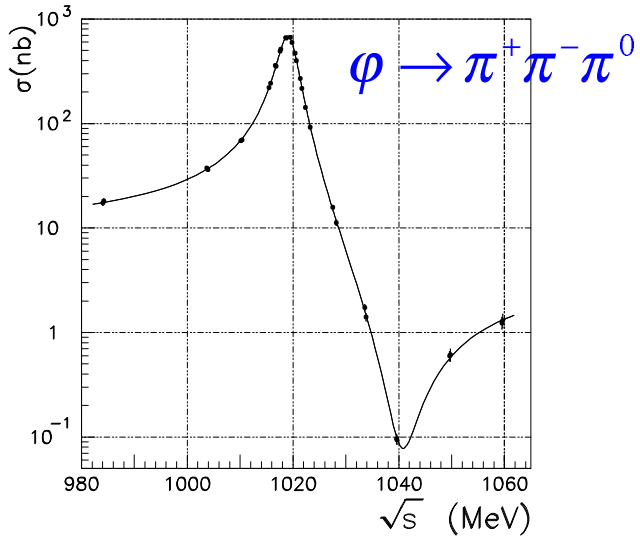


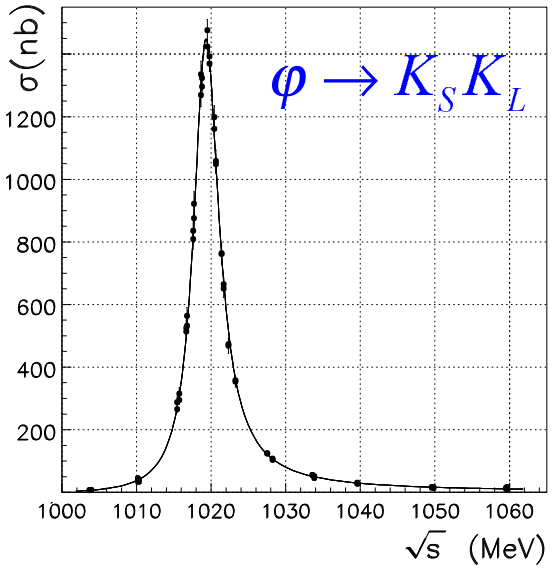
R.R.Akhmetshin et al., Phys. Lett. B476 (2000) 33.

