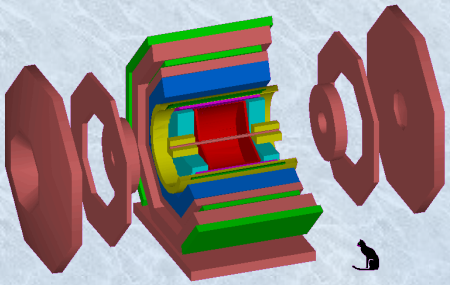


CMD-2 and SND results on e^+e^- -> hadrons cross sections

Fedor Ignatov

on behalf of the CMD2 & SND collaborations

Budker Institute of Nuclear Physics (Novosibirsk, Russia)

Workshop on e^+e^- collisions from φ to ψ

FRASCATI, ITALY, 7-10 APRIL 2008

Cross-section e+e- → hadrons

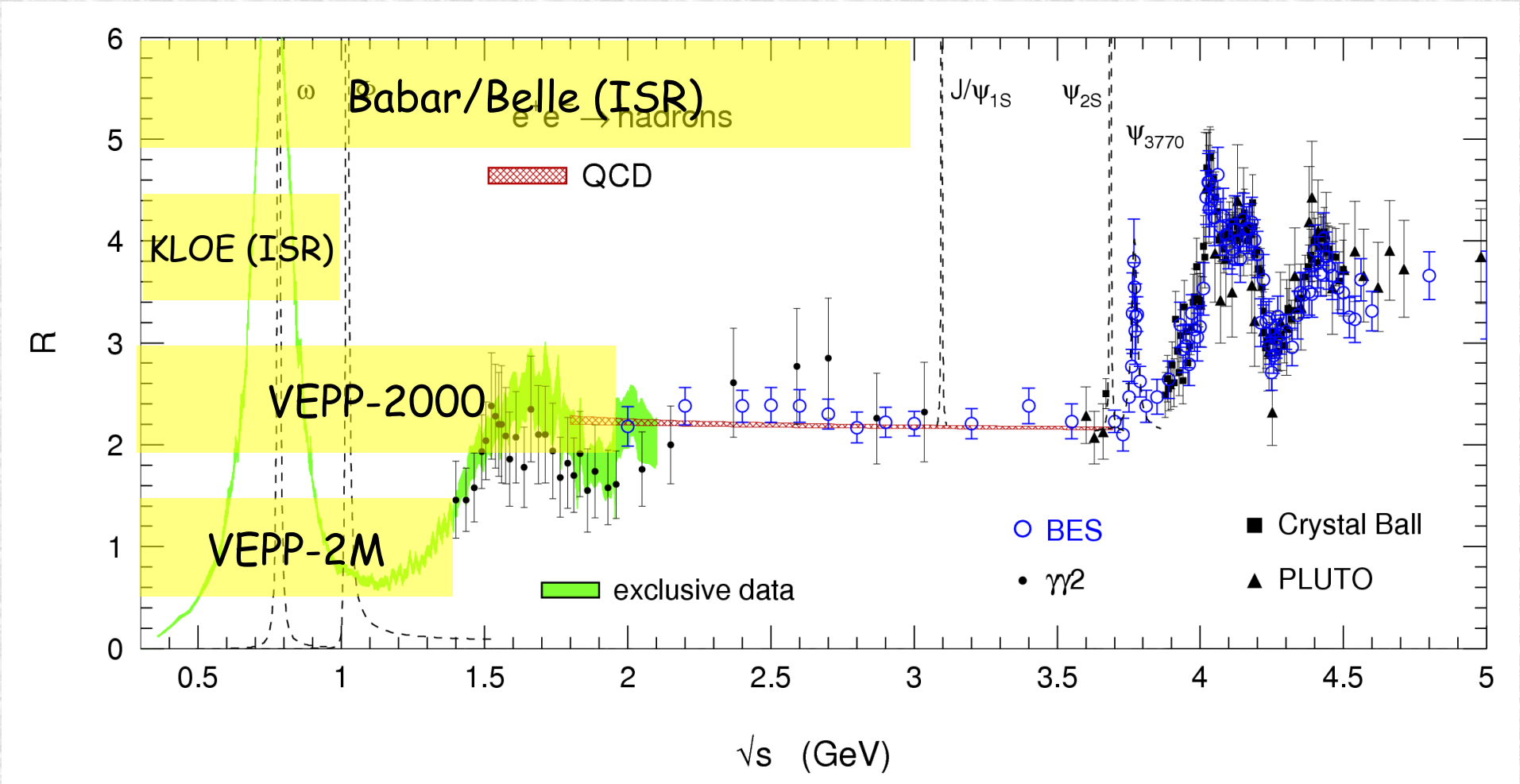
Measurement of the cross-section e+e- → hadrons in VEPP-2M energy range is interesting for:

- measurement of parameters of light vector mesons ρ, ω, φ, ρ′, ρ″, ω′, ω″
- measurement of R(s) :

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

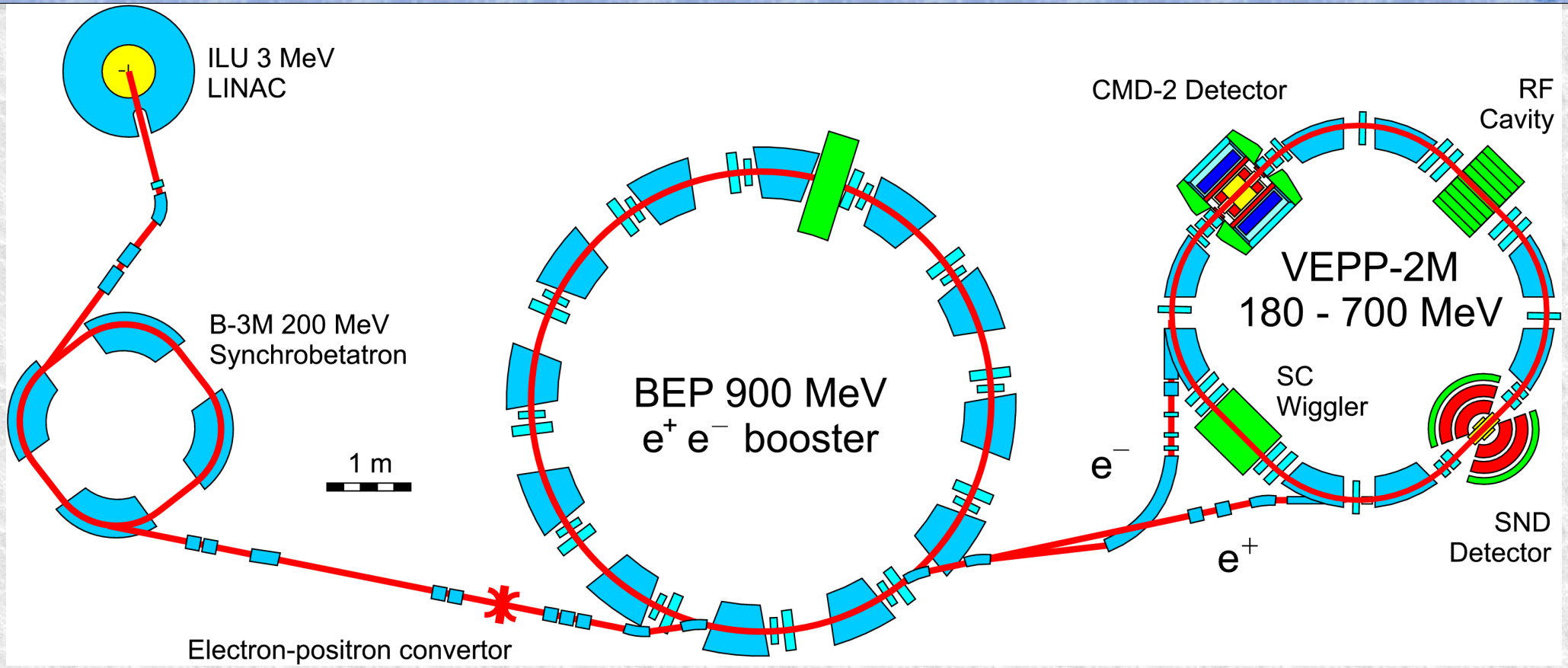
- comparison with spectral functions of the hadronic tau decays

R(s) measurements at low s



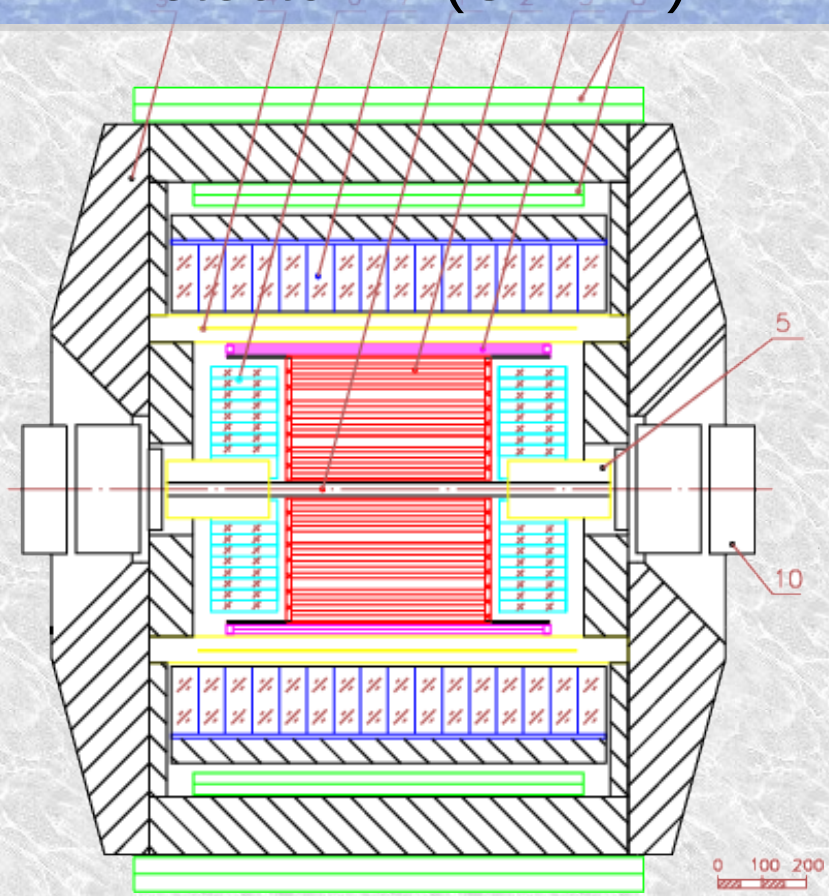
At low s R(s) has to be measured in each channel.
The value and the error of the hadronic contribution to muon's (g-2) are dominated by low energy R(s).

VEPP-2M collider



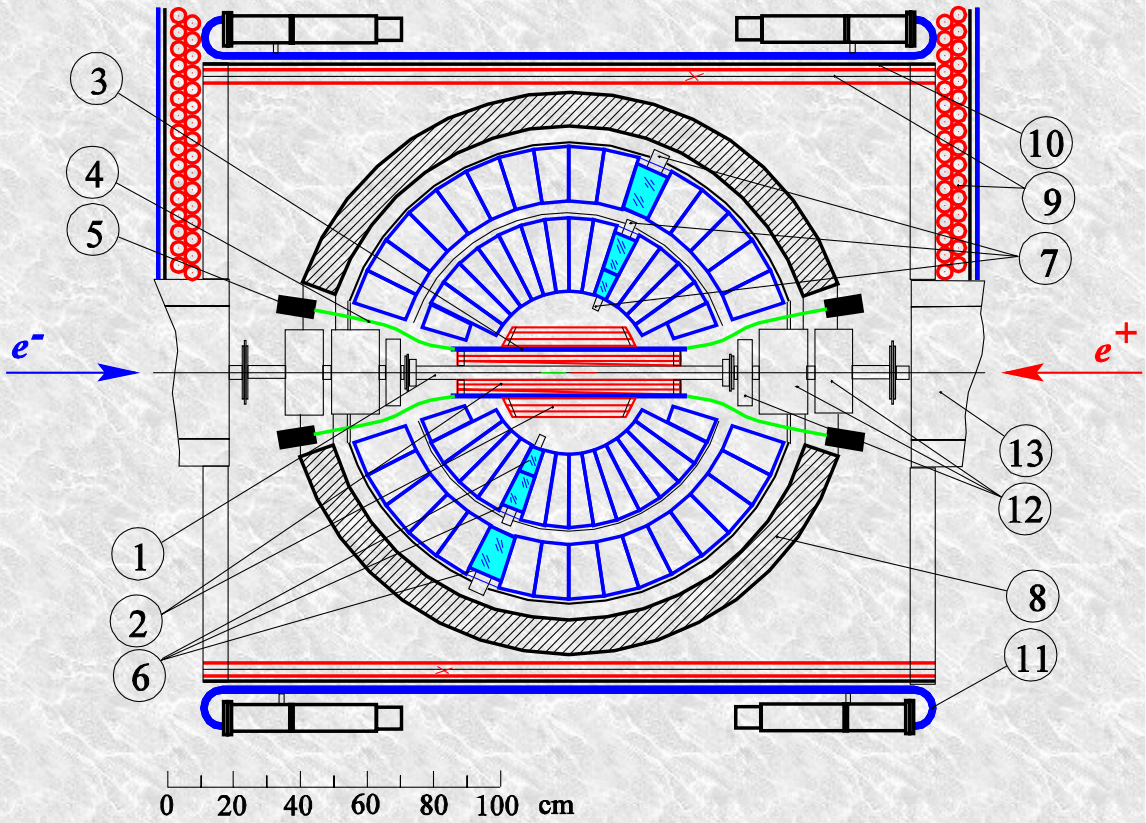
- VEPP-2M collider: 0.36-1.4 GeV in c.m., $L \approx 10^{30}$ 1/cm^{2}s at 1 GeV
- Detectors CMD-2 and SND: $\int L dt \approx 60$ pb^{-1} collected in 1993-2000
- Precise energy: $\Delta E / E \sim 10^{-4}$ with depolarization method;
  10^{-3} from field in magnets
- All major hadronic modes were measured:
  e+e- → 2π, 3π, 4π, KK, ..
  e+e- → ρ, ω, φ

Cryogenic Magnetic Detector- 2 (**CMD-2**)



