Measurement of hadronic cross sections at VEPP-2M and VEPP-2000

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- **Introduction**
- **Overview of the results from VEPP-2M e^+e^- collider.**
- **Status and plans for VEPP-2000**

- A study of e^+e^- annihilation into hadrons at low energies has a long history, but despite decades of experiments, new precise measurements are still highly interesting and can provide important information about interactions of light quarks and spectroscopy of their bound states.

- One of the important subjects is a determination of the total hadron production cross section characterized by the ratio R, which is closely connected to the muon anomalous magnetic moment calculation as well as running electromagnetic and strong interaction constants.

- The former issue became especially interesting in the last 5-7 years, after high precision measurements of the muon anomalous magnetic moment.

$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}, \quad \sigma_{\mu^+\mu^-} = \frac{4\pi\alpha^2}{3s} = \frac{86.85nb}{s\left[GeV^2\right]}$$

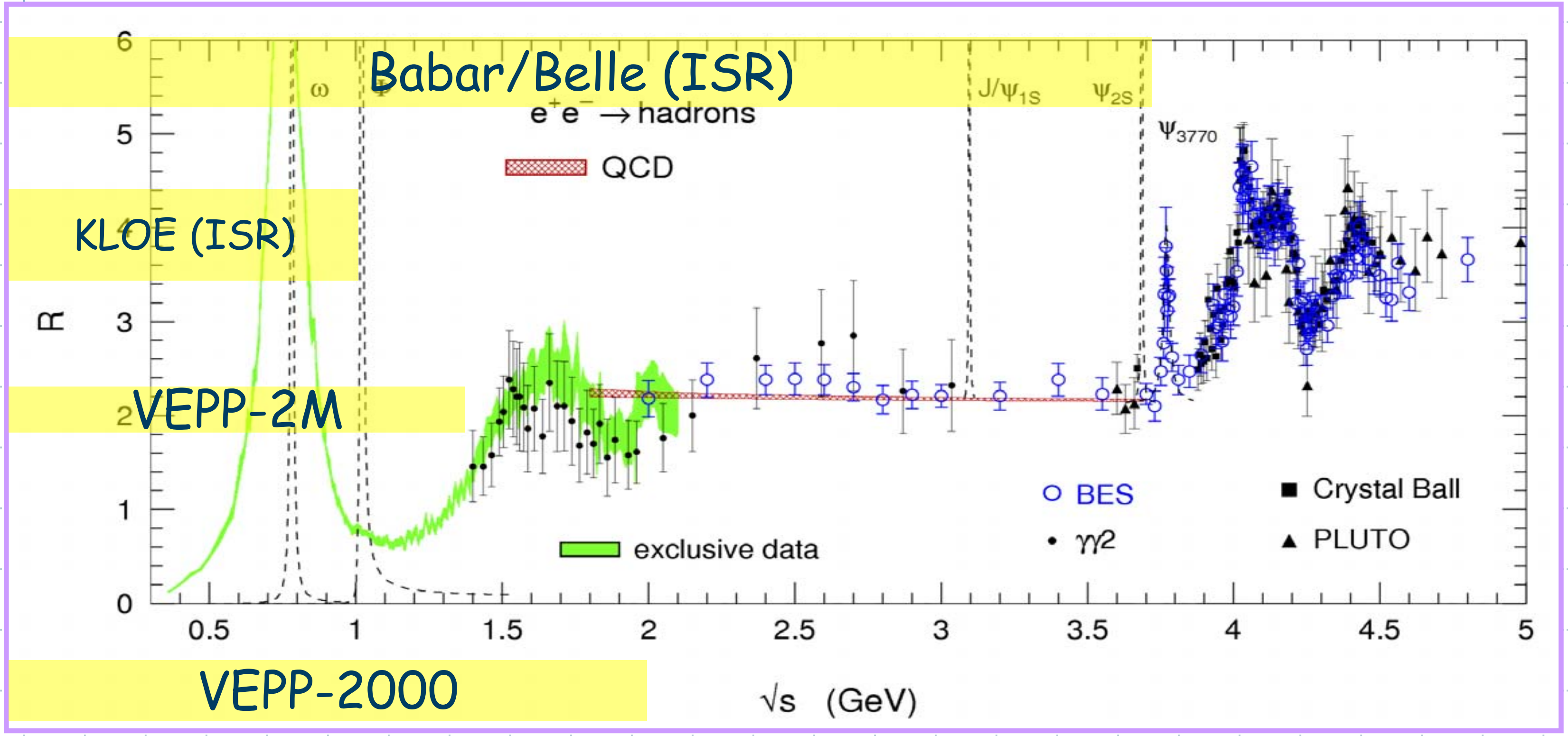
Motivations for precise R measurements

- Tests of perturbative QCD
  - QCD sum rules
  - uark masses, quark and gluon condensates
  - Higher order QCD corrections - Λ_{QCD}, $\alpha(s)$
- Hadronic corrections to fundamental parameters:
  - Running fine structure constant - $\alpha(M_Z^2)$
  - Anomalous magnetic moment of the muon
- measurement of parameters of light vector mesons ρ, ω, φ, ρ', ρ'', ...
- comparison with spectral functions of the hadronic tau decays via CVC

Depending on the problem, different energy ranges are important.

R(s) measurements at low s

$$R_{QCD} = R^{(0)}\left[1+\frac{\alpha_s}{\pi}+C_2\left(\frac{\alpha_s}{\pi}\right)^2+C_3\left(\frac{\alpha_s}{\pi}\right)^3+....\right] R^{(0)} = 3\sum_q e_q^2, \quad C_2 = 1.411, \quad C_3 = -12.8$$



At E_{CM}<2GeV the total cross-section can only be measured as a sum of the exclusive cross sections of all processes

Muon Anomalous Magnetic Moment

$$\vec{\mu} = g \frac{e}{2m} \vec{s}, \qquad a = (g-2)/2.$$

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{had}$$

In Dirac theory for pointlike particles $g = 2$, higher-order effects (or new physics) $g \neq 2$

a_μ is measured with a 5×10^{-7} relative accuracy:

G.W. Bennett et al., 2004, 2006 $a_\mu = (11659208.0 \pm 6.3) \times 10^{-10}$.

Any significant difference of a_{exp} from a_{th} indicates new physics beyond the Standard Model.

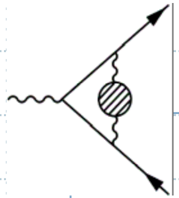
Contribution	a_m, 10^{-10}
Experiment	11659208.0 ± 6.3
QED	11658471.8 ± 0.016
Electroweak	$15.4 \pm 0.1 \pm 0.2$
Hadronic	693.1 ± 5.6
Theory	11659180.3 ± 5.6
Exp. - Theory	27.7 ± 8.4 (3.3σ)

The difference between experiment and theory is 3.3σ!

(some calculations claim even more than 4 σ)

Two new proposals for muon (g-2) measurements (see talks Lee Roberts and T.Mibe). An improvement of the accuracy to about 2×10^{-10} is expected. Then, the accuracy of the hadronic vacuum polarization should be increased.

Hadronic vacuum polarization



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

$\hat{K}$ grows from 0.63 at $s = 4m_\pi^2$ to 1 at $s \rightarrow \infty$, $1/s^2$ emphasizes the role of low energies, particularly important is the reaction $e^+e^- \rightarrow \pi^+\pi^-$ with a large cross section below 1 GeV.

"Direct" measurements in e^+e^-

$\sqrt{s}$, GeV	a_μ (had.LO), 10^{-10}	D/tot,%
2π	504.6±3.1 ±1.0	73.0
ω	38.0 ±1.0 ±0.3	5.5
ϕ	35.7 ±0.8 ±0.2	5.2
0.6 – 1.8	54.2 ±1.9 ±0.4	7.8
1.8 – 5.0	41.1 ±0.6 ±0.0	6.0
J/ψ, ψ'	7.4 ±0.4 ±0.0	1.1
> 5.0	9.9 ±0.2 ±0.0	1.4
Total	$690 \pm 3.9_{exp} \pm 1.9_{rad} \pm 0.7_{QCD}$	100

Other hadronic contributions

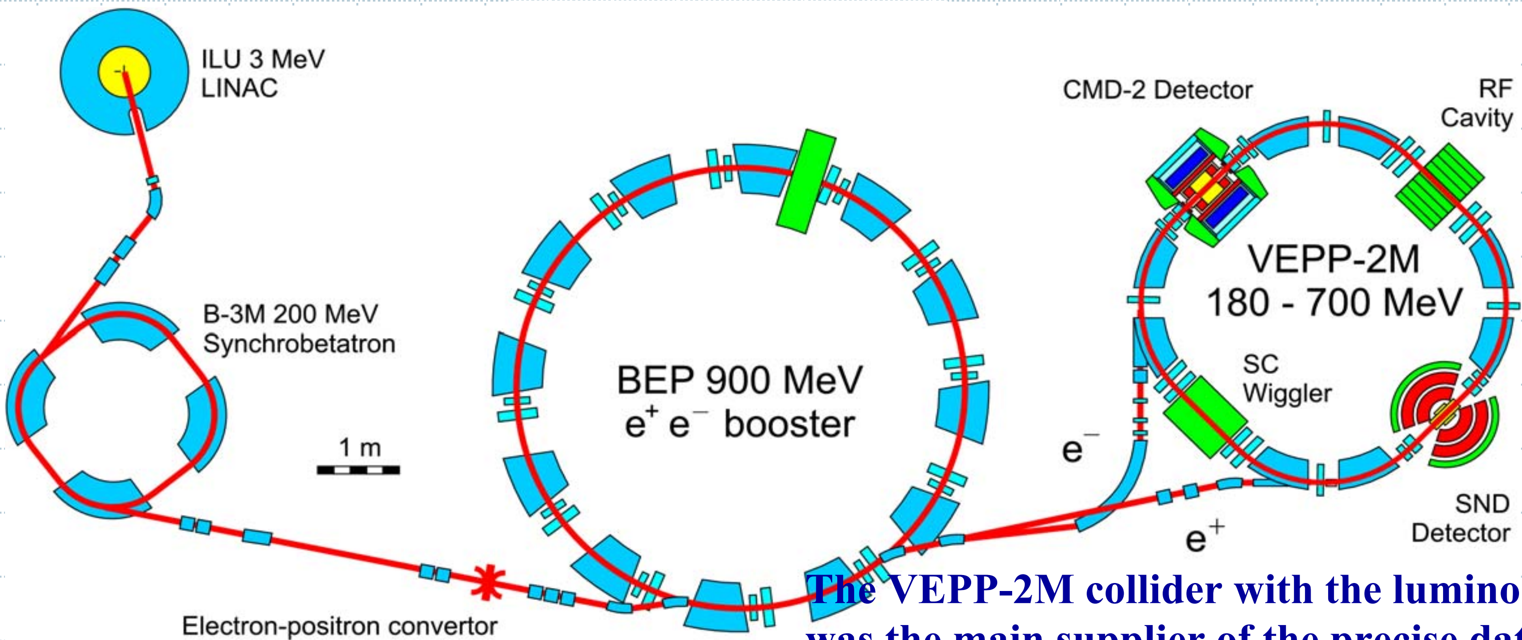
Higher Order Hadronic Contributions

$a(had,HO) = (-9.8 \pm 0.1)\cdot 10^{-10}$ (B. Krause, 1997; K. Hagiwara et al., 2003):