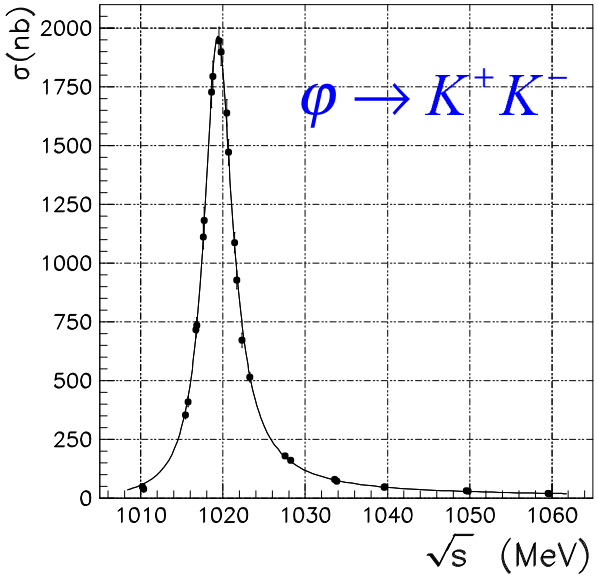
Narrow resonances: φ(1020) meson

CMD-2 and SND studied all major φ decay modes

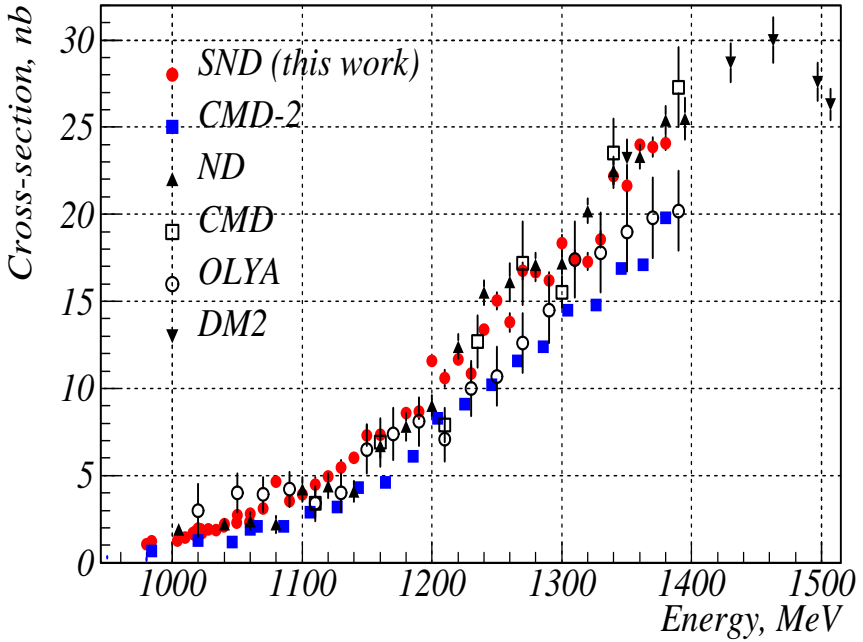
Systematic error ≈ 2%



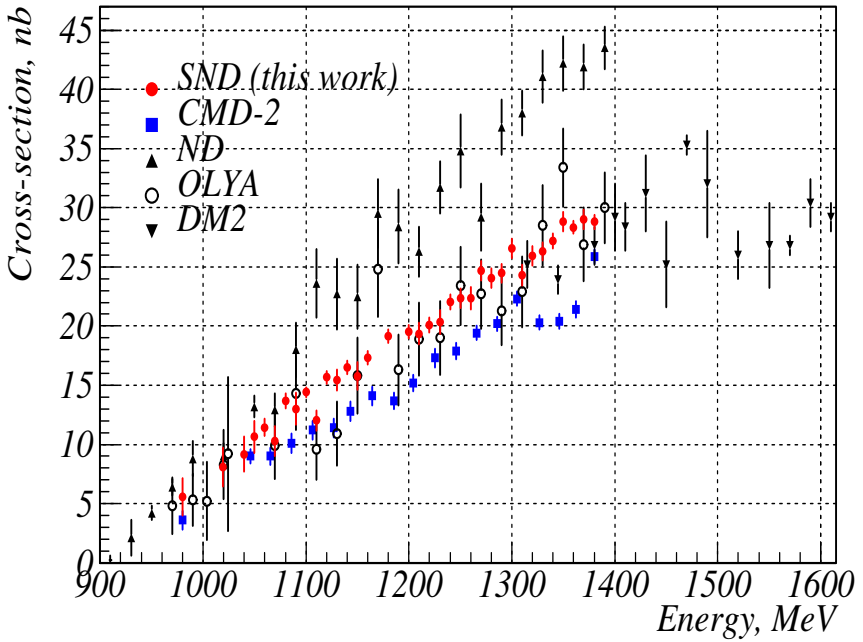




Cross-section $e^+e^- \to 4\pi$



$e^+e^- \to \pi^+\pi^-\pi^+\pi^-$



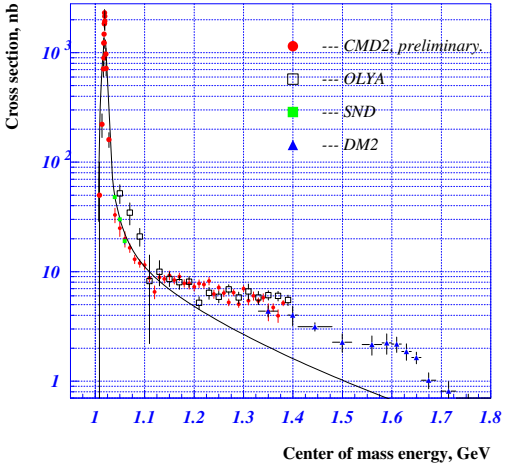
$e^+e^- \to \pi^+\pi^- 2\pi^0$

1997 data

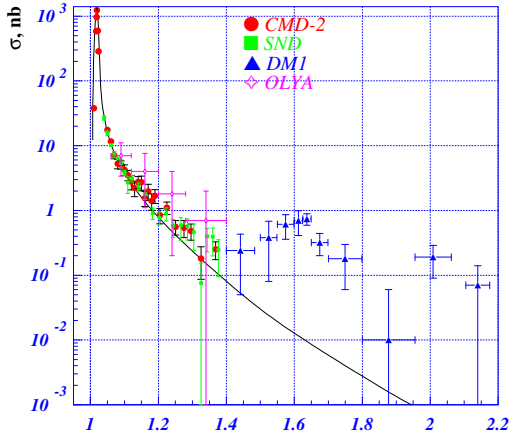
Systematic error: SND – 10%, CMD-2 – 7%

There is disagreement between CMD-2 and SND beyond quoted systematic uncertaincies. CMD-2 continue to analyse the data.