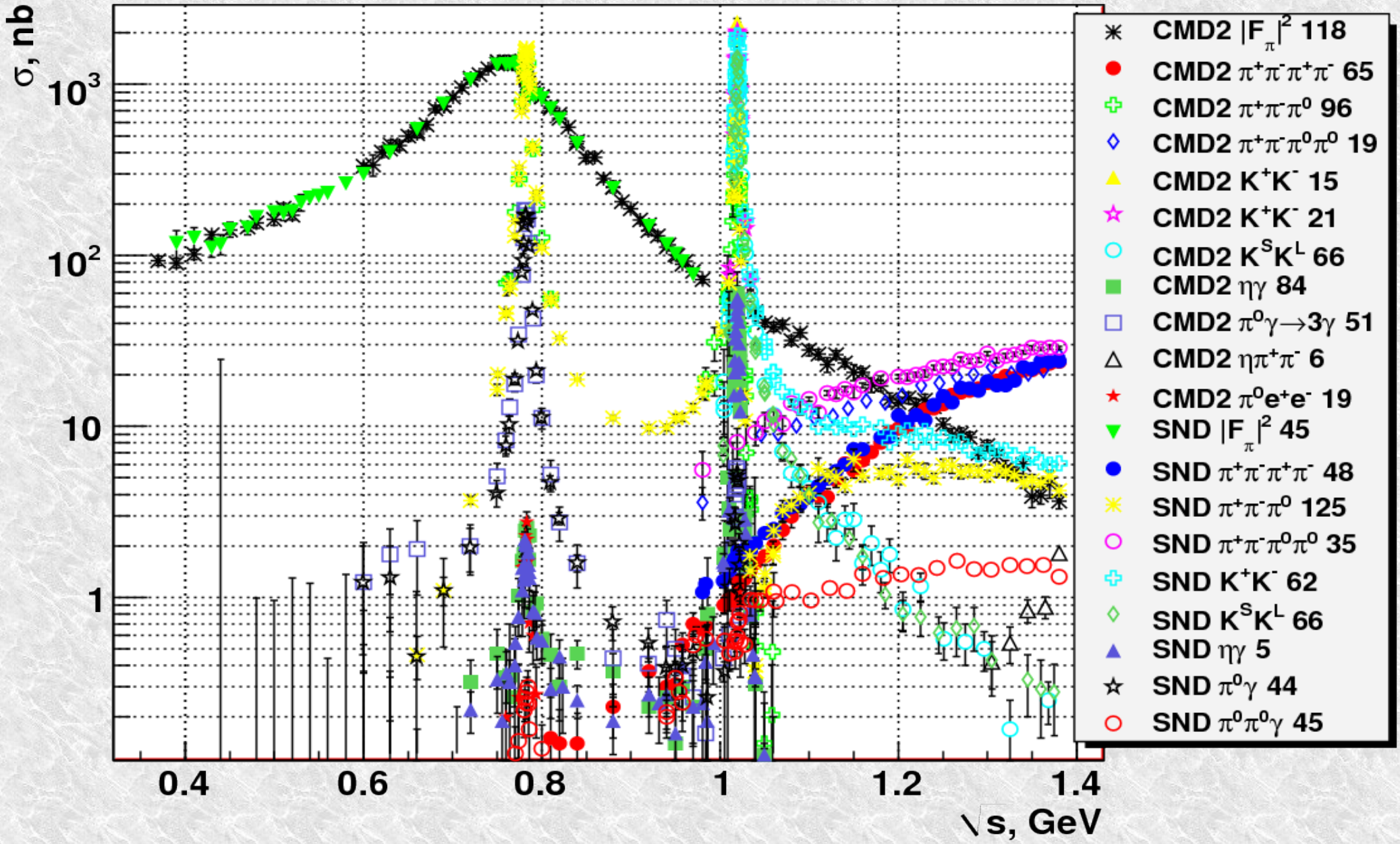
1 – vacuum chamber, 2 – drift chamber,
3 – Z-chamber, 4 – superconducting solenoid, 5 – compensating magnets,
6 – BGO end cap calorimeter,
7 – CsI(Tl,Na) calorimeter,
8 – muon system, 9 – magnet yoke.

Spherical Neutral Detector (**SND**)



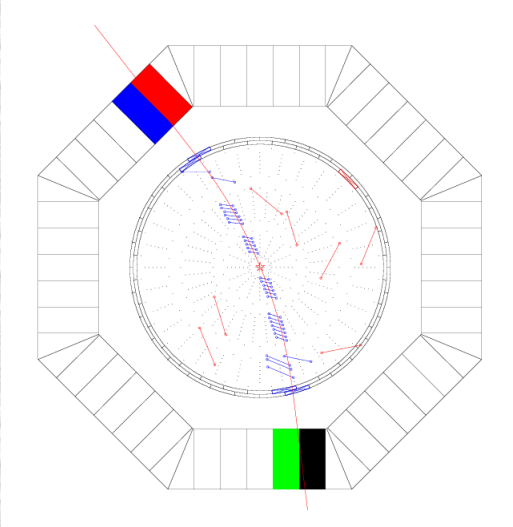
1 – vacuum chamber, 2 – drift chambers,
3 – scintillation counter, 4 – light guides,
5 – PMT, 6 – NaI(Tl) crystals, 7 – VPT,
8 – iron absorber, 9 – streamer tubes,
10 – iron plates,
11 – scintillation counters

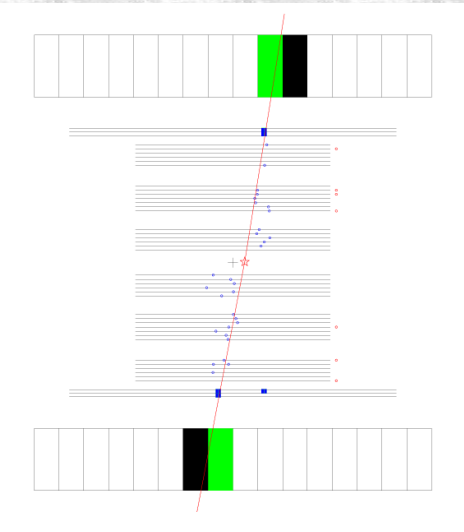
Inclusive Hadronic Cross-Sections with CMD2&SND



Measured cross-sections have difference about 4 orders of magnitude

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





Events signature:

two collinear tracks are almost back-to-back

vertex located near interaction point

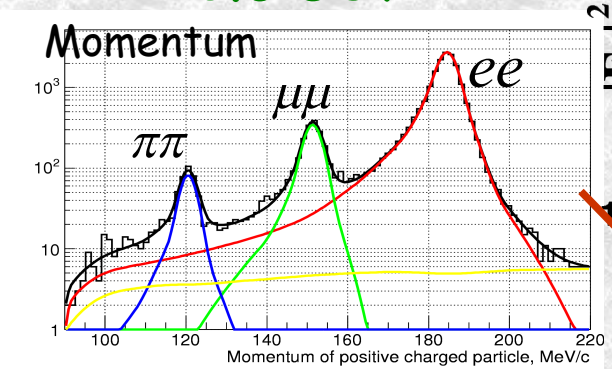
Data sample includes events with:

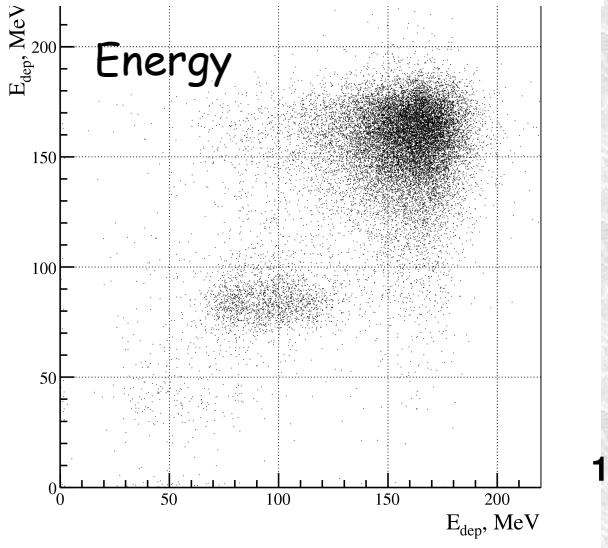
e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$, cosmic muons

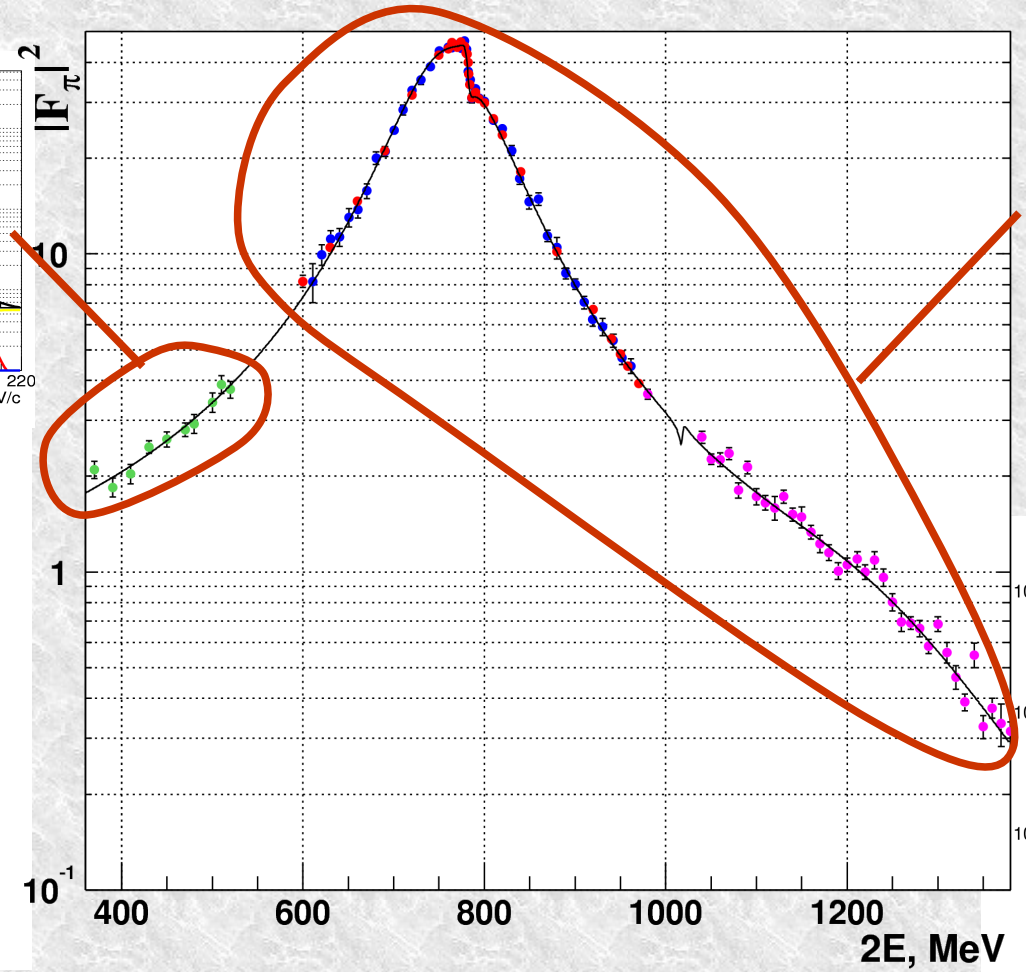
Mostly doesn't have any other background at $\sqrt{s}$ <1 GeV

Event separation (CMD-2)

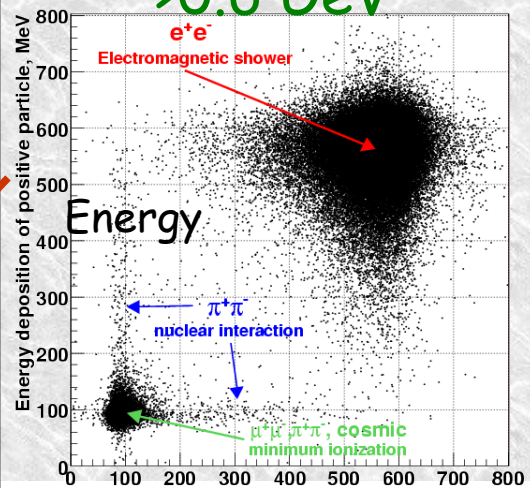
<0.6 GeV

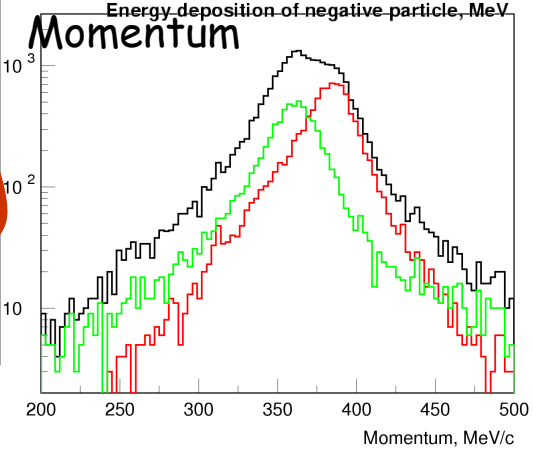






>0.6 GeV





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

Likelihood minimization:

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

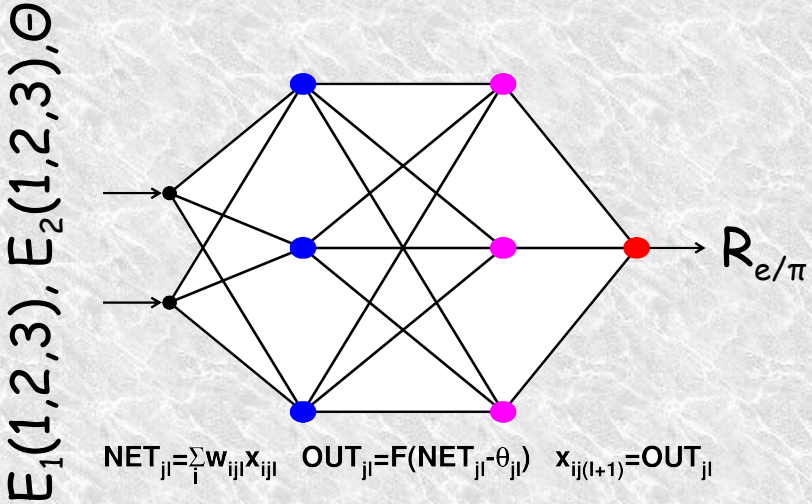
$$\text{type} = e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \text{cosmic}$$

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

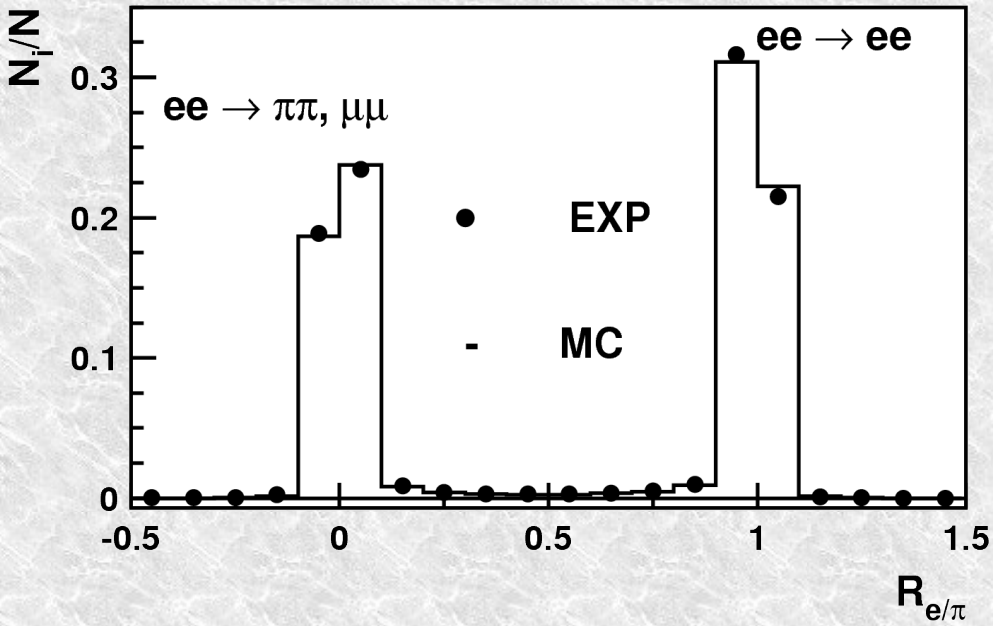
Event separation (SND)