LBL $(10.5 \pm 2.6) \times 10^{-10}$

J. Prades, E. de Rafael, A. Vainshtein

VEPP-2M collider



The VEPP-2M collider with the luminosity of $3 \cdot 10^{30} cm^{-2}s^{-1}$ was the main supplier of the precise data on the hadronic cross section in the energy range below up to 1.4 GeV for more than 25 years.

With $L \approx 10^{30}$ $cm^{-2}s^{-1}$

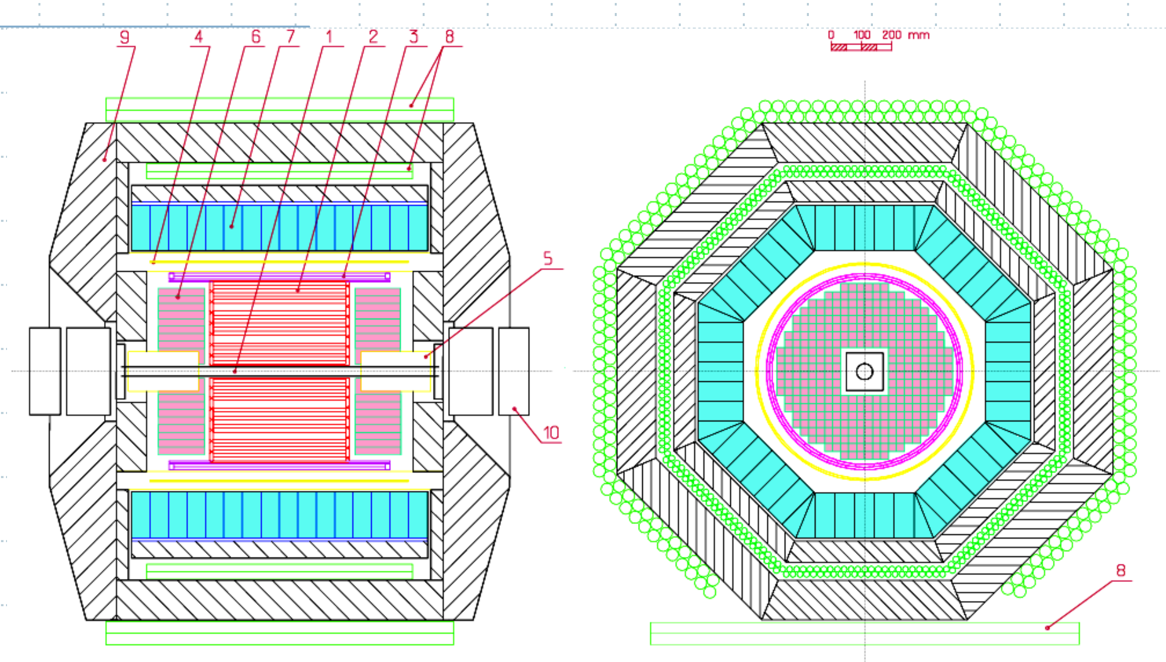
VEPP-2M was pre- ϕ - factory from 1974 to 2000

1st-OLYA, then CMD and ND…

CMD-2 from 1992
SND from 1995

$$\int Ldt \approx 70\, pb^{-1}$$

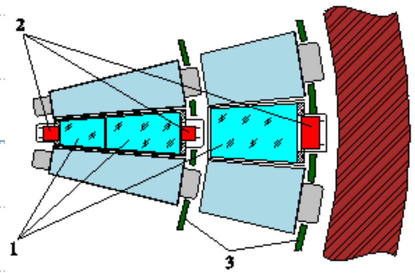
The Cryogenic Magnetic Detector (CMD-2)

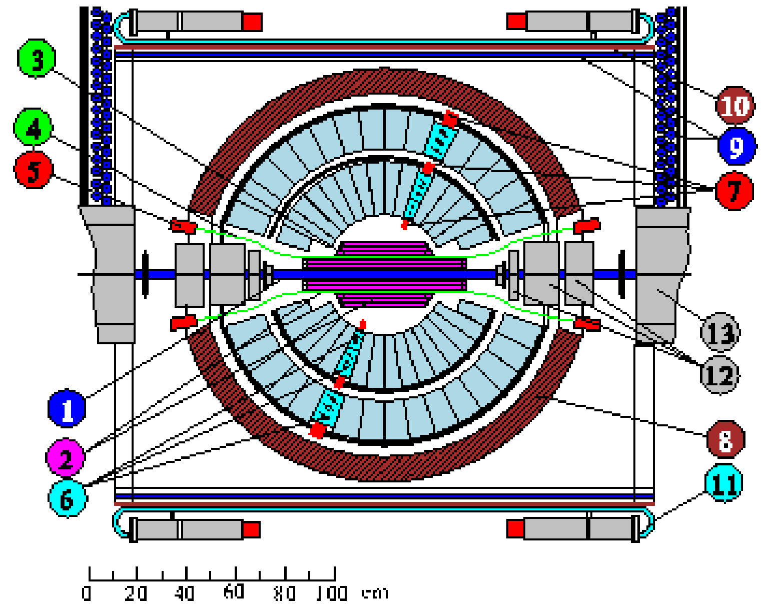


1 - vacuum pipe,
2 - drift chamber,
3 - Z-chamber,
4 - main solenoid,
5 - compensating solenoid,
6 - endcap BGO calorimeter,
7 - barrel calorimeter,
8 - range system,
9 - flux return yoke,
10 - storage ring lens.

The main goal of CMD-2 detector was a measurement of the hadron production cross section in e^+e^- annihilation as well as a study of rare decays of light mesons

SND detector



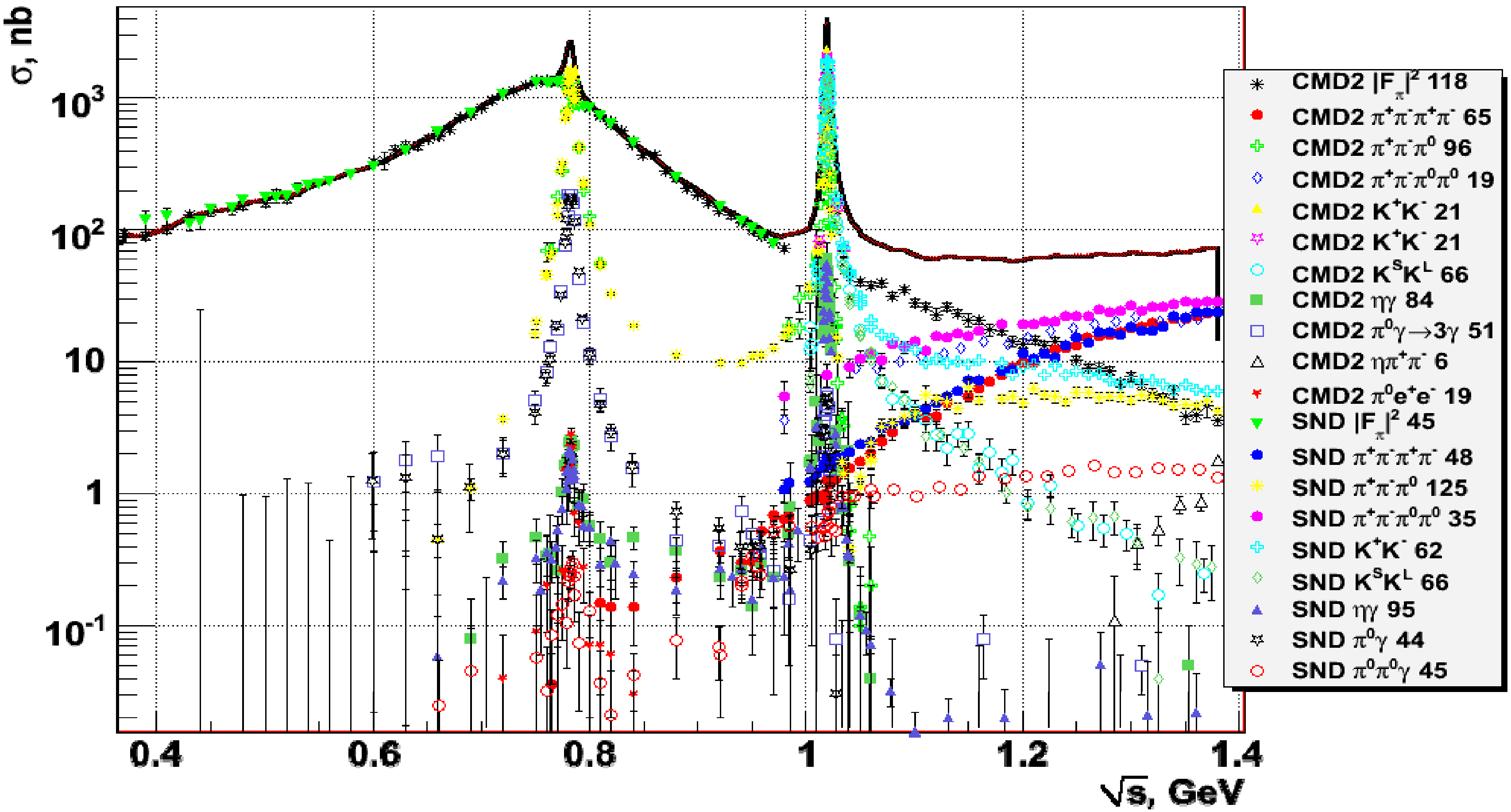


Main characteristics

Total weight	3.5 t NaI(Tl)
Solid angle	90% of 4pi
Thickness of NaI(Tl)	35cm, i.e. 13.5X0
Three spherical layers	2.9X0+4.8X0+5.8X0
Total number of NaI(Tl) counters	1632
Readout	vacuum phototriods (VPT)
Noise per one counter	about 0.3 MeV
Energy resolution for gamma σE/E0	(4-6)%
Angular resolution for gamma	δθ=δϕ =1.5 degrees (E0=300 MeV)