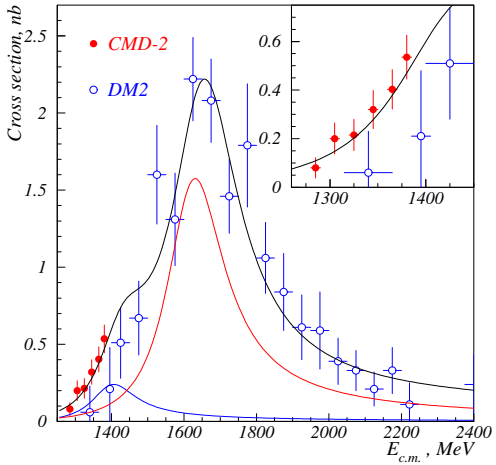
Other modes $e^+e^-\to$hadrons



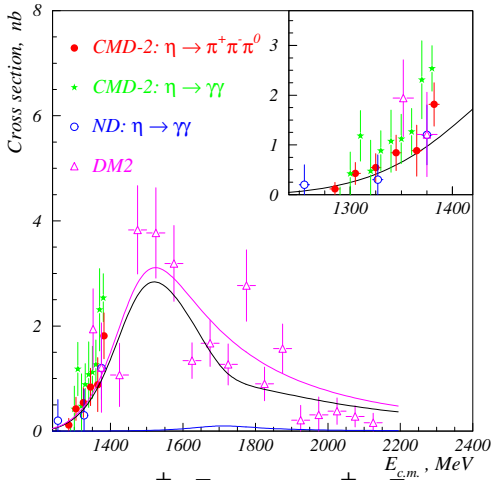
$e^+e^- \to K^+K^-$



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

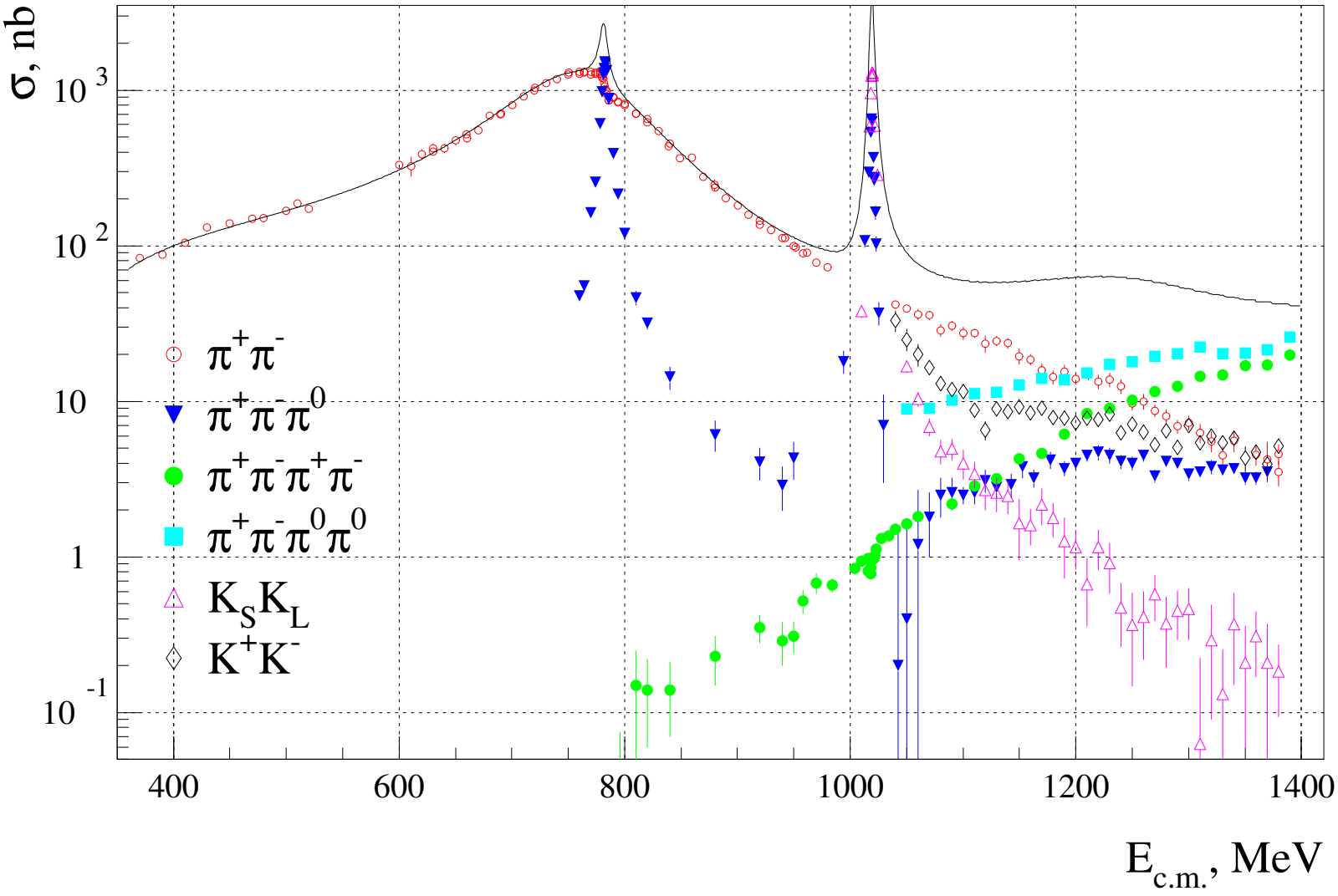


$e^+e^- \to \omega\pi^+\pi^-$



$e^+e^- \to \eta\pi^+\pi^-$

Measurement of $e^+e^- \to$ hadrons at CMD-2



Conclusion

- VEPP-2M era

CMD-2 and SND have collected data over all VEPP-2M energy range
Most of the data is under analysis
2π cross-section was recently published with 0.6% systematic error
It will be cross-checked with additional data collected in 1998

- VEPP-2000

VEPP-2M upgrade with 10-fold increase in luminosity
Direct measurement of cross-sections up to E_{CM}= 2 GeV

- Other experiments

We are eager to see results from ISR experiments
(KLOE, BABAR, BELLE)