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

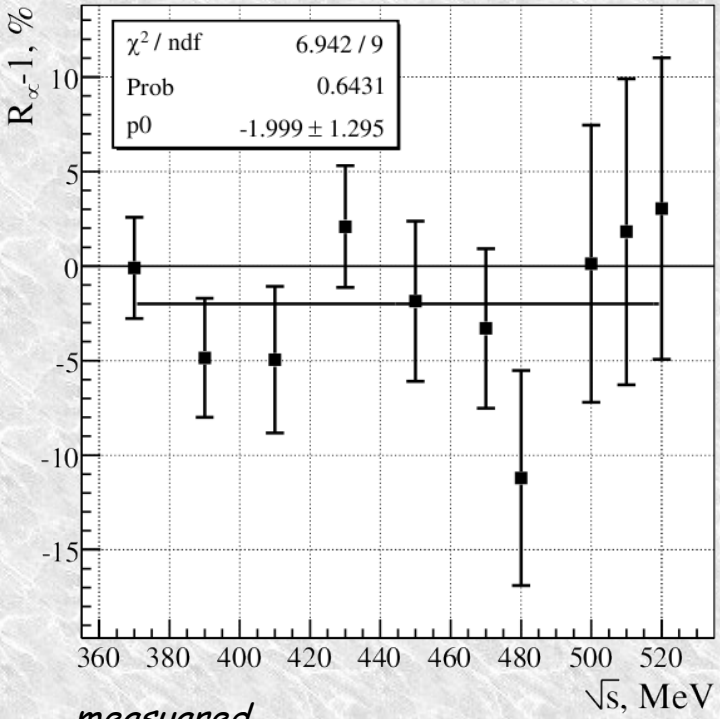


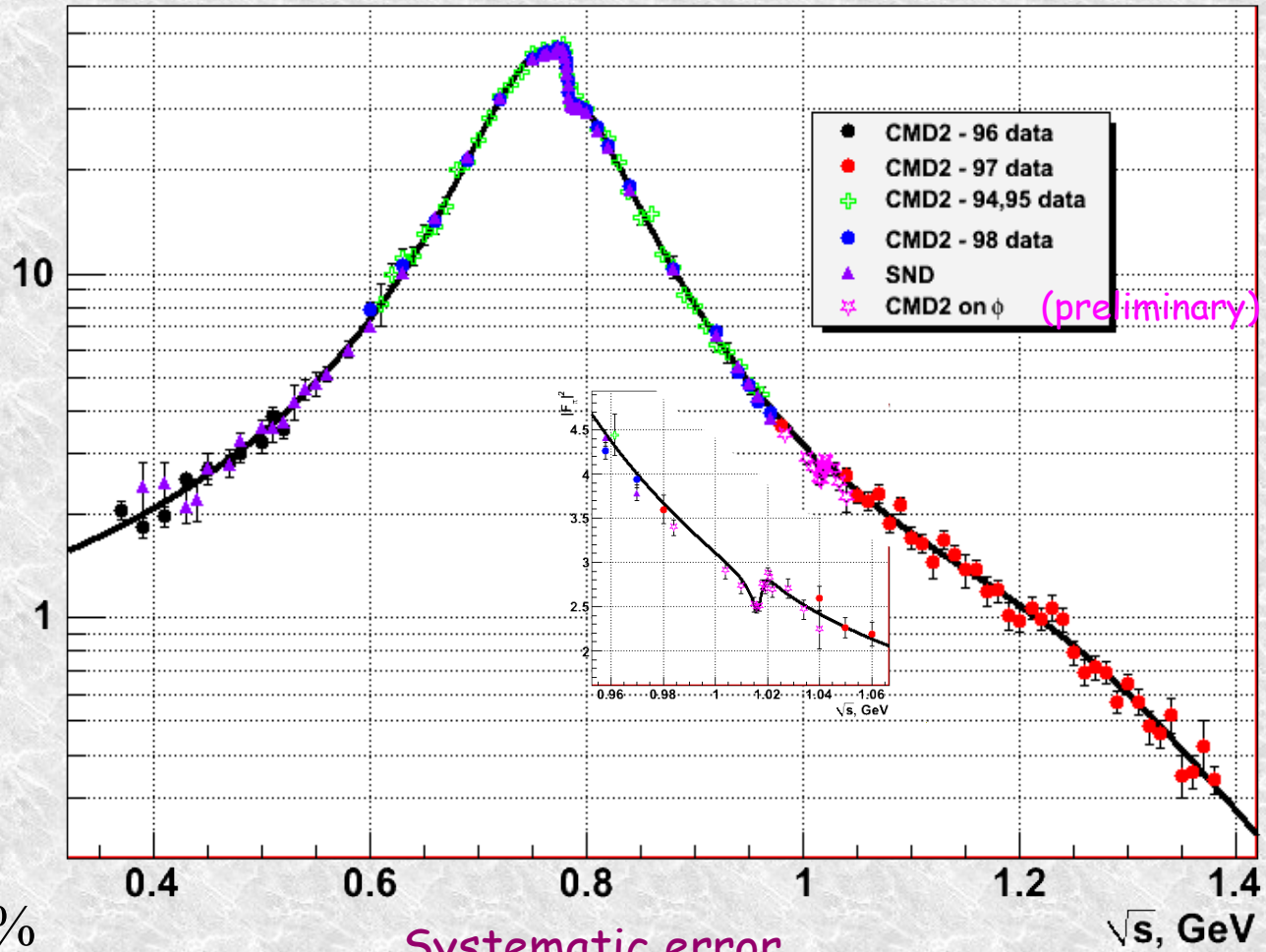
Distribution by separation parameter



Misidentification ~ 0.5--1%

Pion formfactor





$$\frac{\sigma^{measured}_{\mu^+\mu^-}}{\sigma^{QED}_{\mu^+\mu^-}} - 1 = -2 \pm 1.3 \pm 0.7\,\%$$