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

Overview of the VEPP-2M results



Systematic error:	~0.6-0.7%	1.0%	0.6%	1.5%	1.5 -- 3.5 %	Error of R(s)
Total error:	~ 6 -- 1%	1.5%	1--2%	2.0%	2.5 -- 3.5 %	

The largest contribution is from $e^+e^- \to \pi^+\pi^-$

Events signature:

two back-to-back tracks, originated from the interaction region

Data sample includes:

e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$, cosmic muons

There is almost no background at $\sqrt{s}$ <1 GeV

Data were taken in 6 separate runs between 1994 and 2000

Event separation (CMD-2)

Likelihood minimization:

<0.6 GeV

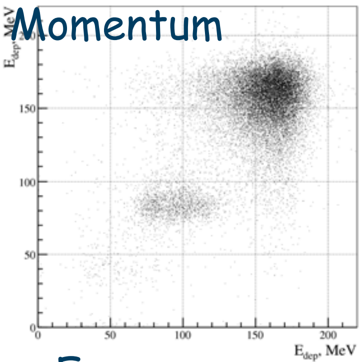
$$L = -\sum_{events} \ln\left(\sum_{a} N_a \cdot f_a\left(E_+, E_-\right)\right),$$

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

>0.6 GeV

Energy

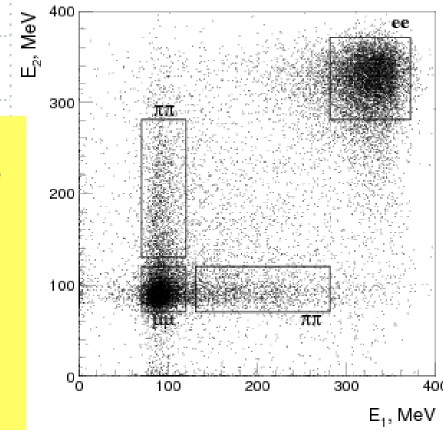
Momentum



Energy

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

- e/μ/π separation using energy deposition
- N(μμ)/N(ee) is fixed according to QED

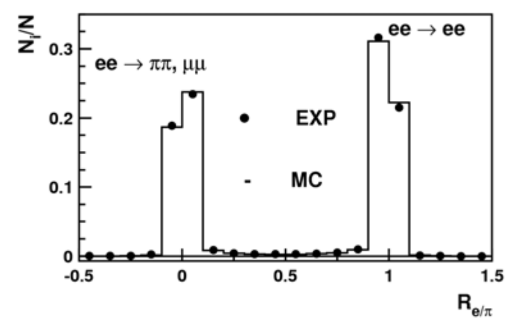


Event separation (SND)

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 – $R_{e/\pi}$**
- **Trained on simulated events**
- **Checked on experimental 3π and e+e- events**

Distribution of the separation parameter



Pion formfactor evaluation

Master formula:

$$\left|F_\pi\right|^2 = \frac{N_{\pi\pi}}{N_{ee}} \cdot \frac{\sigma_{ee}^B \cdot \left(1+\delta_{ee}\right) \cdot \varepsilon_{ee}}{\sigma_{\pi\pi}^B \cdot \left(1+\delta_{\pi\pi}\right) \cdot \left(1-\Delta_N\right) \cdot \left(1-\Delta_D\right) \cdot \varepsilon_{\pi\pi}} - \Delta_{bg} - \Delta_{corr}$$

Nππ/Nee is measured, other values are calculated:

- σ^B – Born cross-section (F_π=1)
- δ – radiative correction
- ε – reconstruction efficiency
- Δ_N – correction for nuclear interactions
- Δ_D – correction for decay in flight
- Δ_{bg} – correction for e+e-→3π,4π,2K background
- Δ_{corr} – correction for $E^+ \leftrightarrow E^-$ correlation

Radiative corrections (real photon emission from the initial and final states and other higher order contributions)

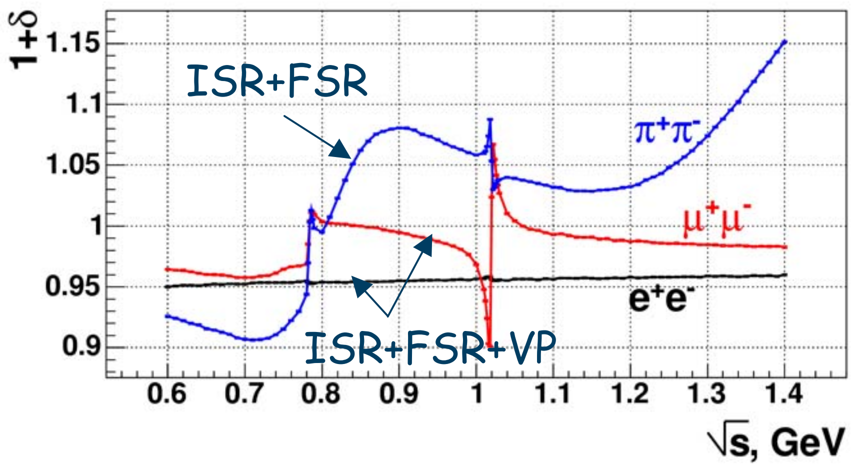
• CMD-2 uses custom Monte-Carlo generator to calculate RC

ee, $\mu\mu$, $\pi\pi$ final states: 1 γ at large angle, multiple γ's along initial or final particles (≲0.2%)

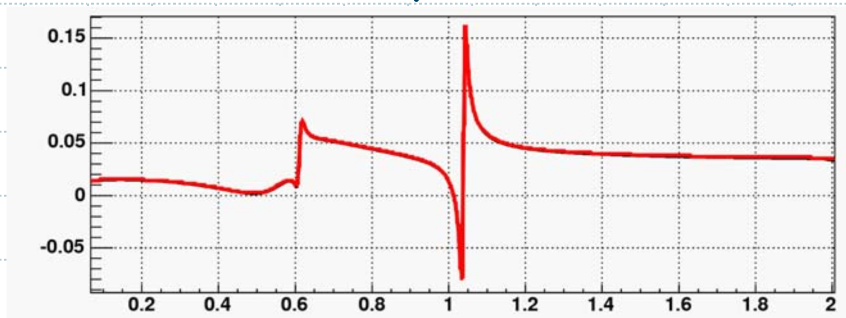
• CMD-2 calculation is consistent with independent calculations (BHWIDE, KKMC)

• SND uses BHWIDE for ee final state and CMD-2 generator for $\mu\mu$, $\pi\pi$ final states