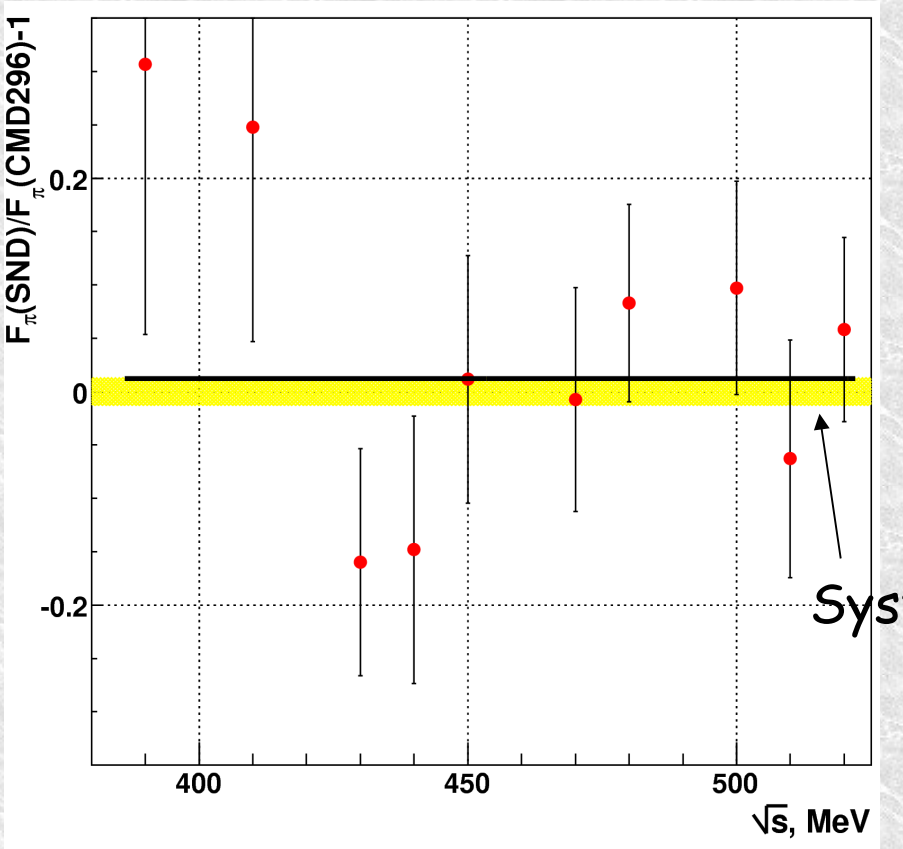
Systematic error

CMD2: 0.7% | 0.6% (95)/ 0.8% (98) | 1.2-4.2%

SND: 3.2% | 1.3%

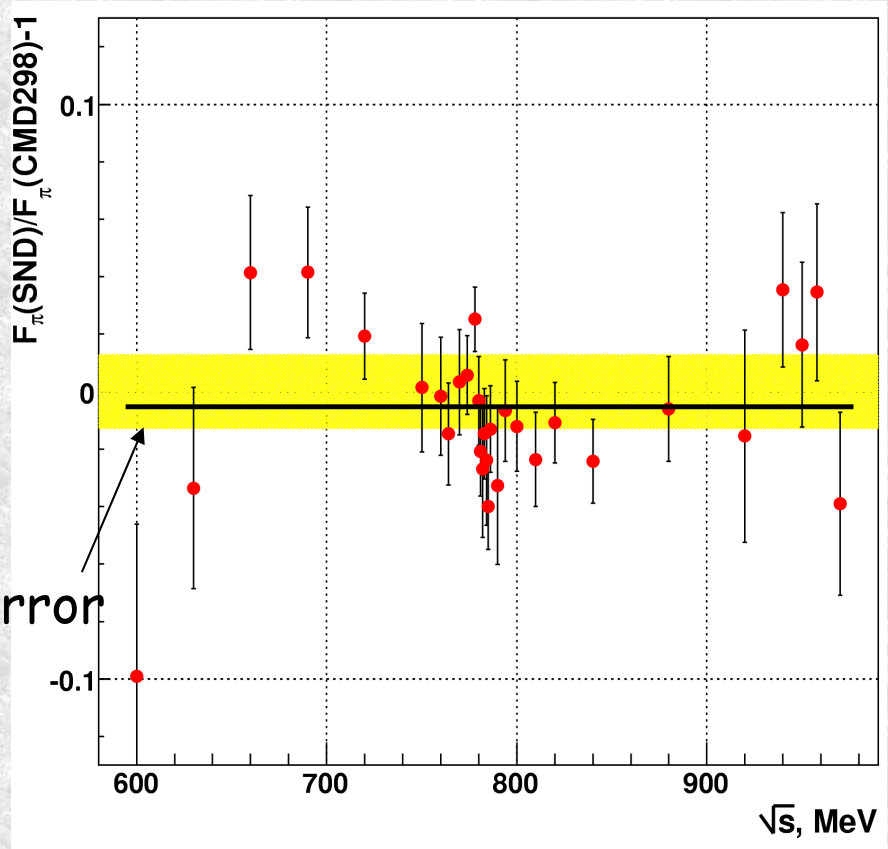
Comparison of CMD-2 and SND

$\sqrt{s}<0.55$ GeV



Syst.error

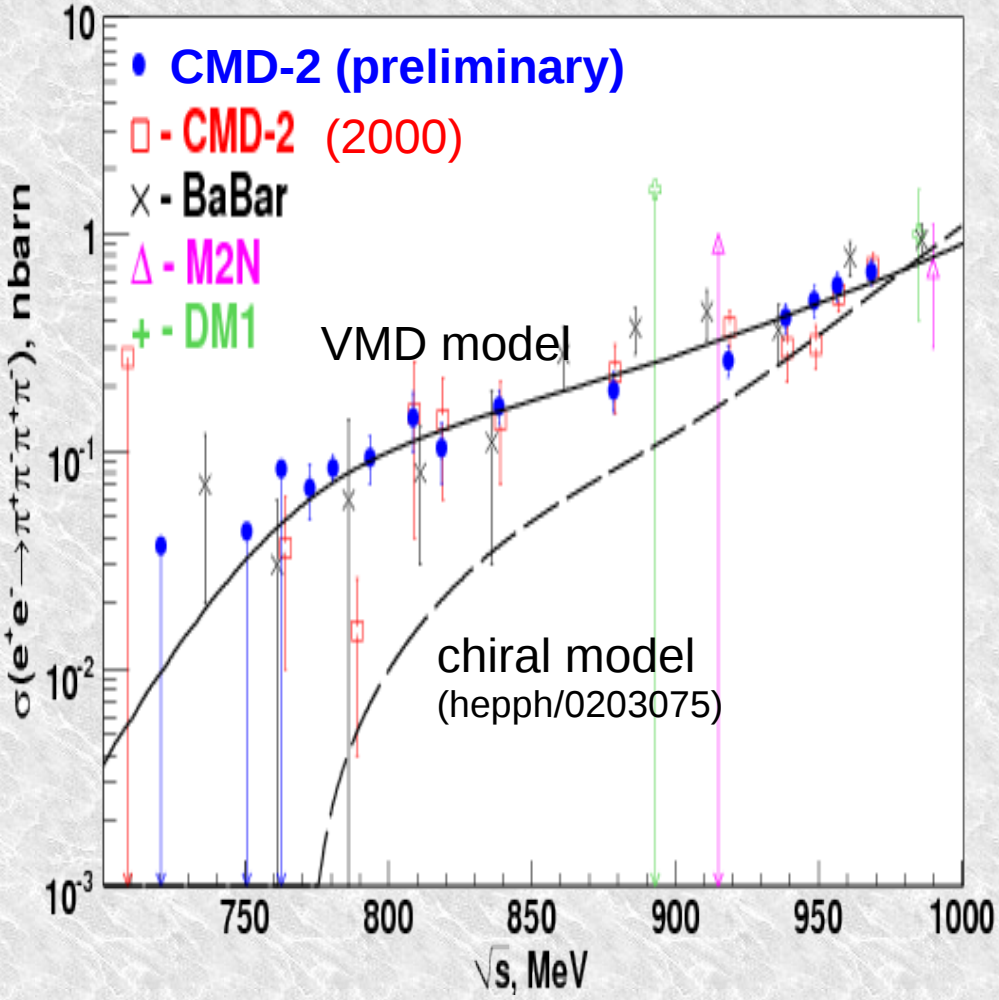
$0.6<\sqrt{s}<1$ GeV

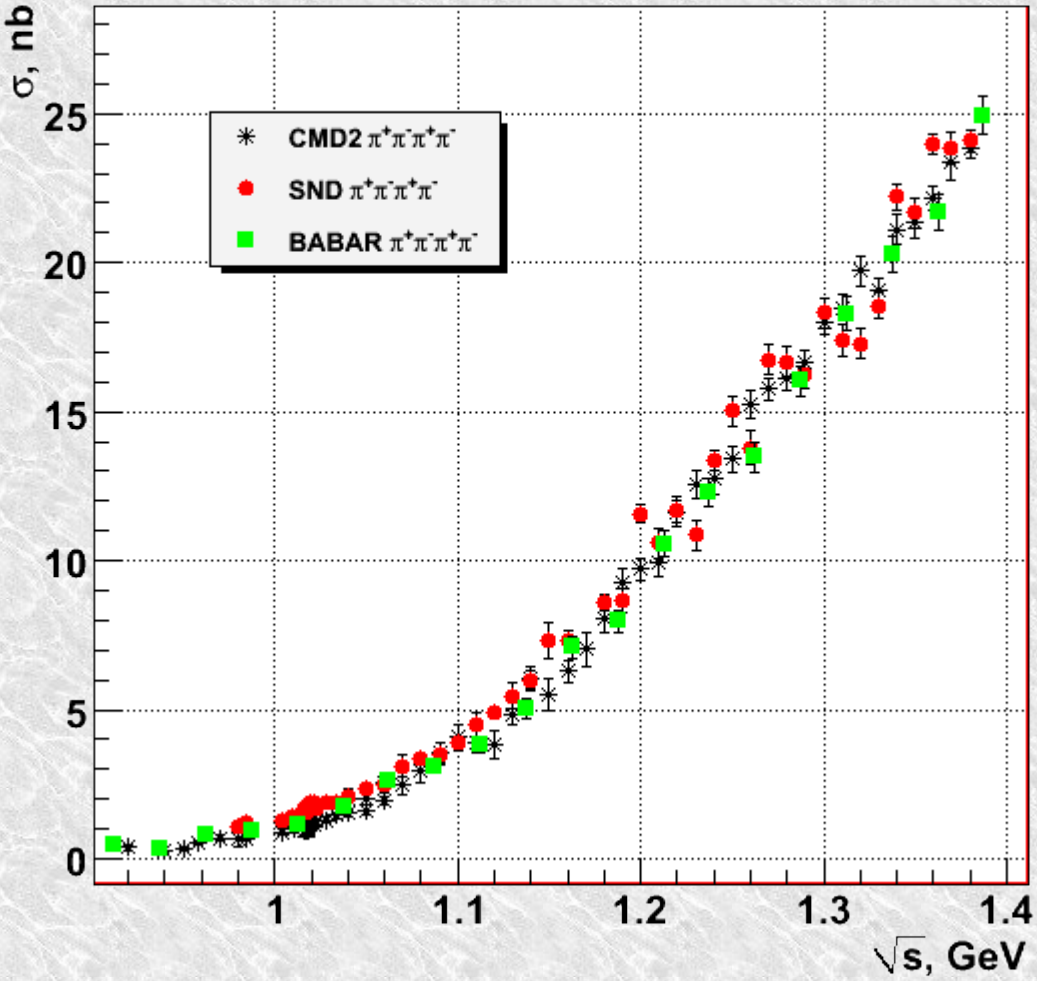


Δ(SND-CMD2)≈1.2%±3.6%

Δ(SND-CMD2)≈-0.53%±0.34%

Cross-section e+e- → π+π-π+π-





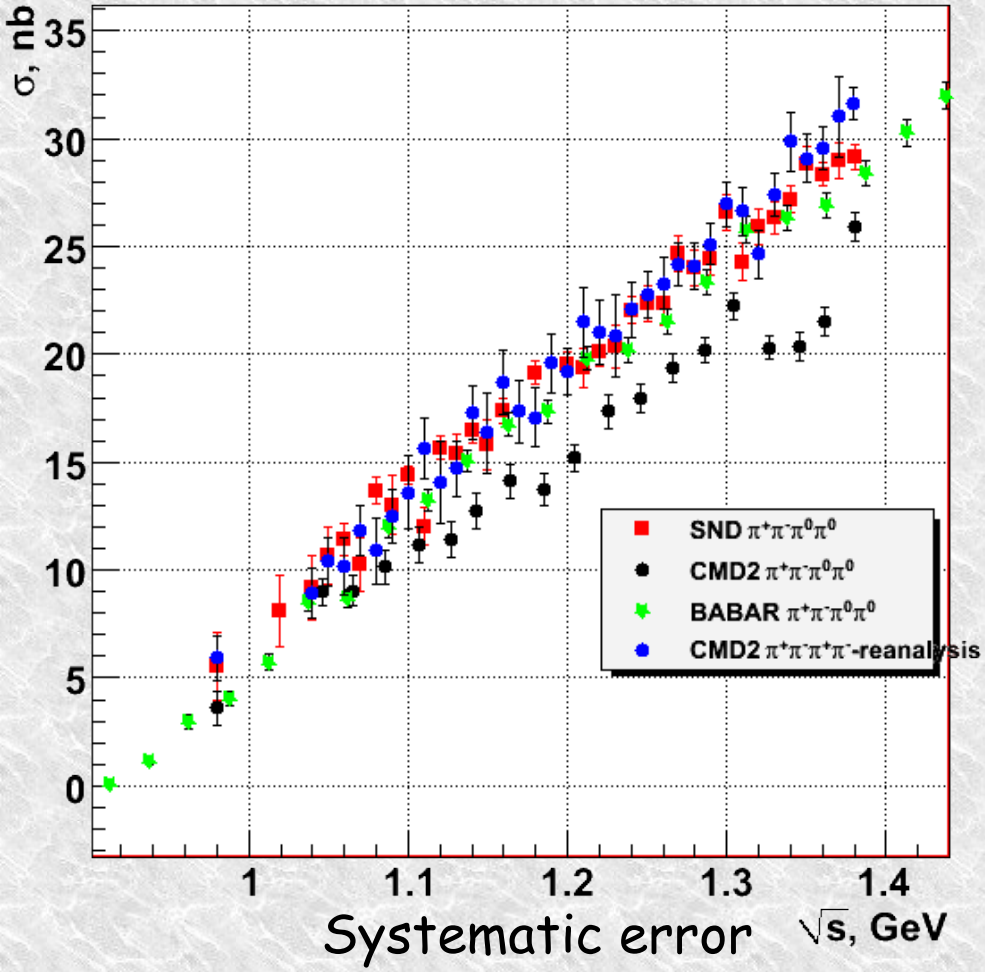
Systematic error ≈10%

Systematic error ≈5-7%

Efficiency determination gives main contribution to the systematic error

Cross-section e+e- → π+π-2π0 ;π+π-π0

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



Systematic error

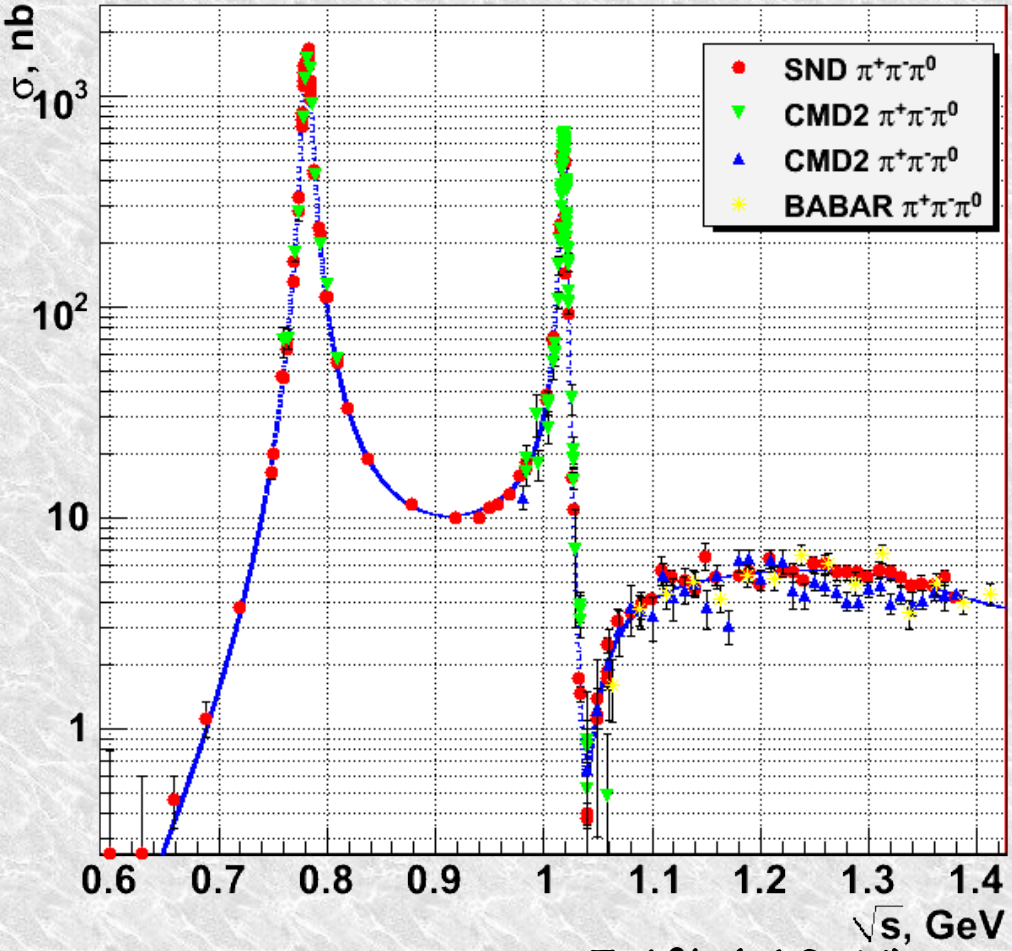
SND = 8%

CMD2= 15% (discrepancy 15-25%)

problem with efficiency determination was understood

CMD2-reanalysis preliminary = 8%

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



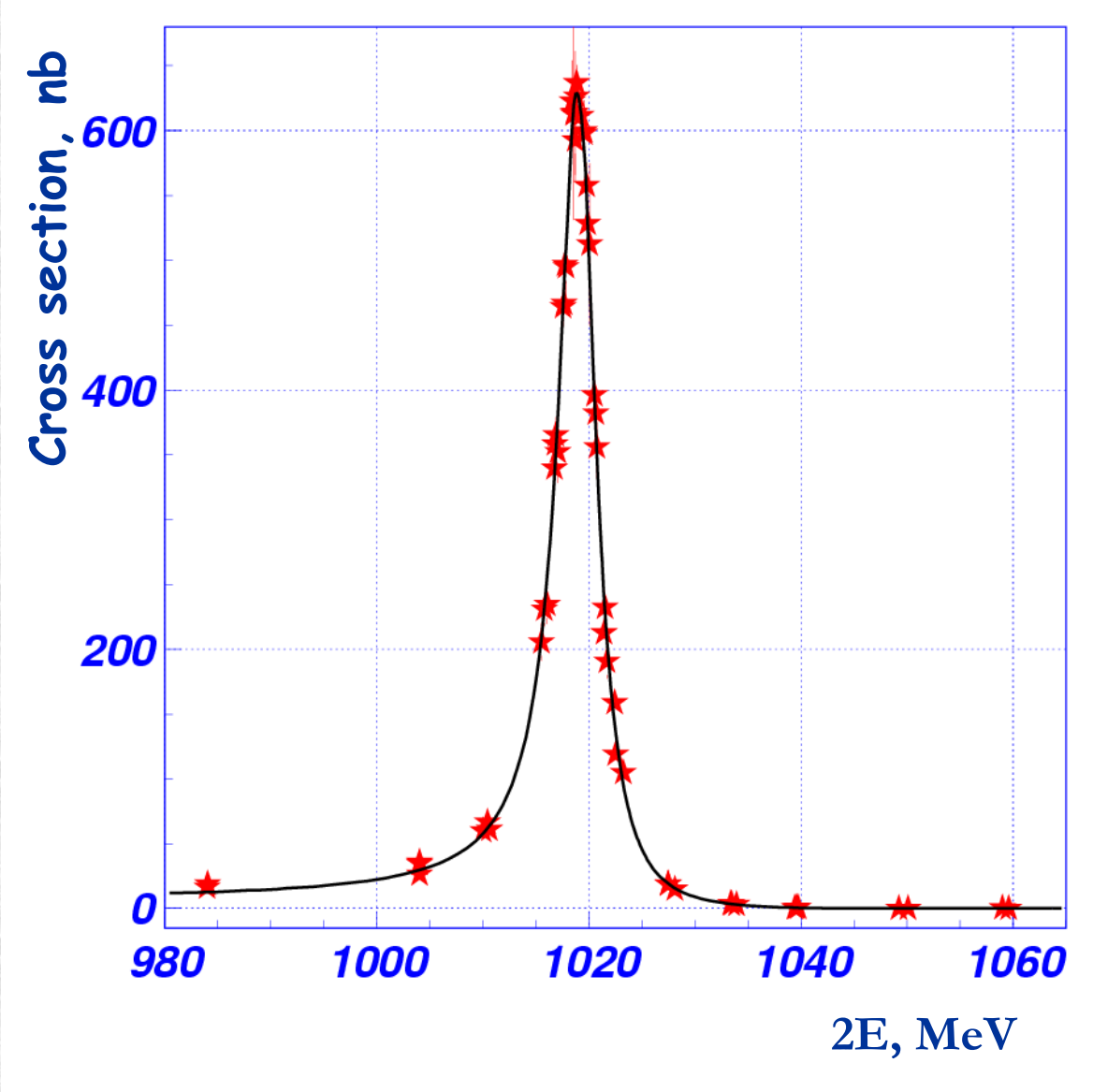
Systematic error: 5.6% (>1GeV),

1.3% on omega;

2.5% on phi

The curve is the result of the fit taking into account $\omega, \rho, \phi, \omega', \omega''$.

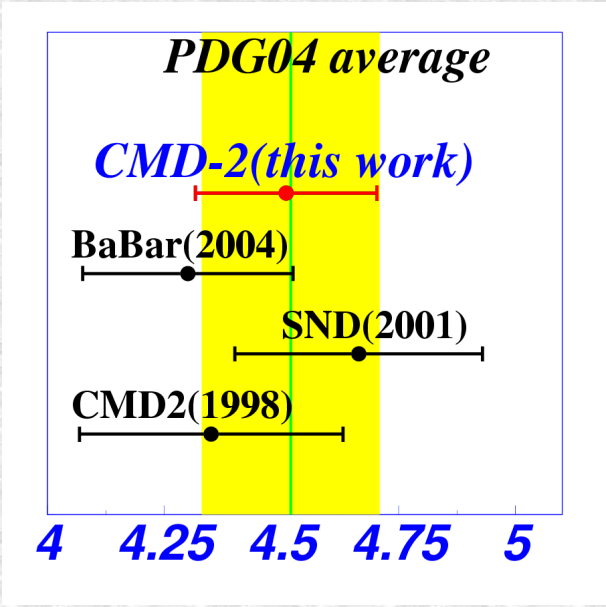
e+e- → π+π-π0 at ϕ (CMD2)



$\int Ldt = 12\ pb^{-1}$

$N_\Phi = 16 \cdot 10^6$

$B_{ee}B_{3\pi}=(4.35 \pm 0.27 \pm 0.08)\times 10^{-5}$



$\sigma_{3\pi}=(637 \pm 23 \pm 16)$ nb

$\Gamma_\phi = (4.30 \pm 0.06 \pm 0.17)$ MeV

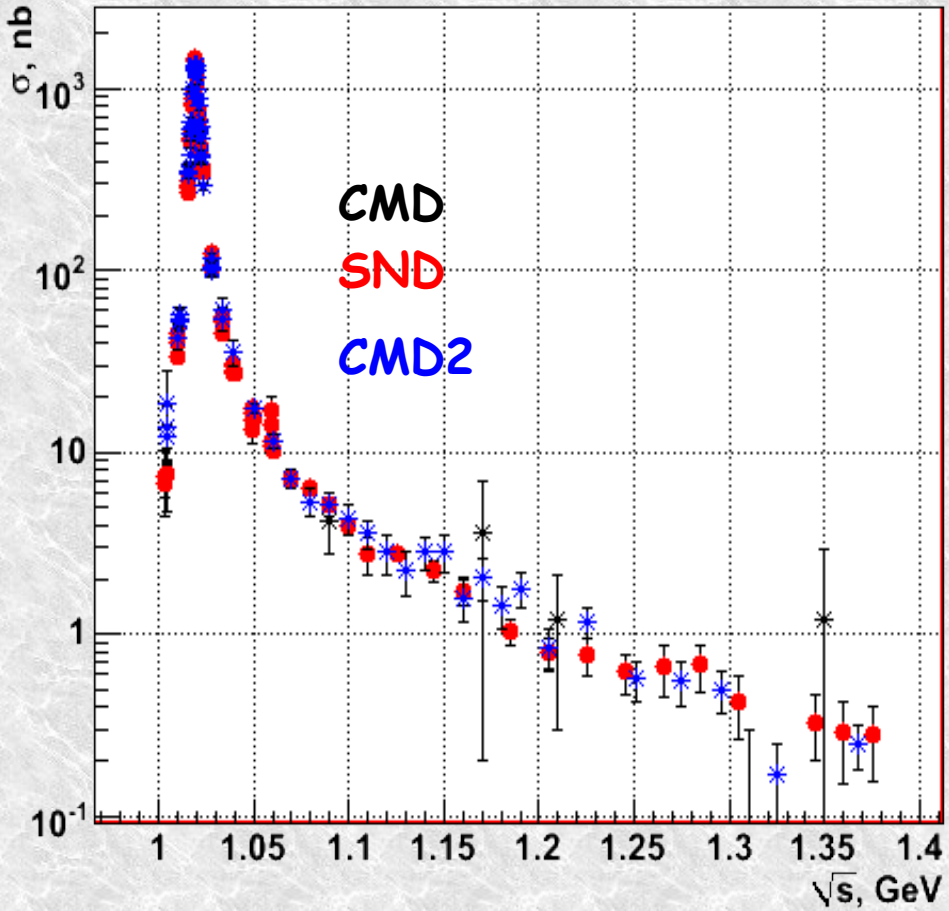
$\varphi_{\omega\phi} = 167° \pm 14° \pm 10°$

Systematic error:

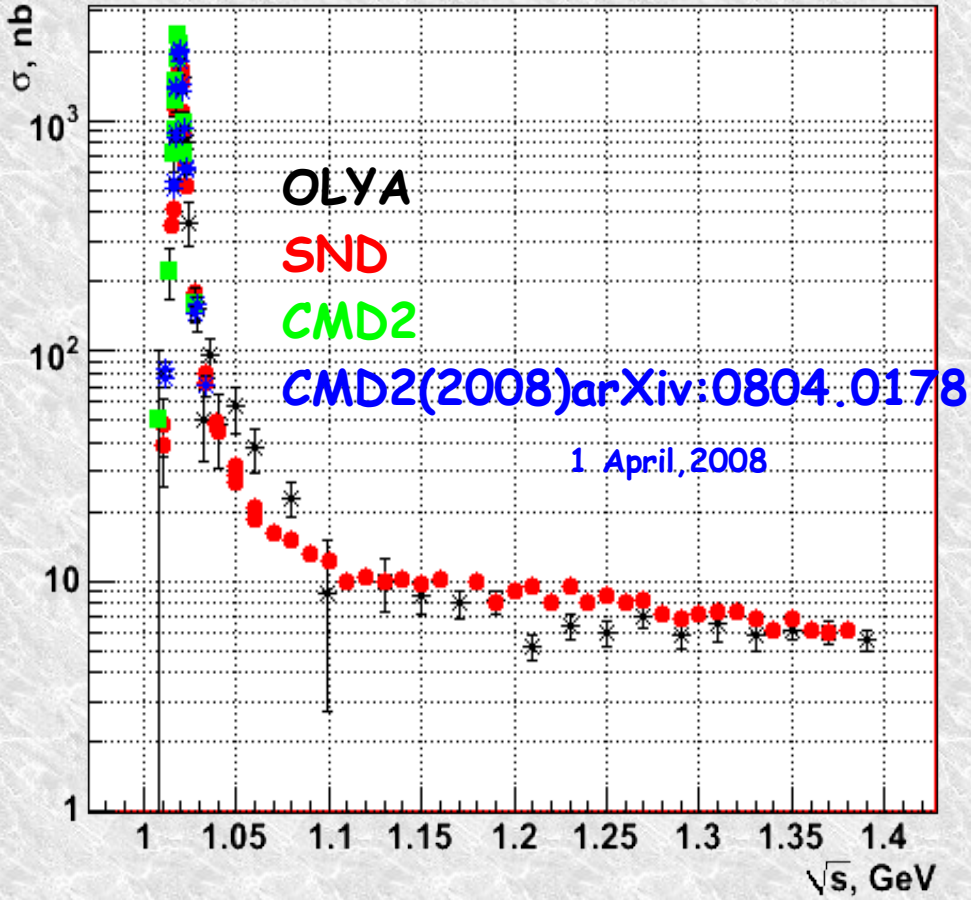
CMD2(1998)	5%
SND(2001)	5%
CMD2(2006)	2.5%

Cross-section e+e- → 2K

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



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



Systematic error: SND ≈ 3%

CMD2 ≈ 8-9%

Systematic error ≈4-6%

Systematic error is ≈ 2% at φ resonance

For data description the $\phi, \rho, \omega, \phi'$ resonances are required.

Cross-section e+e- → K+K- (CMD2)

1.0 pb^{-1} of integrated luminosity, collected in E_{cm} = 1010 – 1034 MeV

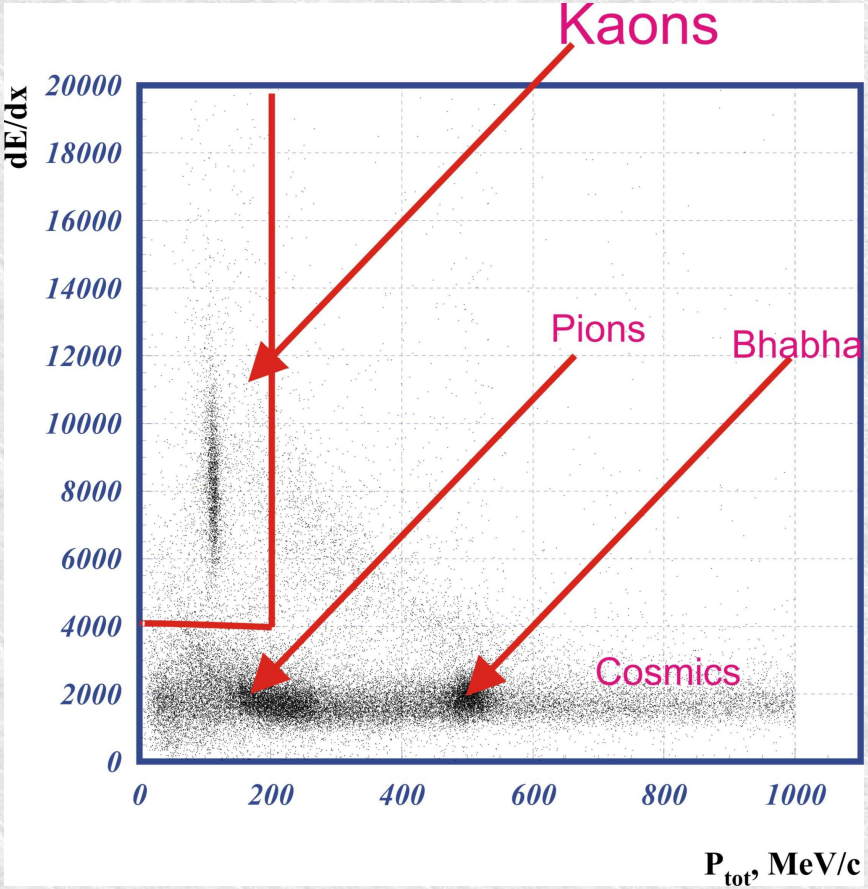
Idea of selection

Kaon from ϕ meson decay is a low momentum track with big dE/dx value, coming from the beam.

We determine "good" kaon as:

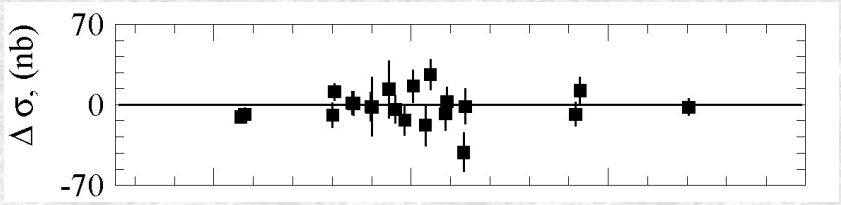
- $P_{tot} < 200$ MeV/c
- $dE/dx > 2\ dE/dx_{MIP}$
- $R_{min} < 0.4$ cm
- $1.0 < \theta_K < \pi - 1.0$.
- $N_{R\phi} > 6$, $N_{RZ} > 3$
- $\sigma_{R\phi} < 0.07$ cm, $\sigma_{RZ} < 3.0$ cm

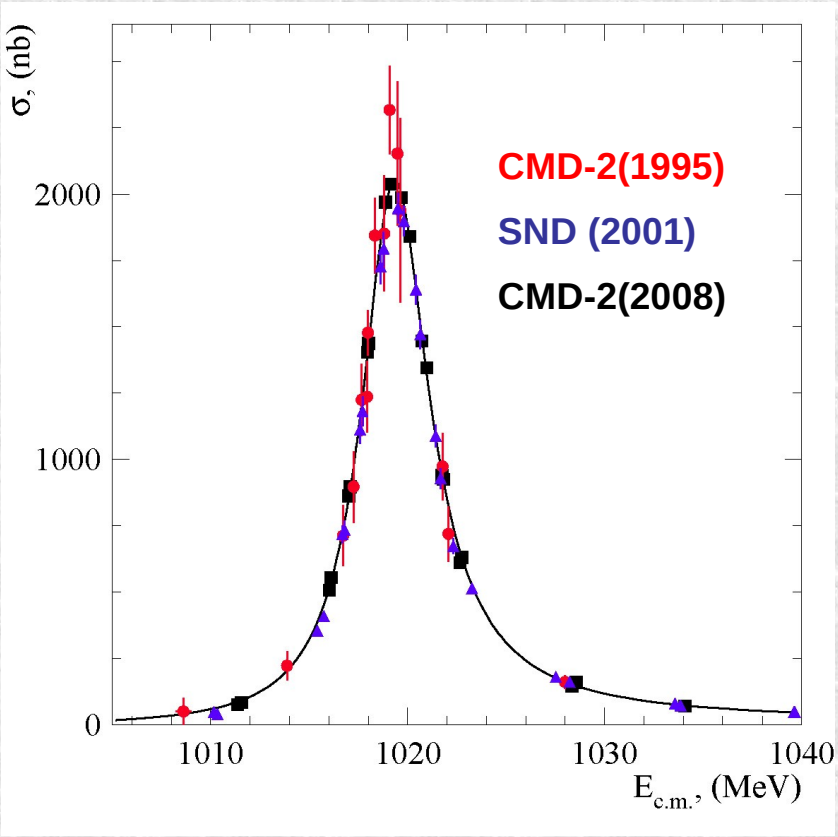
We select events with one or two "good" kaons.



542 000 events with one or two "good" kaons were used in the analysis

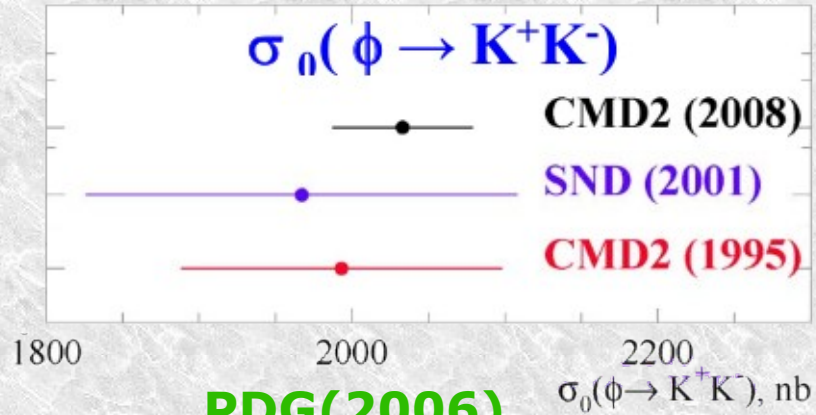
Cross-section e+e- → K+K-





Systematic errors CMD2 (2008)

Source	, %
Selection criteria	1.4
Trigger efficiency	1
Luminosity	1
Acceptance	0.7
Radiative corrections	0.5
Total	2.2



CMD-2 (2008)

$B_{ee}B_{KK} = (14.29 \pm 0.05 \pm 0.31) \cdot 10^{-5}$

$m_\phi = 1019.441 \pm 0.008 \pm 0.080$ MeV/c²

$\Gamma_\phi = 4.24 \pm 0.02 \pm 0.03$ MeV

PDG(2006)

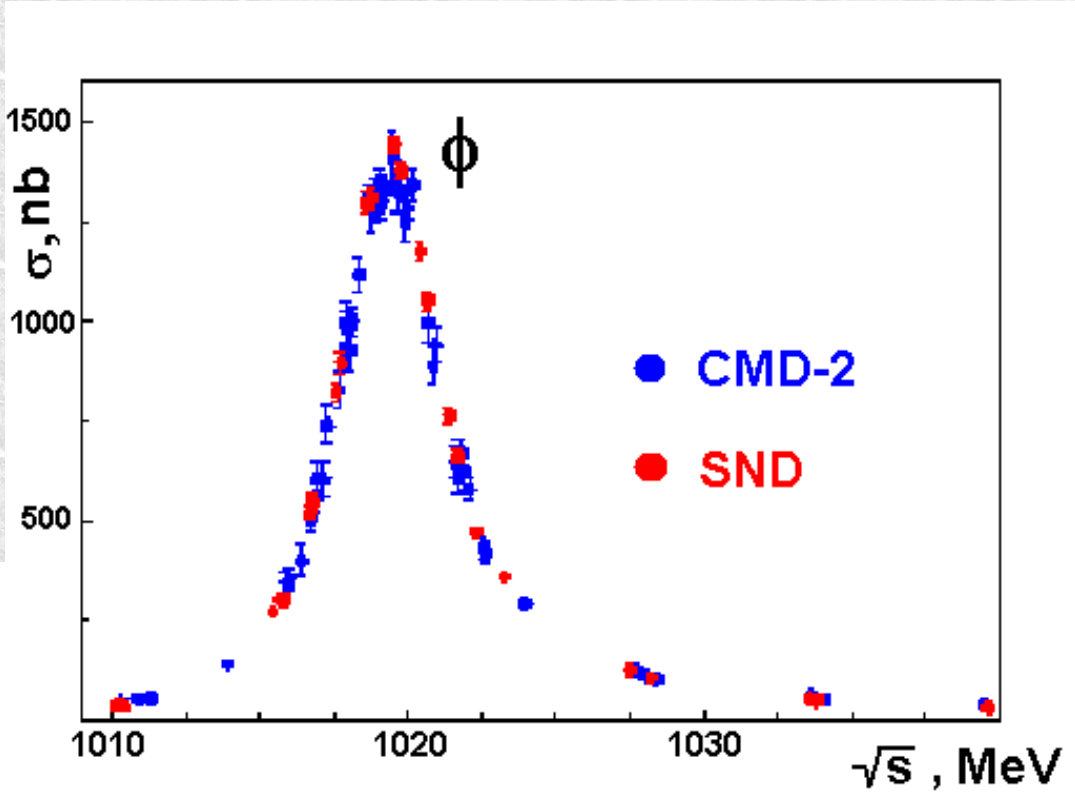
$B_{ee}B_{KK} = (14.60 \pm 0.33) \cdot 10^{-5}$

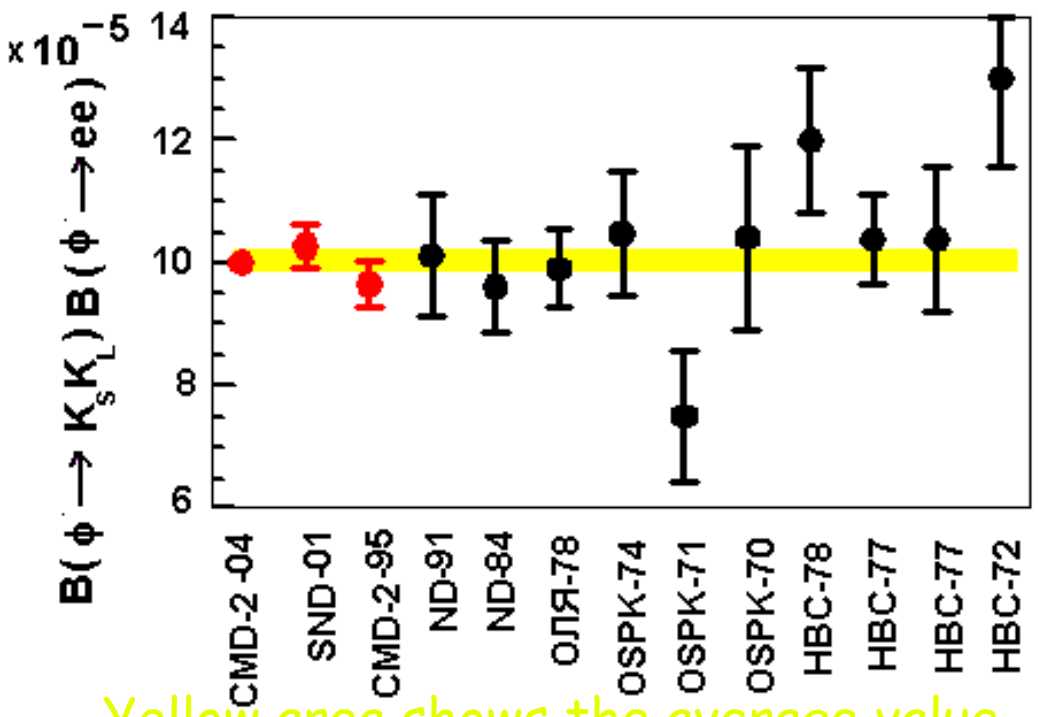
$m_\phi = 1019.455 \pm 0.020$ MeV/c²

$\Gamma_\phi = 4.26 \pm 0.04$ MeV

The e+e- → $K_S K_L$ cross section

The cross section measurements were based on the $K_S \to \pi^0\pi^0$ and $\pi^+\pi^-$ decays.





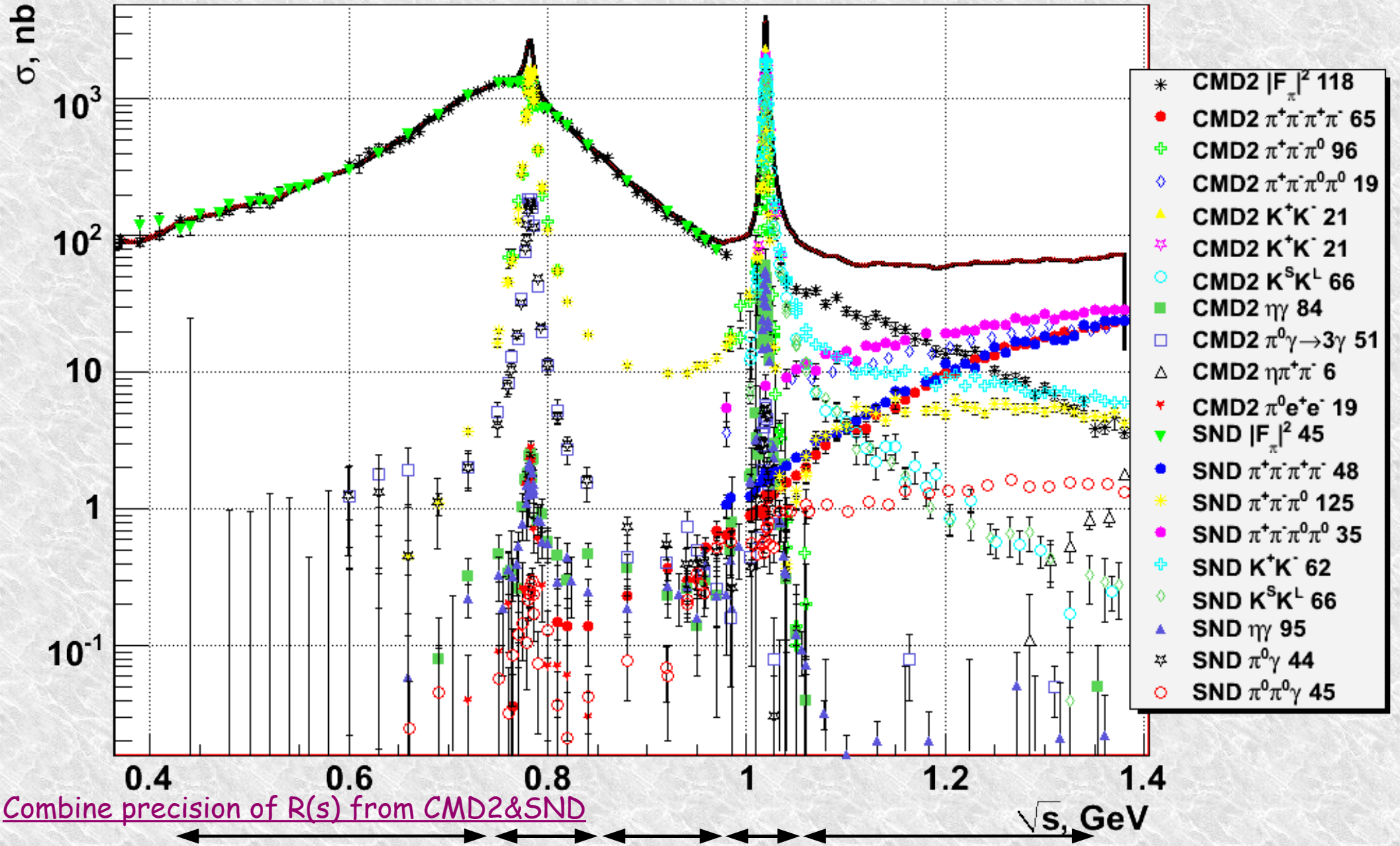
Yellow area shows the average value.

Systematic errors:

SND - 3.3%

CMD-2 - 1.7%

Inclusive Hadronic Cross-Sections with CMD2&SND



Combine precision of R(s) from CMD2&SND

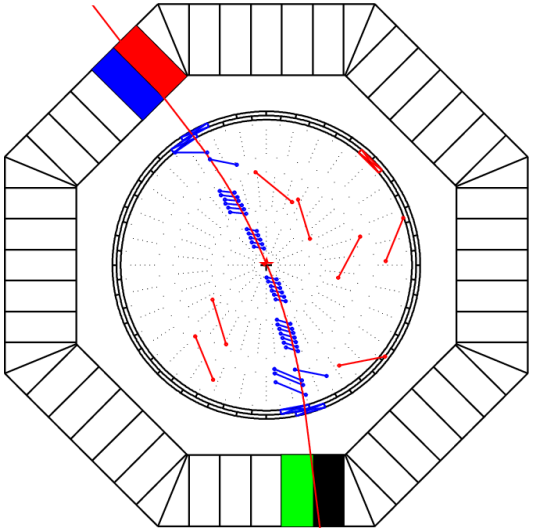
Systematic error:	~0.6-0.7%	1.0%	0.6%	1.5%	1.5 -- 3.5 %
Total error:	~ 6 -- 1%	1.5%	1--2%	2.0%	2.5 -- 3.5 %

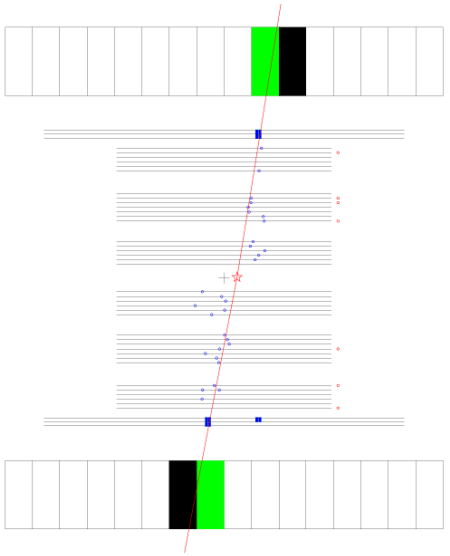
Conclusions

- Despite decades of experiments, precise studies of e^+e^- annihilation into hadrons at low energies are still interesting and provides a lot of important information.
- In the 1995-2000 the experiments with CMD-2 and SND detectors at VEPP-2M were fulfilled.
- CMD-2 and SND data analyses are nearly completed.
- Cross sections of all major modes of e+e- $\rightarrow$ hadrons are measured in the energy region $\sqrt{s}$ = 0,36 – 1,38 GeV.
- Results of these experiments determine nowadays the accuracy of the light vector mesons parameters knowledge. Them are one of the main sources of information about particle physics at low energies.
- In a few years new high precision data from CMD-3 and SND working at VEPP-2000 are expected

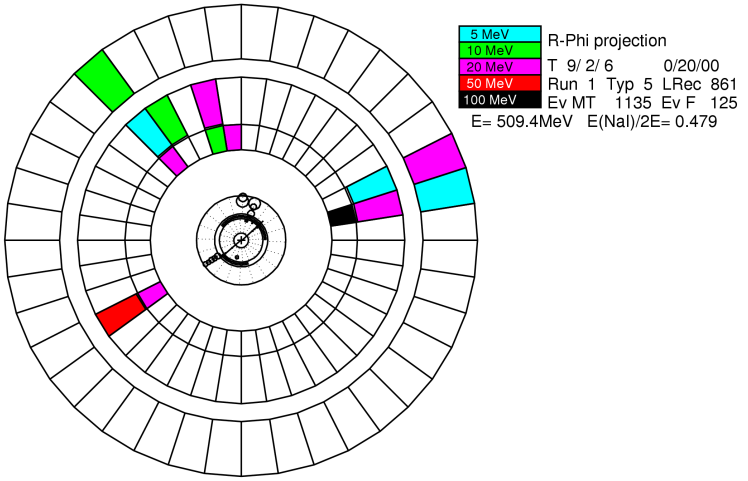
Example of CMD-2 and SND events

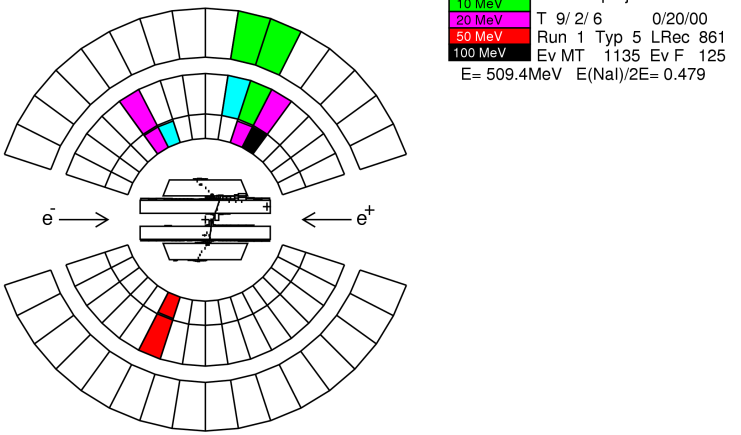
$e^+e^- \to \pi^+\pi^-$ in CMD-2





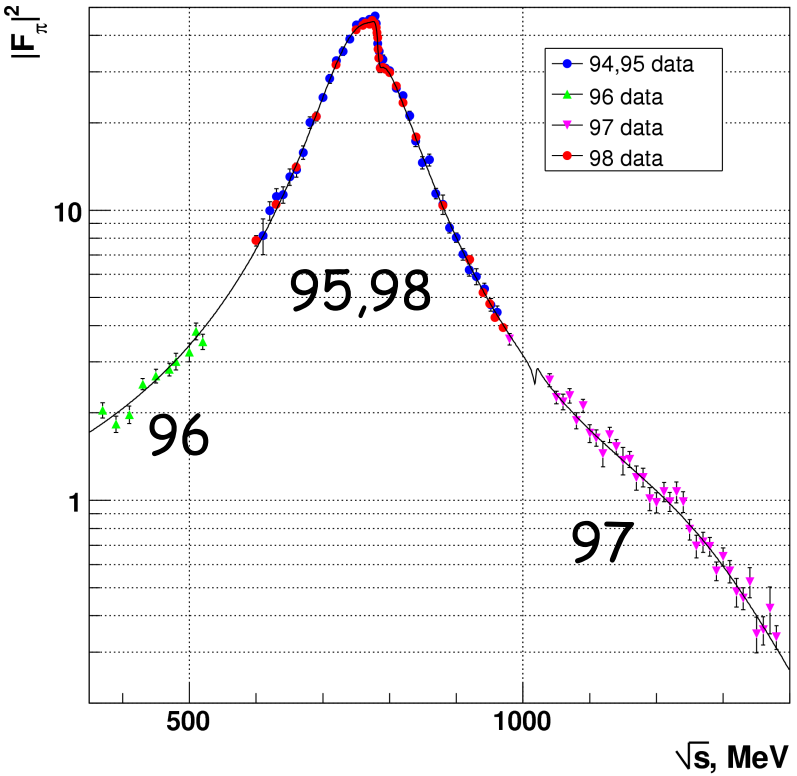
$e^+e^- \to K^+K^-$ in SND





Data taking history

CMD-2



1994-1995

114k $\pi^+\pi^-$

1996

4k $\pi^+\pi^-$

1997

33k $\pi^+\pi^-$

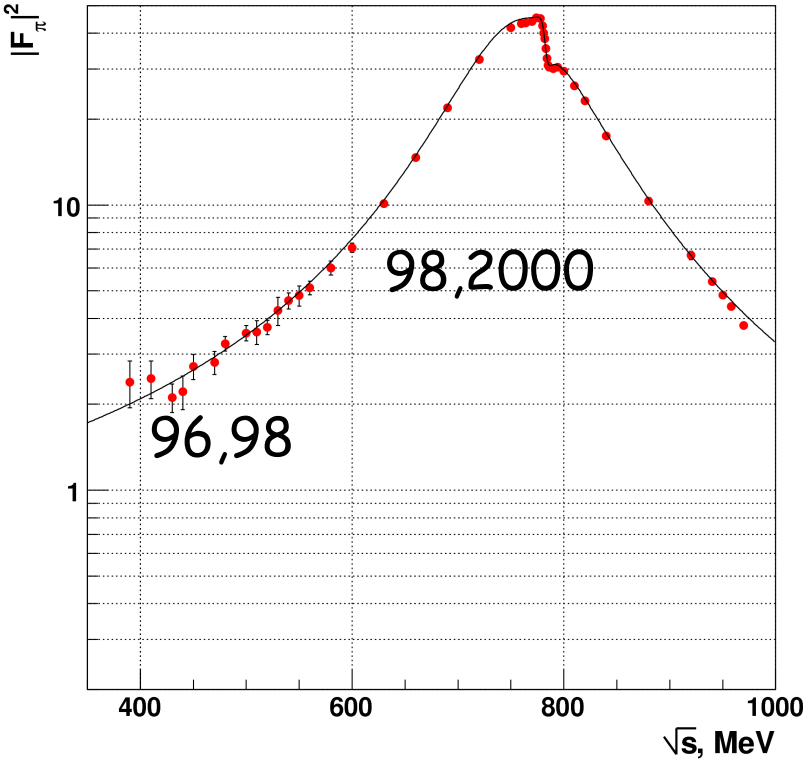
1998

~1M $\pi^+\pi^-$

2000

~2M $\pi^+\pi^-$

SND



Systematic errors

Source of error	CMD-2 $\sqrt{s}$<1 GeV	SND	CMD-2 $\sqrt{s}$>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%

How cross-section is measured

All modes except 2π

$$\sigma(e^+e^- \to H) = \frac{N_H - N_{bg}}{L \cdot (1+\delta_H) \cdot \varepsilon_H}$$

- Luminosity L is measured using Bhabha scattering at large angles
- Efficiency ε is calculated via Monte Carlo + corrections for imperfect detector
- Radiative correction δ accounts for ISR effects only

2π

$$|F_\pi|^2 = \frac{N_{\pi\pi}}{N_{ee}} \cdot \frac{\sigma_{ee}^{B} \cdot (1+\delta_{ee}) \cdot \varepsilon_{ee}}{\sigma_{\pi\pi}^{pointlike} \cdot (1+\delta_{\pi\pi}) \cdot \varepsilon_{\pi\pi}}$$

- Ratio $N(\pi\pi)/N(ee)$ is measured directly $\Rightarrow$ detector inefficiencies are cancelled out
- Virtually no background
- Analysis does not rely on simulation
- Radiative corrections account for ISR and FSR effects
- Formfactor is measured to better precision than L

What is really measured?