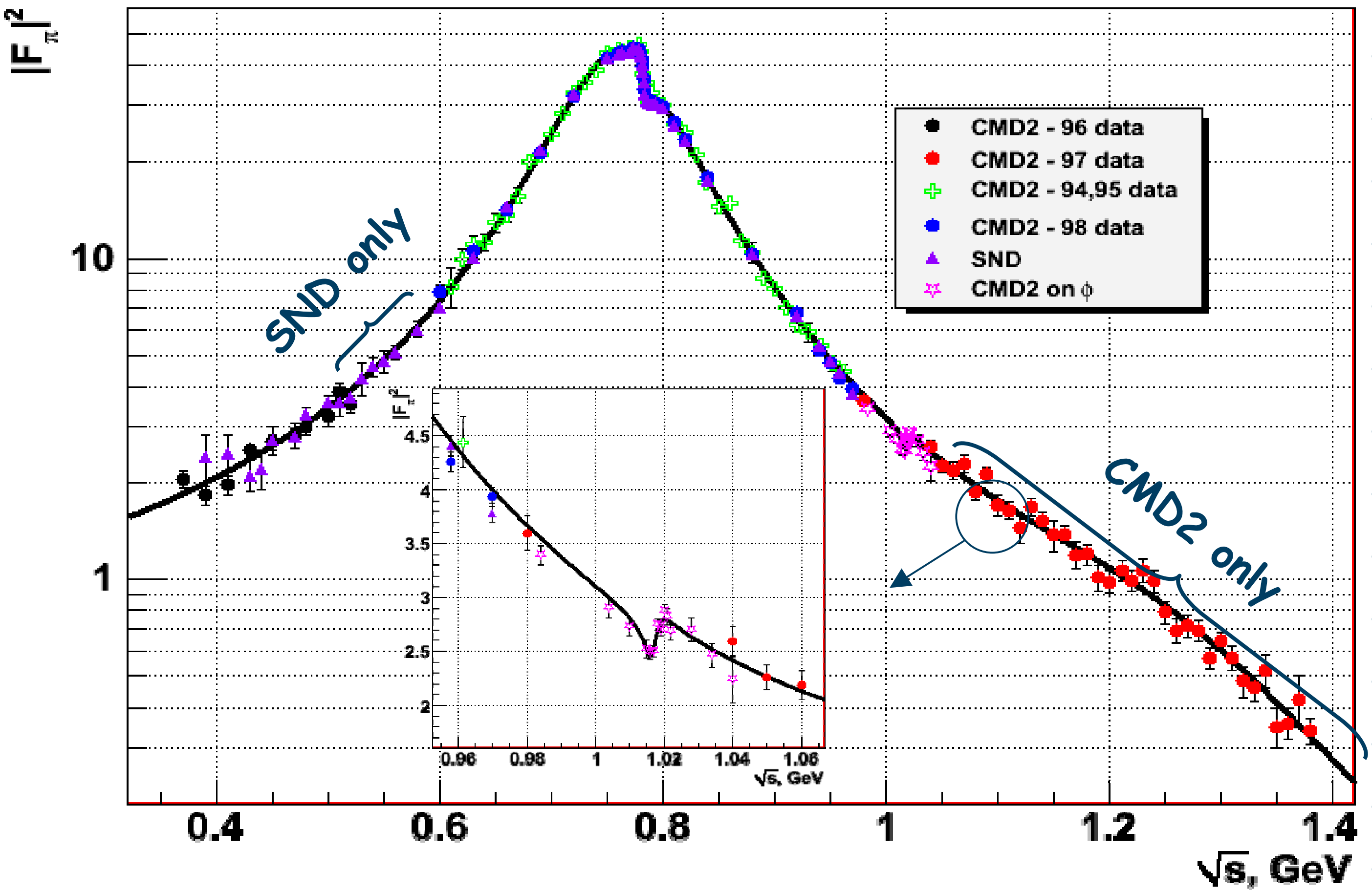
Radiation terms



Vacuum polarization



Pion formfactor - results

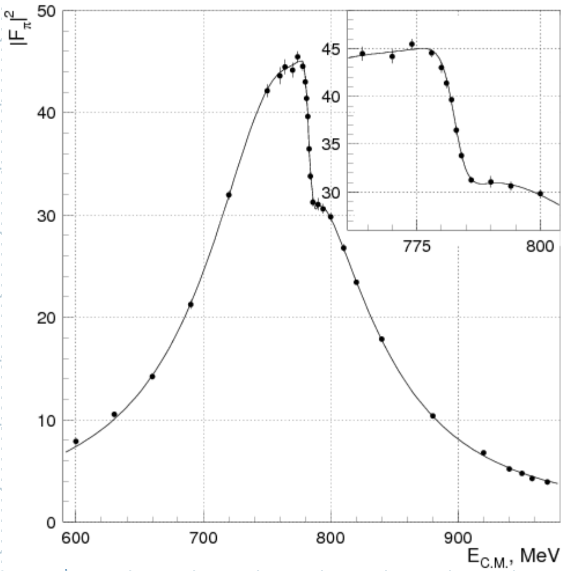


CMD2	0.7%	0.6% (95)/ 0.8% (98)	1.2-4.2%
SND	3.2%	1.3%	

Systematic errors

Source of error	CMD-2 √s<1 GeV	SND	CMD-2 √s>1.0 GeV
Event separation	0.2-0.4%	0.5%	0.2-1.5%
Fiducial volume	0.2%	0.8%	0.2-0.5%
Energy calibration	0.1-0.3%	0.3%	0.7-1.1%
Efficiency correction	0.2%-0.5%	0.6%	0.5-2.0%
Pion losses (decay, NI)	0.2%	0.2%	0.2%
Other	0.2%	0.5%	0.6-2.2%
Radiative corrections	0.3-0.4%	0.2%	0.5-2.0%
Total	0.6-0.8%	1.3%	1.2-4.2%

Resonances and rare decays



$M\rho = (775.97 \pm 0.46 \pm 0.70)$ MeV,

$\Gamma\rho = (145.98 \pm 0.75 \pm 0.50)$ MeV,

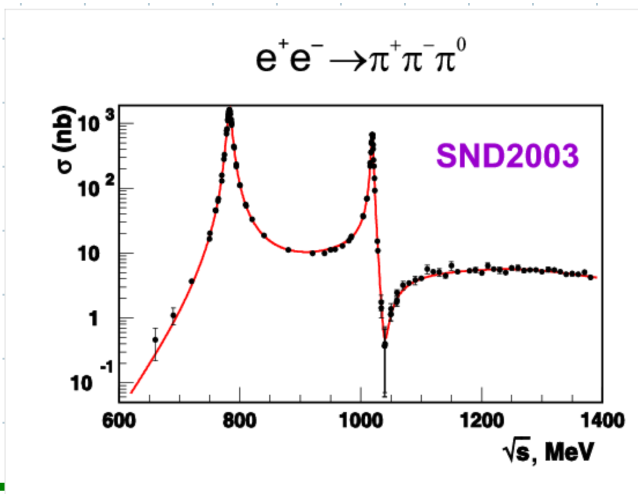
$\Gamma(\rho \to e^+e^-) = (7.048 \pm 0.057 \pm 0.050)$ keV,

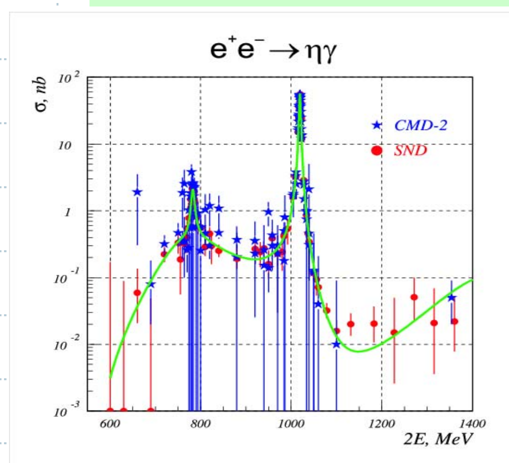
$B(\omega \to \pi^+\pi^-) = (1.46 \pm 0.12 \pm 0.02)\%$,

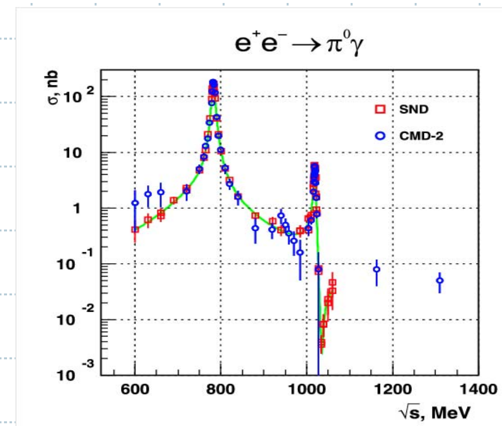
$\Phi_{\rho\omega} = 10.4^\circ \pm 1.6^\circ \pm 3.5^\circ$,

$\beta = -0.0859 \pm 0.0030 \pm 0.0027.$

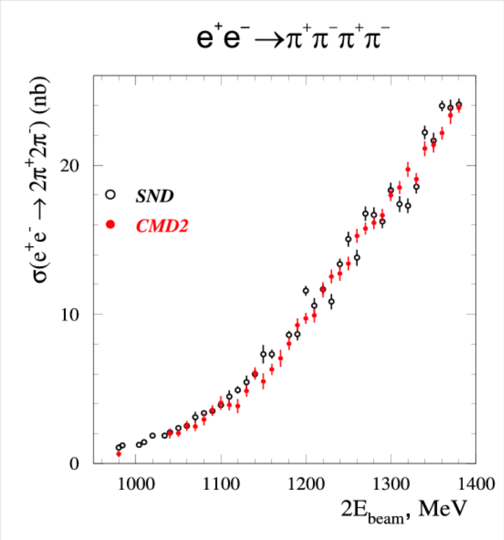
$$F_\pi(s) = \frac{GS_{\rho(770)}(s) \cdot \left(1 + \delta e^{-i\Phi_{\rho\omega}} \frac{s}{M_\omega^2} BW_\omega(s)\right) + \beta \cdot GS_{\rho(1450)}(s)}{1 + \beta}$$

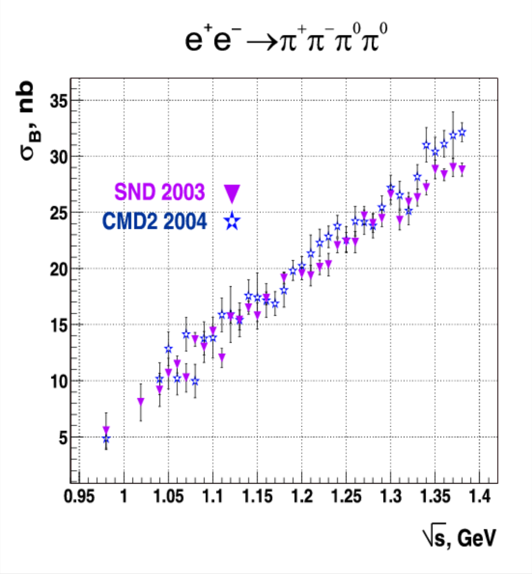




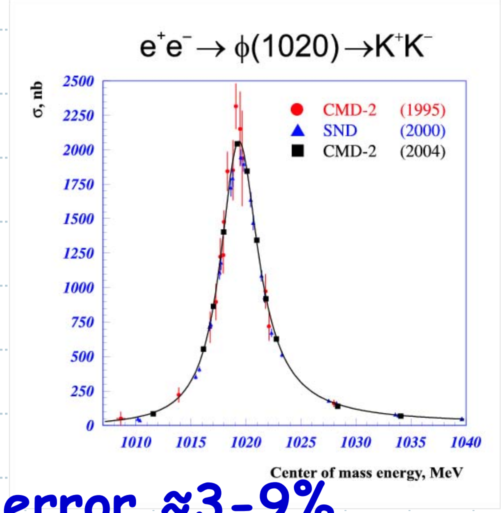


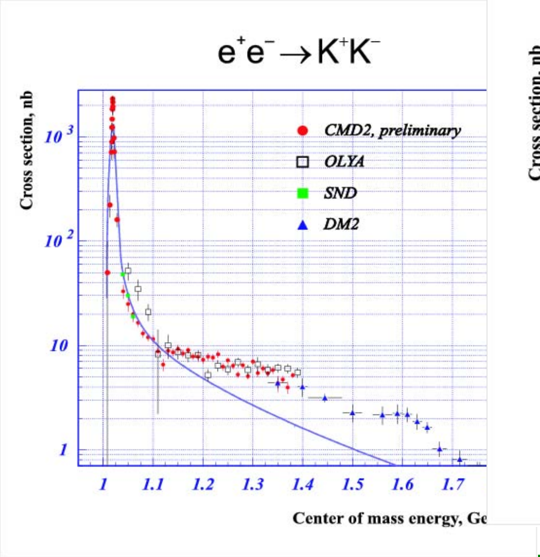
Other processes

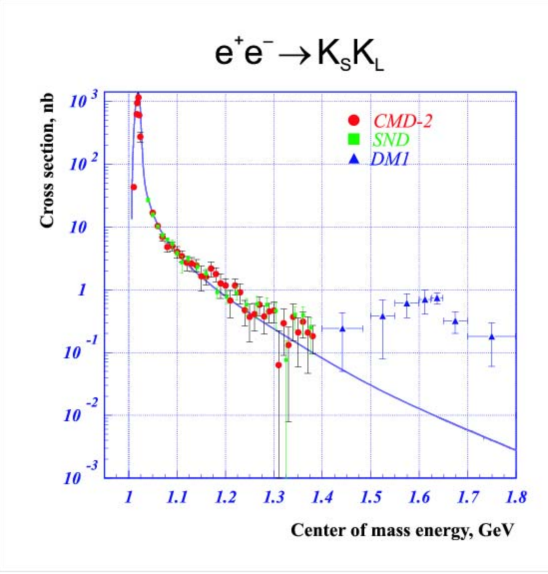




Systematic error ≈5-8%

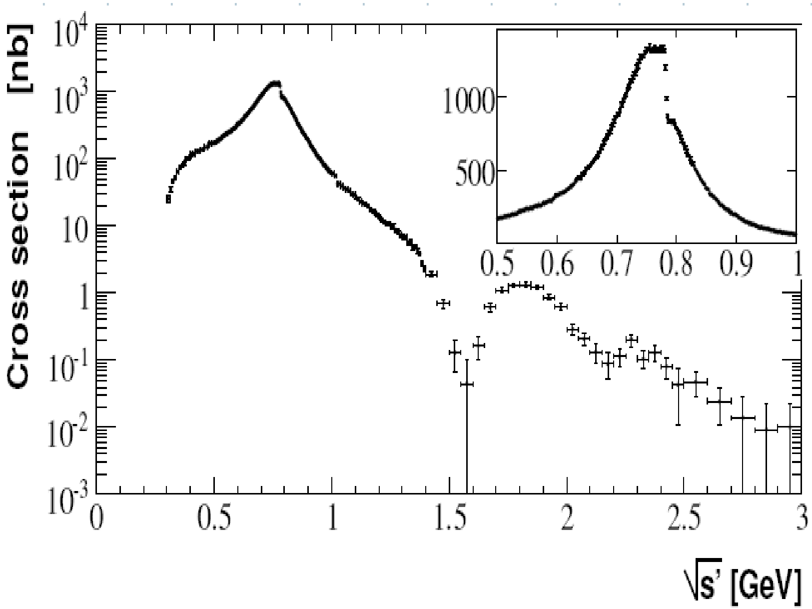


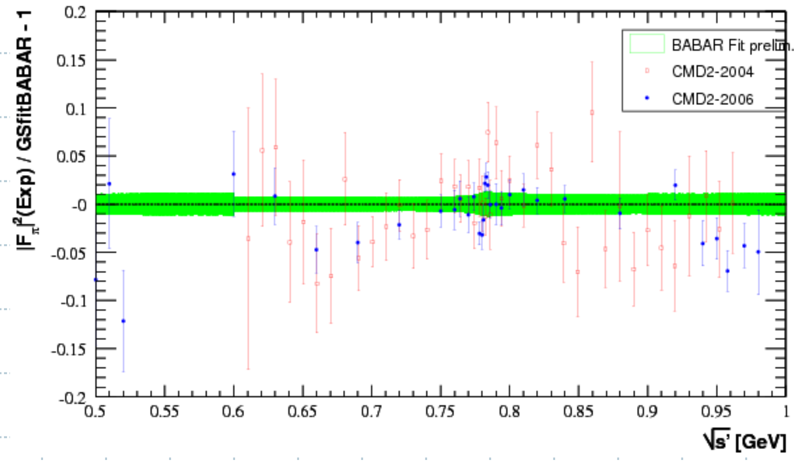




Systematic error ≈3-9%

Comparison with $\pi^+\pi^-\gamma$ - from BaBar





$a_m^{\pi\pi}$ from $\pi^+\pi^-$ threshold to 1.8 GeV (BaBar):

$(514.1 \pm 2.2 \pm 3.1) \times 10^{-10}$

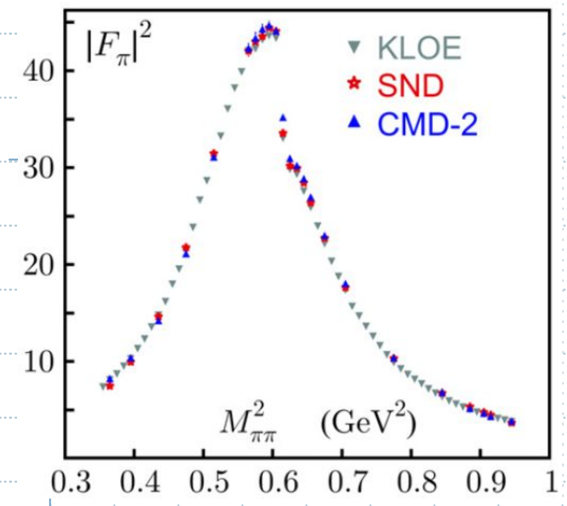
Previous e^+e^- data (combined)*: $(503.5 \pm 3.5) \times 10^{-10}$

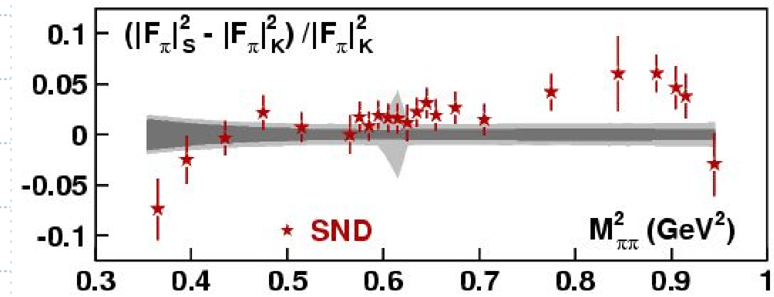
Updated value from $\tau^- \to \pi^-\pi^0\nu_\tau$ *: $(515.2 \pm 3.5) \times 10^{-10}$

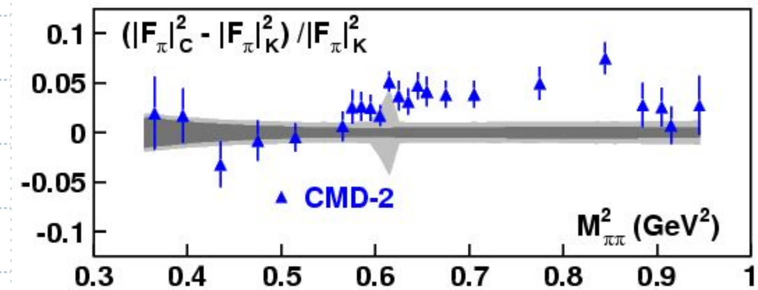
*M.Davier et al., arXiv:0906.5443v1 (hep-ph)

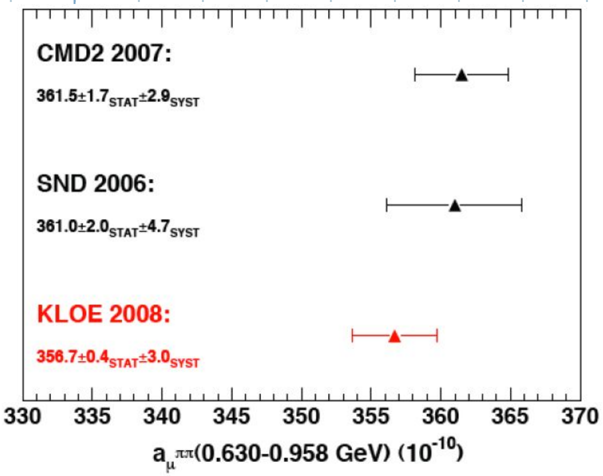
According to these results $\Delta a_{\mu,hadr}$ reduces to $\sim 2\sigma$