Definition of $\sigma(e^+e^-\to\text{hadrons})$ depends on the application

- Hadron spectroscopy: vacuum polarization (VP) is the part of the cross-section ("dressed"), final state radiation (FSR) is not
- "Bare" cross-section used in R: vice versa – FSR is the part of the cross-section, VP is not
- Measured number of events include VP and part of FSR allowed by the event selection

CMD-2 published 2 cross-sections $e^+e^-\to 2\pi$:

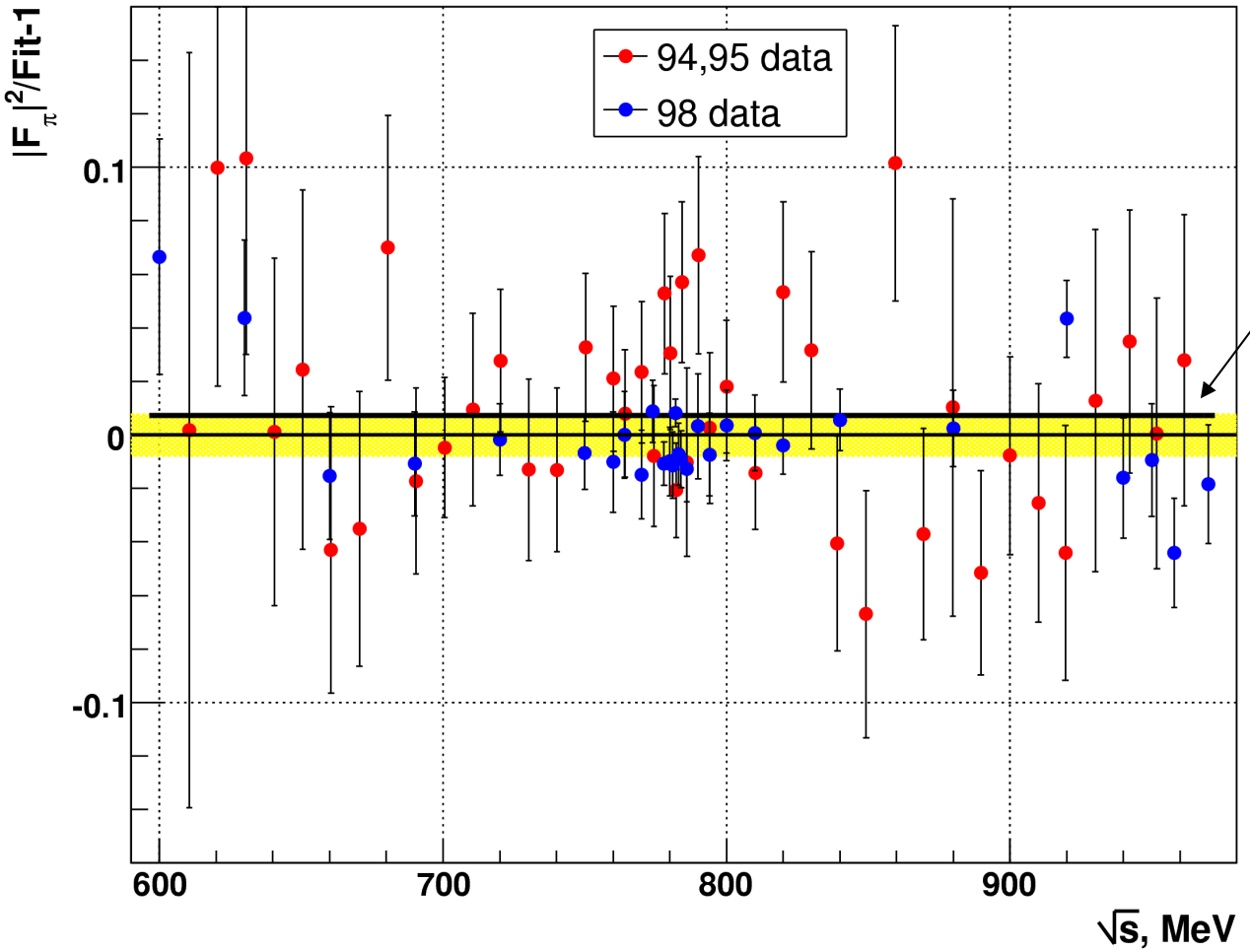
$\sigma_{\pi\pi}$ { radiative correction take into account part of FSR, allowed by the event selection (thus remove FSR completely from the measured cross-section); VP is left untouched.
Used to get rho-meson mass, width, …

$\sigma^0_{\pi\pi(\gamma)}$ { VP is removed, all FSR is added.
Used for R calculation

FSR VP

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

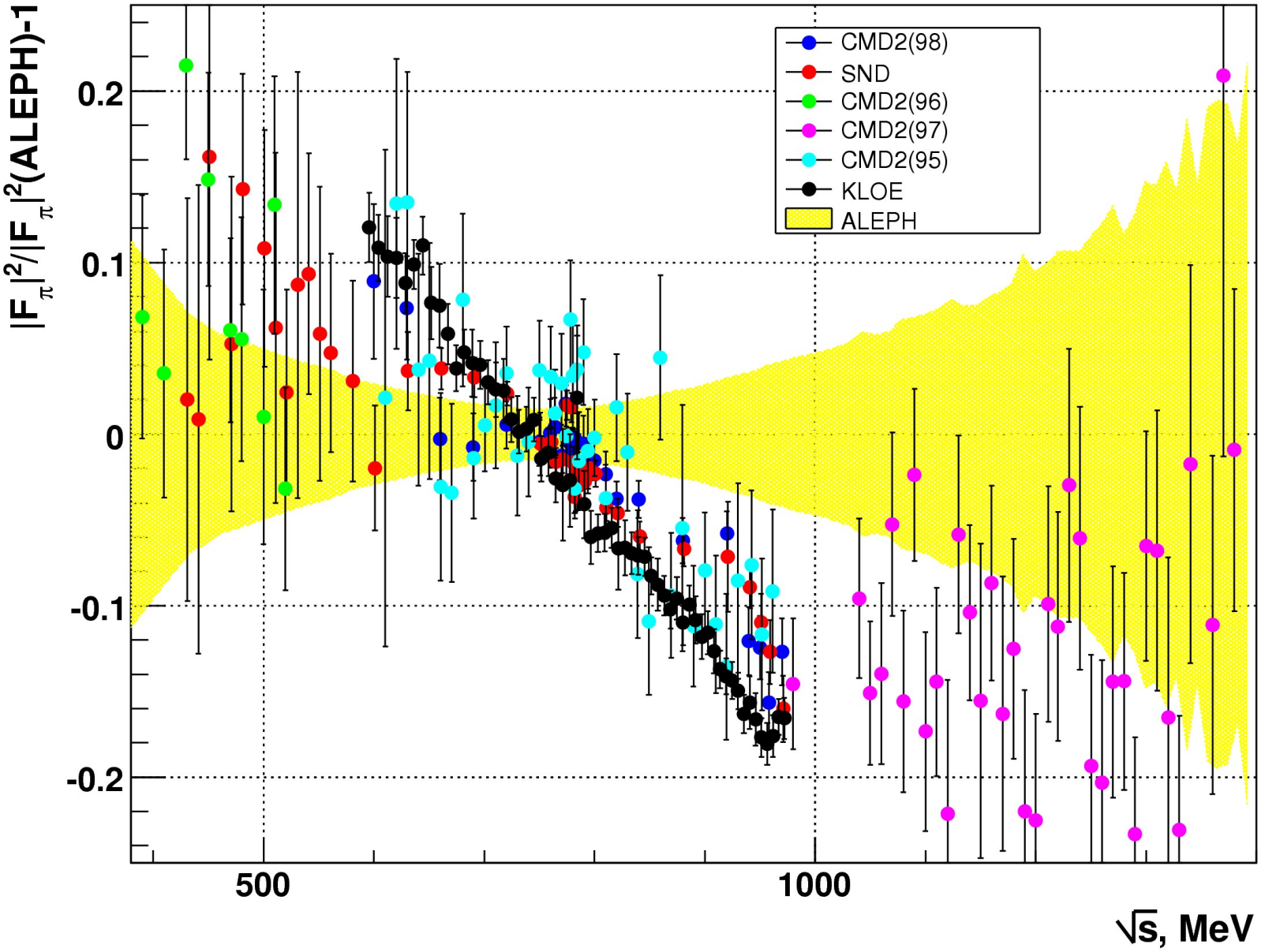
Comparison of CMD2(95) and CMD2(98)



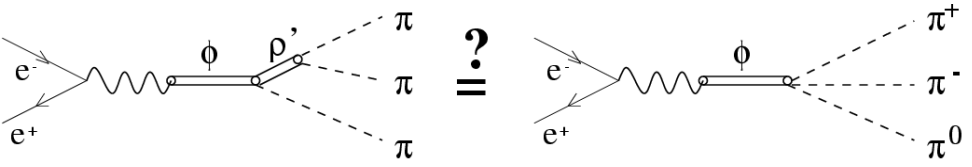
Δ(95-98)≈0.7%±0.5%

Plotted is $\frac{\Delta F}{F} = \frac{|F_\pi|^2(\text{exp})}{|F_\pi|^2(\text{CMD-2 fit})} - 1$

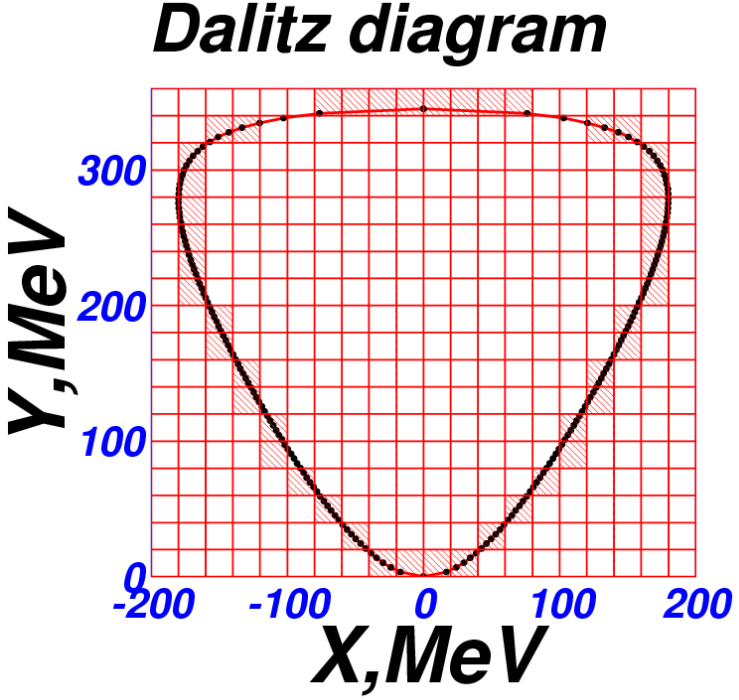
Comparison with ALEPH ($\tau \to \pi\pi^0\nu$)

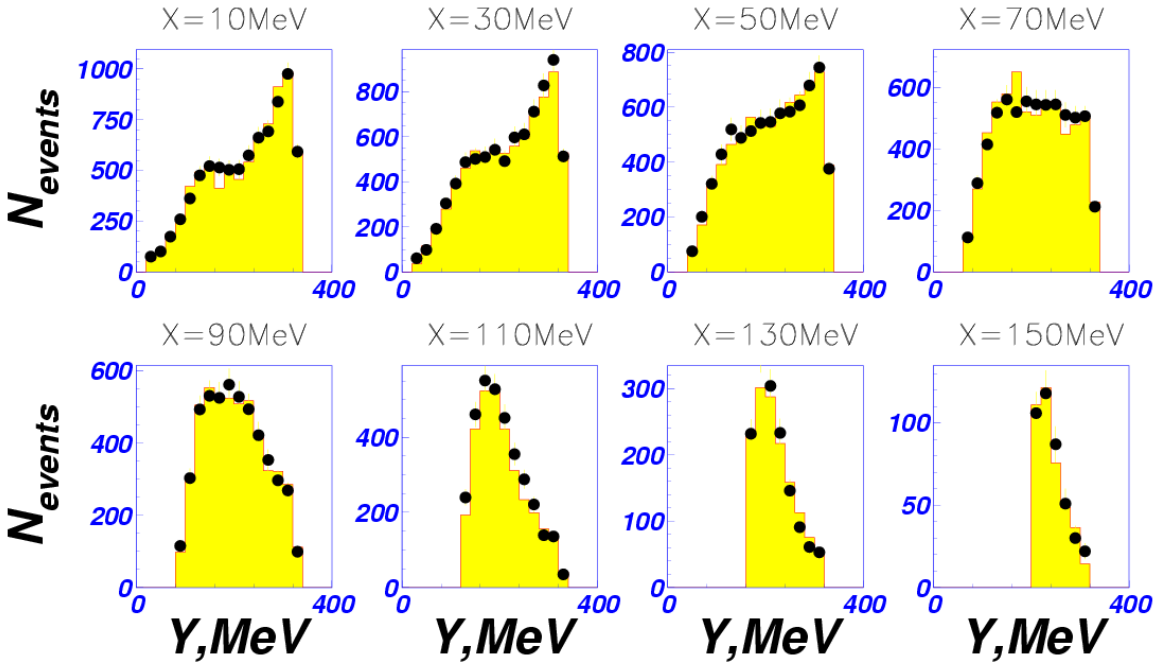


$e^+e^- \to \pi^+\pi^-\pi^0$ at ϕ (CMD2)



$$N_k^{th} : \sum_k dXdY \,|\, \vec{p}_+ \times \vec{p}_- \,|^2 \,|\, A_n a e^{i\varphi} + A_{\rho\pi} \,|^2$$





CMD-2	KLOE
$a = 0.101 \pm 0.044 \pm 0.017$	$a = 0.104 \pm 0.010 \pm 0.020$
$\varphi = -2.91 \pm 0.14 \pm 0.07$	$\varphi = -2.47 \pm 0.08 \pm 0.08$

$$a \equiv \frac{g_{\phi\rho\pi} g_{\rho\pi\pi}}{g_{\phi\rho\pi} g_{\rho\pi\pi}}$$

… but addition of $\rho'(1450)\pi$ provides equally good description with

$a' = 0.215 \pm 0.092 \pm 0.036$

$\varphi' = 0.177 \pm 0.132 \pm 0.051$

$e^+e^- \to K_L K_S$, $K_S \to \pi^+\pi^-$ (CMD-2)