KLOE - comparison









$a_\mu^{\pi\pi}$ ***(0.397-0.918 GeV2):***

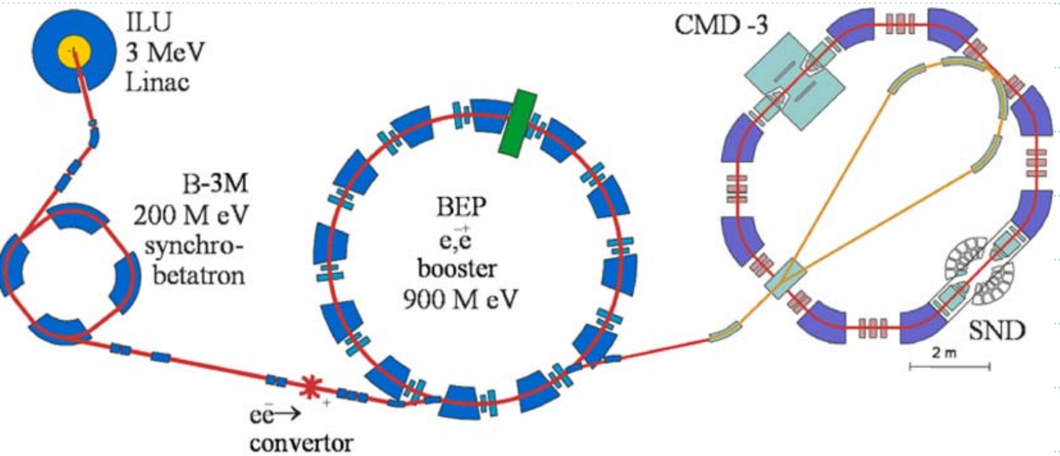
KLOE08 (small angle) $a_\mu = (356.7 \pm 0.4\text{stat} \pm 3.1\text{sys}) \cdot 10^{-10}$

a_μ CMD-2 $= (361.5 \pm 1.7\text{stat} \pm 2.9\text{sys}) \cdot 10^{-10}$

a_μ SND $= (361.0 \pm 2.0\text{stat} \pm 4.7\text{sys}) \cdot 10^{-10}$

KLOE strengthens the discrepancy ~ 3.4 σ between the SM prediction and the BNL measurements

VEPP-2000 storage ring at BINP



- Up to 2 GeV c.m. energy
- Factor >10 in luminosity

  $L=10^{31}\ cm^{-2}c^{-1}$, $\sqrt{s}=1.0$ GeV

  $L=10^{32}\ cm^{-2}c^{-1}$, $\sqrt{s}=2.0$ GeV

≈100 1/pb per detector per year

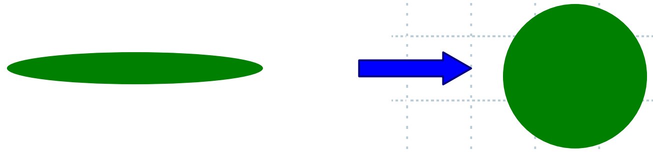
Status:

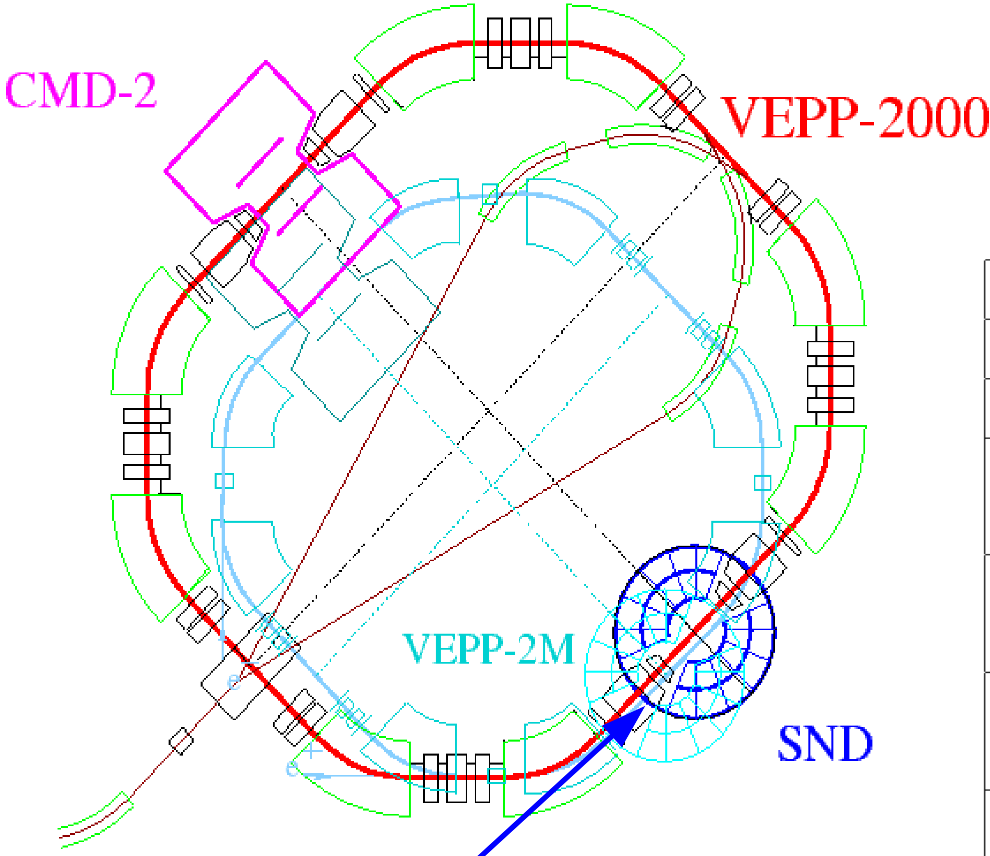
- the first run has been performed in the spring 2010;
- first data (~5 pb^{-1}) have been collected in a scan from M_{ϕ} to 1.9 GeV energy range;
- the obtained specific luminosity – $10^{31}cm^{-2}s^{-1}$

New collider VEPP-2000

2Emax: 1.4 GeV $\rightarrow$ 2 GeV

The main idea – round beams!



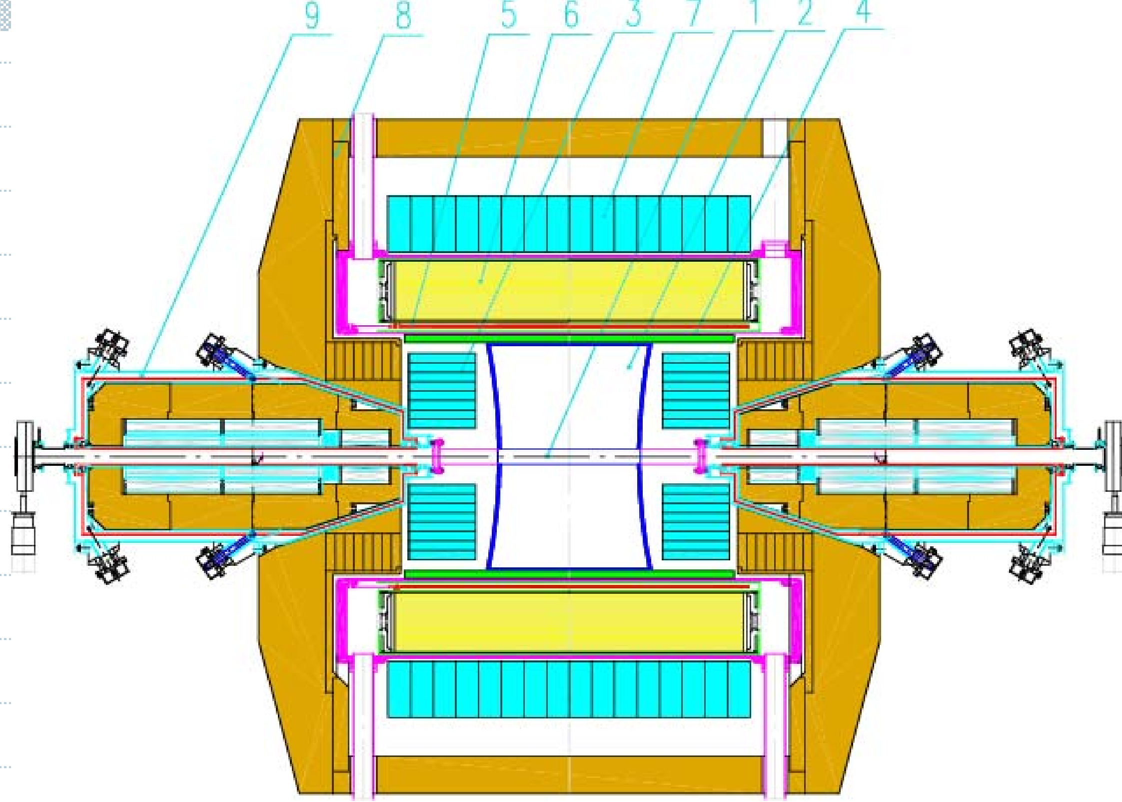


Focussing solenoids
B=12 T

VEPP-2M & VEPP-2000 parameters

	VEPP-2M	VEPP-2000	
E (MeV)	510	510	900
Π (cm)	1788	2235	2235
$\mathcal{I}^+, \mathcal{I}^-$ (mA)	40	34	200
$\varepsilon \cdot 10^5$ (cm · rad)	3	0.5	1.6
β_x (cm) β_z (cm)	40 5	6.3 6.3	6.3 6.3
ξ_x ξ_z	0.016 0.050	0.075 0.075	0.075 0.075
$\mathcal{L}(cm^{-2}s^{-1})$	$3 \cdot 10^{30}$	$1 \cdot 10^{31}$	$1 \cdot 10^{32}$

CMD-3 Detector

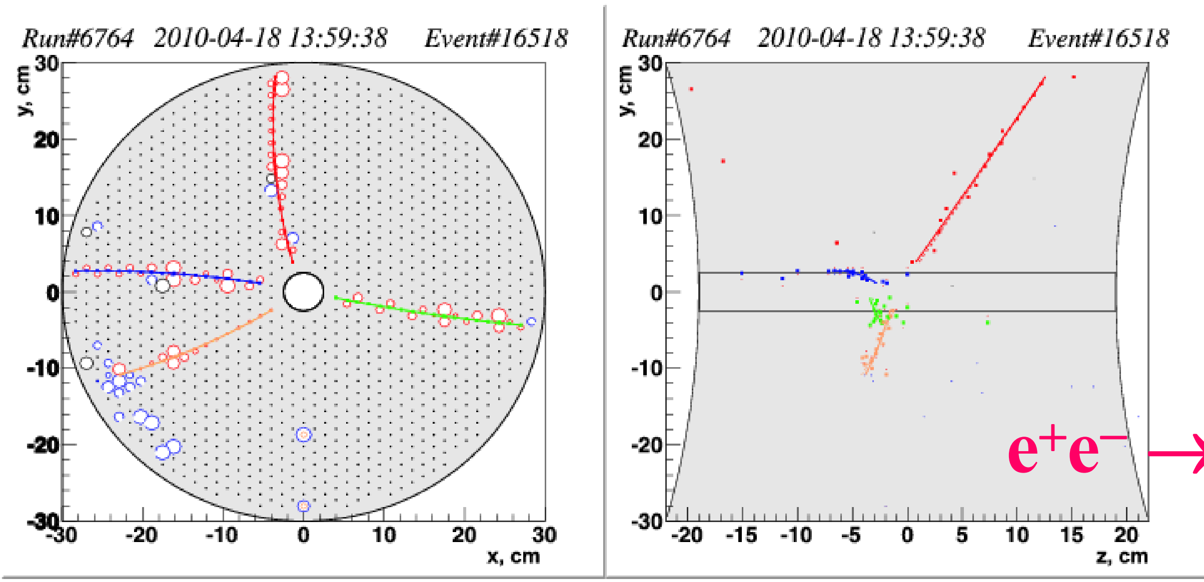


Advantages compared to CMD-2:

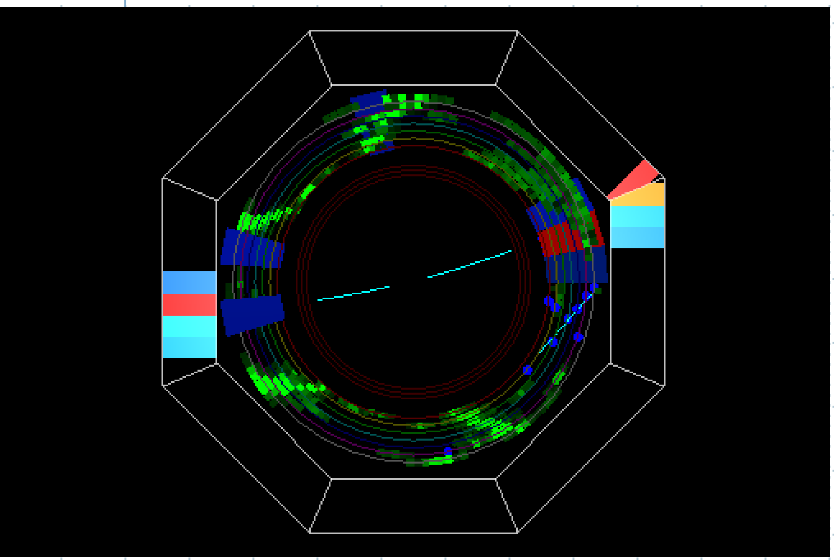
- new drift chamber with x2 better resolution
  better tracking
- thicker barrel calorimeter
  better separation
- LXe calorimeter
  - much better spatial resolution for γ's
  - shower profile

1 – vacuum 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.

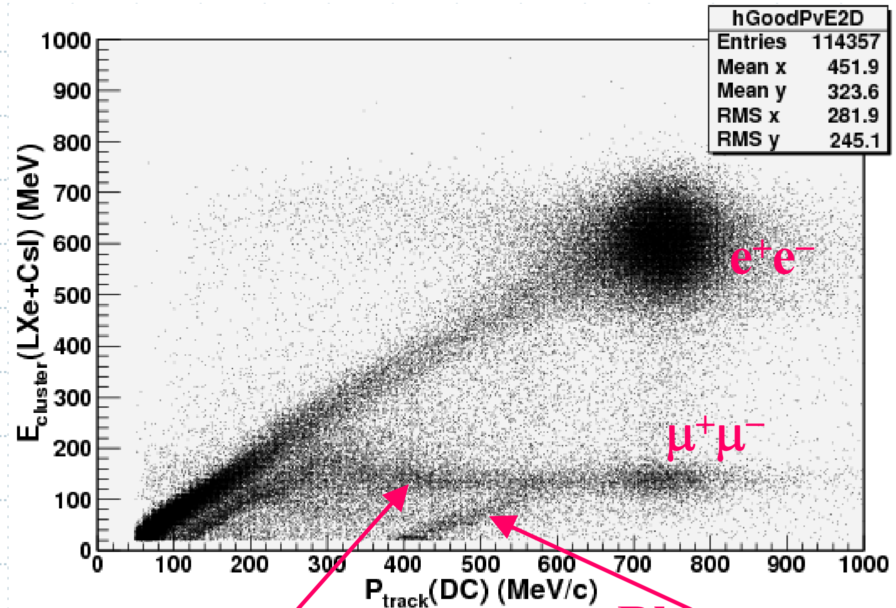
CMD-3 event display



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



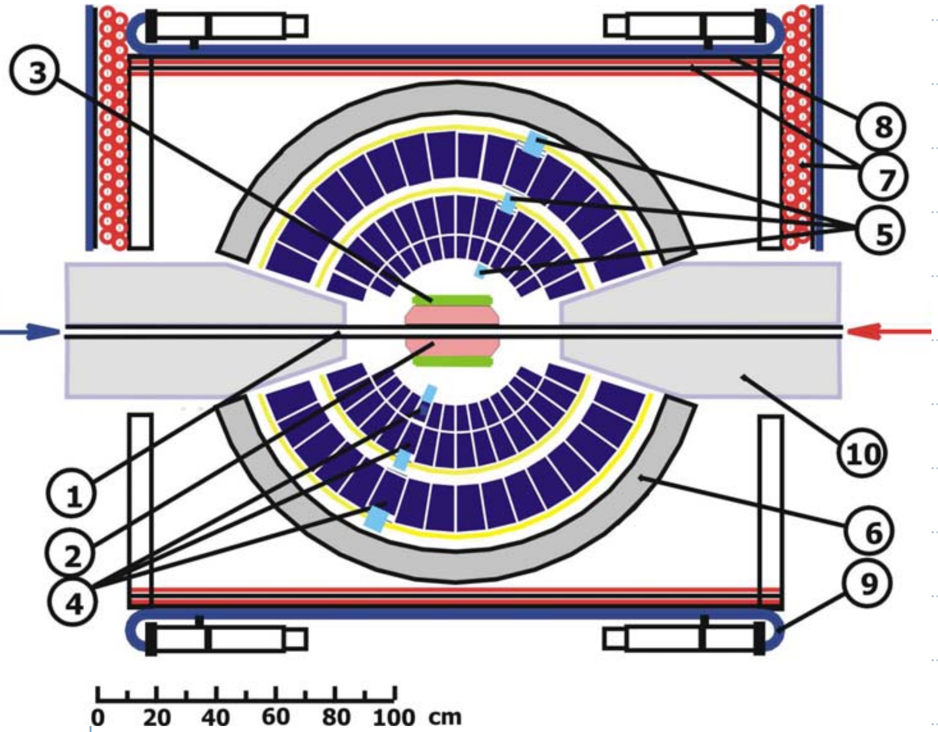
CMD-3 $e^+e^- \rightarrow e^+e^-$

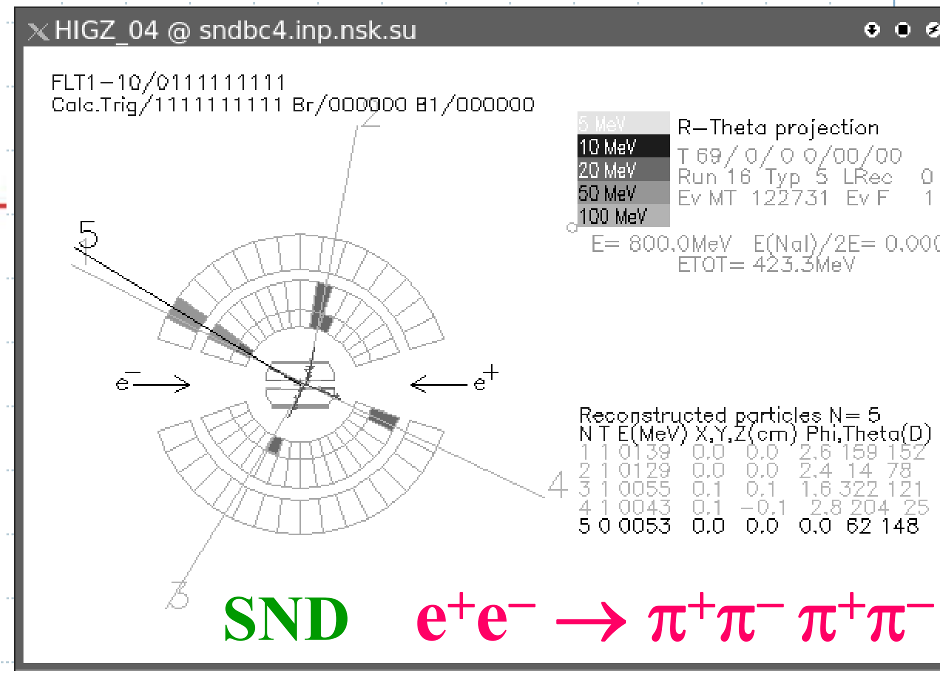


cosmic

Bkg.protons

SND 2000





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

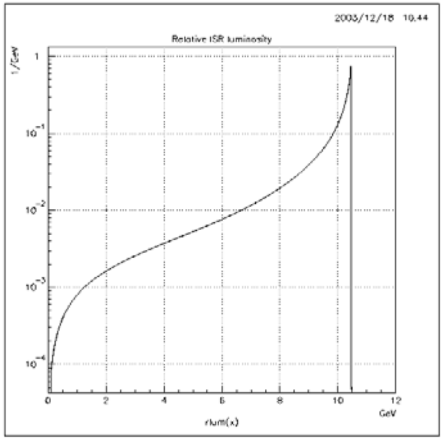
Advantages compared to "old" SND:

- new system - cherenkov counters (n= 1.13)
  - e/π separation E<450 MeV
  - π/K separation E<1 GeV
- new drift chamber
  - better tracking
  - better determination of solid angle

Expectation on systematic errors achievable for R measurement at CMD-3

Source of error	CMD3, 2pi $\sqrt{s}<1$ GeV	CMD3, 4pi $\sqrt{s}>1.1$ GeV
Event separation	0.2%	1% (cuts)
Fiducial volume	0.2%	2% (model)
Energy calibration	0.1%	
Efficiency correction	0.1%	1% (tr+bg)
Pion losses (decay, NI)	0.1%	
Radiative corrections	0.1%	1%
Total	0.35%	2.5%

Future ISR: competition or complementarity?



$$\frac{dl}{Ldm} = \frac{2\alpha m}{\pi s}\left\{\frac{s+m^4}{s(s-m^2)}\left(\ln\frac{s}{m_e^2}-1\right)\right\}$$

Number of events of the vector meson production at 8000 fb^{-1} (@Y(4s)

ϕ	1.5×10^8
ψ	2.3×10^8
ψ(2S)	7.8×10^7
ψ(3770)	9.7×10^6
Y(1s)	1.3×10^8
Y(2s)	1.2×10^8
Y(3s)	2.4×10^8

Comparison to VEPP-2000 project, e^+e^- up to 2 GeV

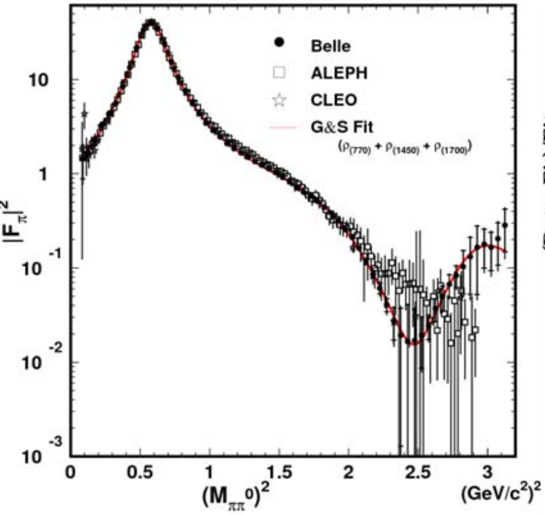
	KEKB	VEPP-2000
Luminosity, см$^{-2}$ s^{-1}	$8\cdot10^{35}$	10^{32}
Integrated lum. (per 10^7 s)	8000 fb^{-1}	1 fb^{-1}
Integrated in the range [1-2] GeV	8 fb^{-1} (~0.8 @ θ>0.7)	1 fb^{-1}

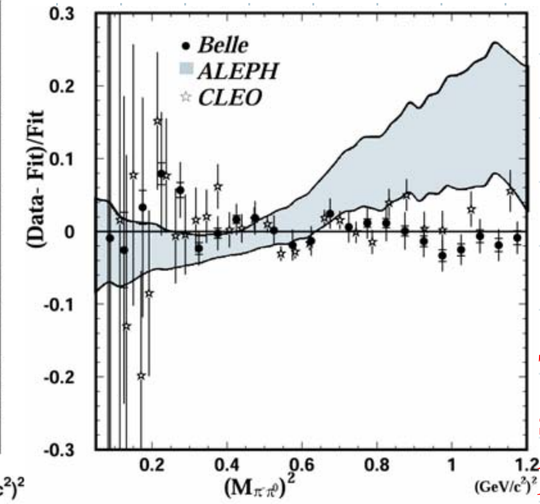
Conclusion

- In the last 30 years VEPP-2M produced abundant and accurate results on the hadronic cross sections in the e^+e^- annihilation. At present these data are, probably, the most precise measurements of the hadronic cross sections in the particle physics.
- Experiments at the new collider, VEPP-2000, have started. Two new detectors are in use.
- New measurement of R by the energy scan is one of the priority tasks for VEPP-2000.
- High luminosity of VEPP-2000, improved detectors and advances in calculation of the radiative corrections should substantially reduce the systematic errors

Back up

$\tau^- \to \pi^-\pi^0\nu_\tau$ – recent results from Belle



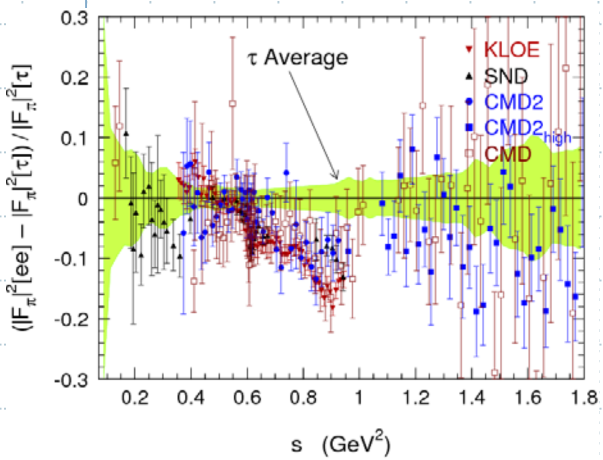


Systematics, %

$M^2_{\pi\pi}$	threshol d	ρ region	ρ’	ρ”
Total	**5.3**	**0.7**	**1.8**	**11.4**

The branching from all groups is systematically higher than the CVC prediction:

$B_\tau - B_{ee} = (0.92 \pm 0.21)\%$ or 4.5σ from 0. The discrepancy is a 3.6% effect, about twice the SU(2) correction.



- Belle(τ)

$$a_\mu^{\pi\pi} = (523.5 \pm 1.5(exp.) \pm 2.6(Br) \pm 2.5(isospin))x10^{-10}$$

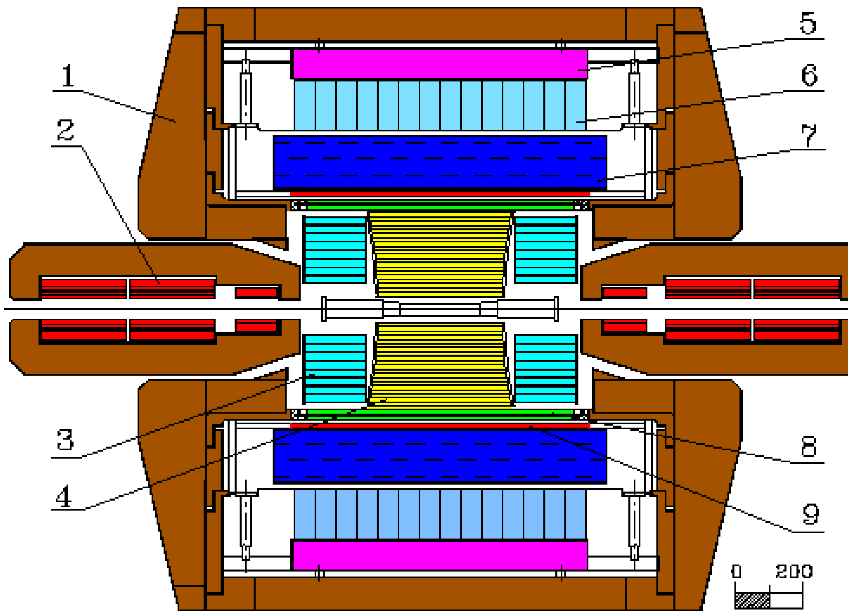
- ALEPH, CLEO, OPAL (τ) Ref. Eur. Phys. J. C27, 497 (2003)

$$a_\mu^{\pi\pi} = (520.1 \pm 2.4(exp.) \pm 2.7(Br) \pm 2.5(isospin))x10^{-10}$$

- CMD2,SND (e^+e^-) Ref. Nucl. Phys. Proc. Suppl. 169, 288 (2007)

$$a_\mu^{\pi\pi} = (504.6 \pm 3.1(exp.) \pm 0.9(rad.))x10^{-10}$$

CMD-3 project



1 - magnet yoke; 2 - focusing solenoid; 3 - BGO endcap calorimeter; 4 - drift chamber; 5 - support and electronics of CSI crytals; 6 - CSI barrel calorimeter; 7 - liquid xenon barrel calorimeter; 8 - Z-chamber; 9 - superconductive solenoid

Main Parameters of the CMD-2 and CMD-2M Detectors

System	CMD-2	CMD-2M
Drift Chamber	512 signal wires $\sigma_{R\text{-}\varphi} = 250\ \mu m$, $\sigma_Z = 5$ mm, $\sigma_\theta = 1.5\cdot10^{-2}$, $\sigma_\varphi = 7\cdot10^{-3}$ $\sigma_{dE/dx} = 0.2\cdot\langle dE/dx\rangle$	1218 signal wires $\sigma_{R\text{-}\varphi} = 140\ \mu m$, $\sigma_Z = 2$ mm, $\sigma_\theta = 7\cdot10^{-3}$, $\sigma_\varphi = 4\cdot10^{-3}$ $\sigma_{dE/dx} = 0.15\langle dE/dx\rangle$
Z - chamber	Two layers of the proportional chambers. Signal wires are combined to 2×32 sectors. Z-coordinate is measured by 512 strips. $\sigma_Z = 250 \div 1000\ \mu m$, $\sigma_t = 5$ nsec, $\Omega_Z = 0.8\times4\pi$ steradian	
Barrel Calorimeter	892 CsI crystals in 8 octants, thickness is 8.1 X_0, $\sigma_E/E = 8.5\%$ in the range $E\gamma = 100 \div 700$ MeV, $\sigma_{\theta,\varphi} = 0.03 \div 0.02$ radian	1152 CsI crystals in 8 octants, 400 l of LXe, the thickness is $5X_0$Lxe + 8.1X_0CsI $\sigma_E/E = 4.7 \div 3\%$ for $E\gamma = 100 \div 900$ MeV, $\sigma_{\theta,\varphi} = 0.005$ radian
Muon System	Strimer tubes d=40 mm, $\sigma_Z = 5 \div 7$ cm	Scintillation counters, $\sigma_t = 0.8$ nsec
Superconducting solenoid	B = 1 T, thickness in front of calorimeter 0.38 X_0	B = 1.5 T, thickness in front of calorimeter 0.18 X_0