- **2E=1.0-1.04 GeV**

  L=2 pb^{-1}, N=2.7×10^5

  $\sigma_0(\phi \to K_L K_S)$=1413±6±24 nb

  m_ϕ=1413±6±24 MeV/c^2

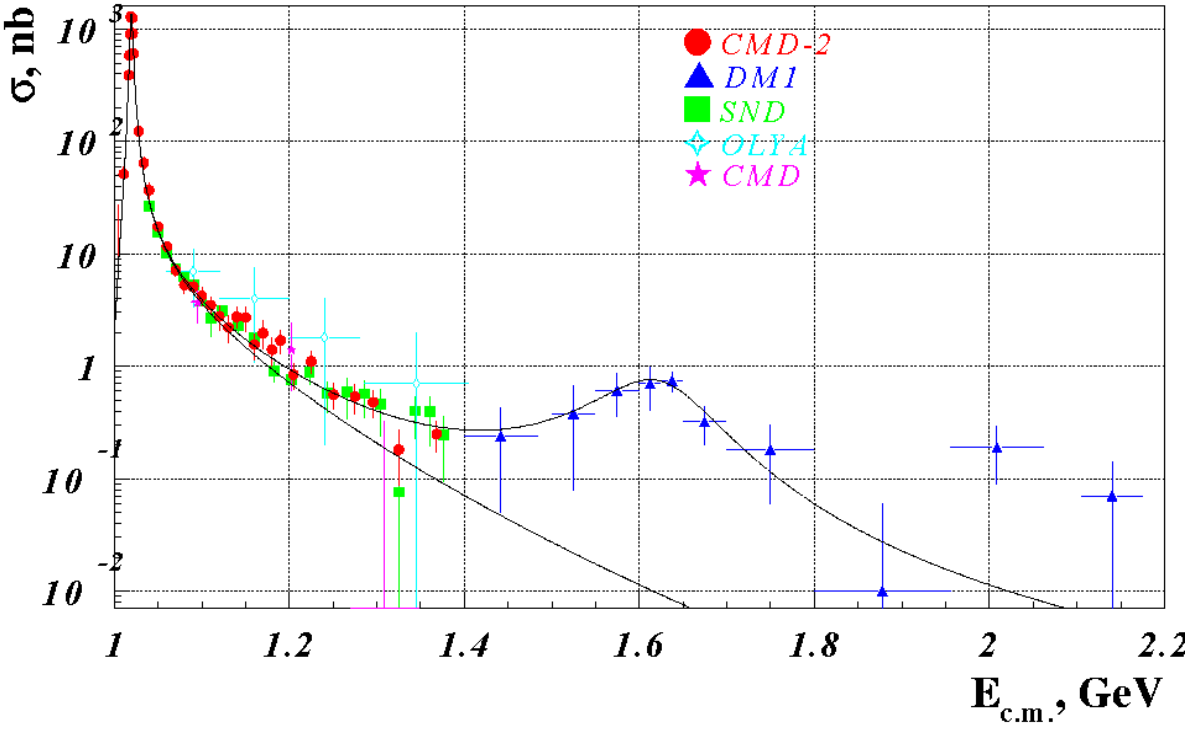
  Γ_ϕ=4.280±0.033±0.025 MeV

  systematic error in $\sigma(e^+e^- \to K_L K_S)$ 1.7%

- **2E=1.05-1.38 GeV,**

  L=5.8 pb^{-1}, N=10^3

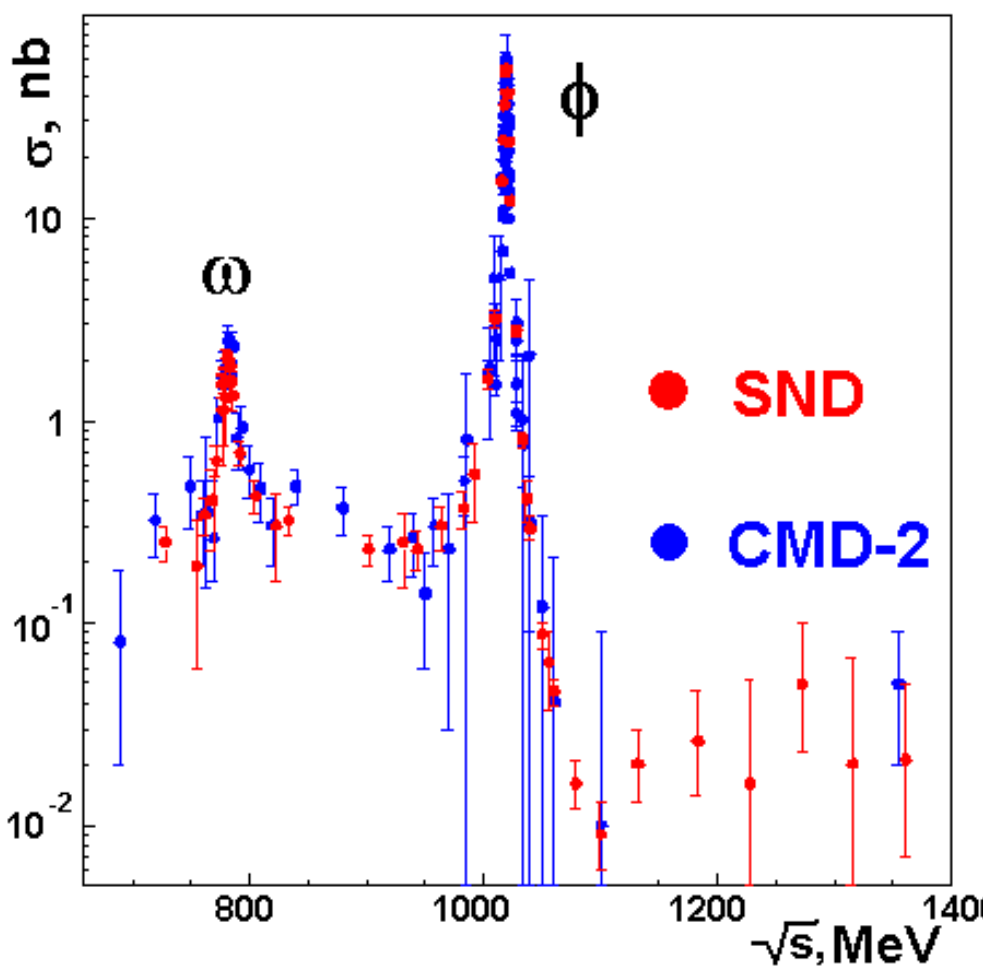
  systematic error in $\sigma(e^+e^- \to K_L K_S)$ 5-10%

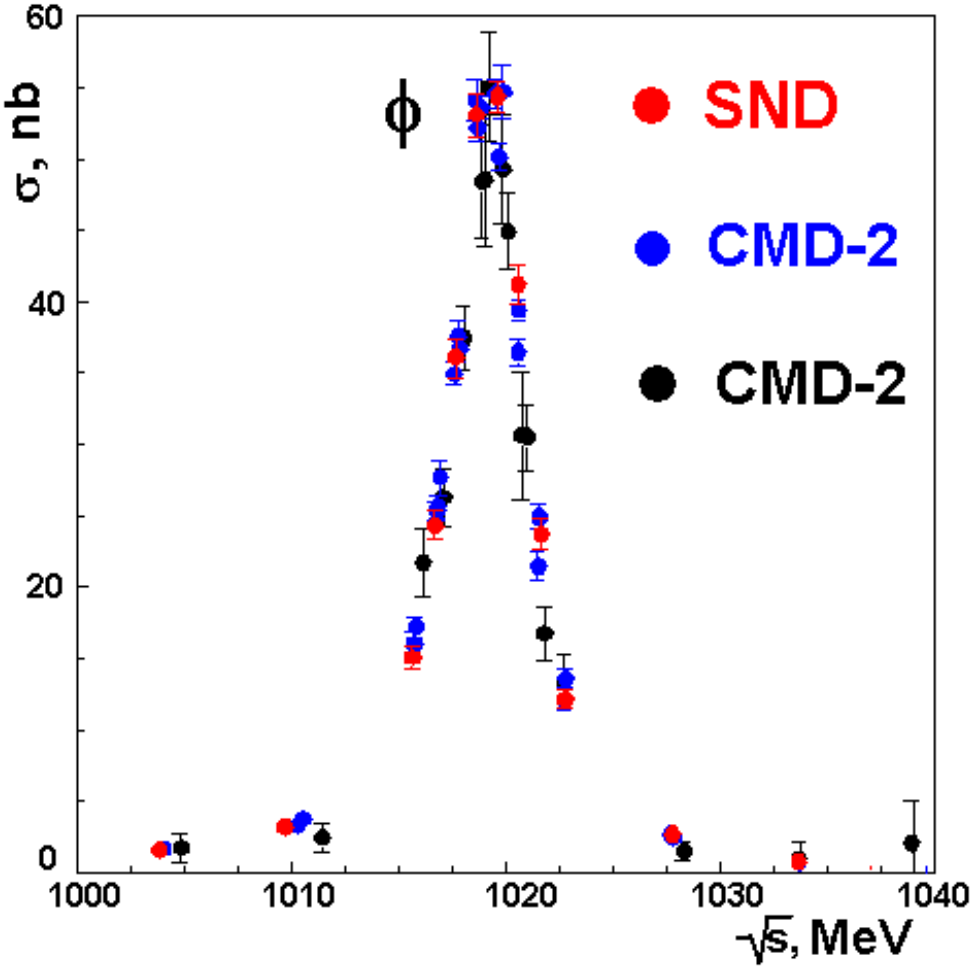


solid curve is VDM with $\rho(770),\omega(783),\phi(1020)$ + X

dash curve is VDM with $\rho(770),\omega(783),\phi(1020)$ only

The $e^+e^- \to \eta\gamma$ cross section

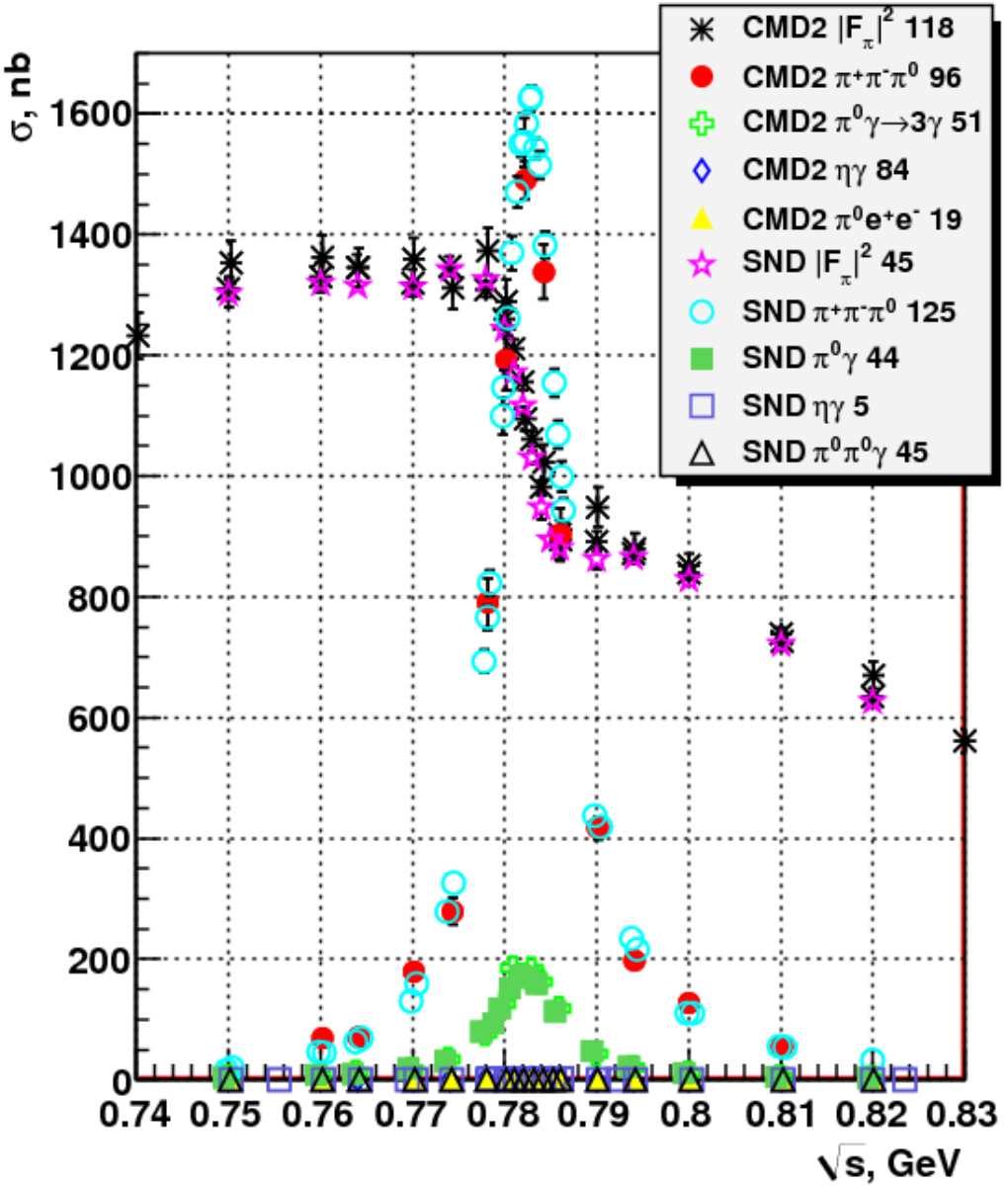


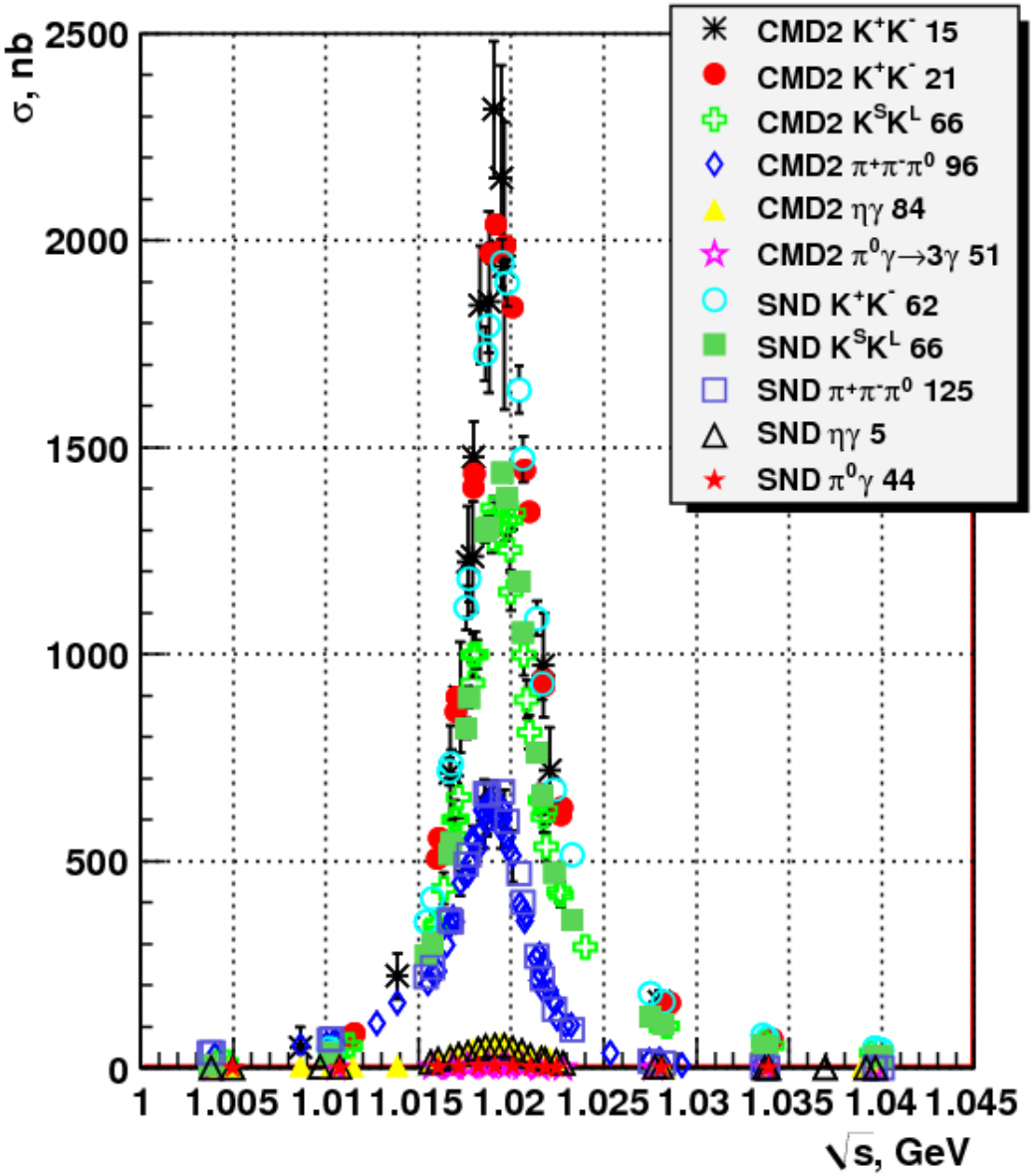


s n

$\pi^0\pi^0\pi^0$, $\pi^+\pi^-\pi^0$, $\gamma\gamma$ decays. For data description the following states are required ϕ, ρ, ω, ρ'. The systematic errors in the vicinity of the ϕ–meson peak are 3-7%

Inclusive Hadronic Cross-Sections





$$M_\omega = 782.68 \pm 0.09 \pm 0.04\ MeV$$
$$\Gamma_\omega = 8.68 \pm 0.04 \pm 0.15\ MeV$$
$$\Gamma_\omega^{e^+e^-} = 0.653 \pm 0.003 \pm 0.021\ keV$$

$$M_\phi = 1019.30 \pm 0.02 \pm 0.10\ MeV$$
$$\Gamma_\phi = 4.280 \pm 0.033 \pm 0.025\ MeV$$
$$Br_\phi^{e^+e^-} = 2.88 \pm 0.09 \cdot 10^{-4}\ keV$$