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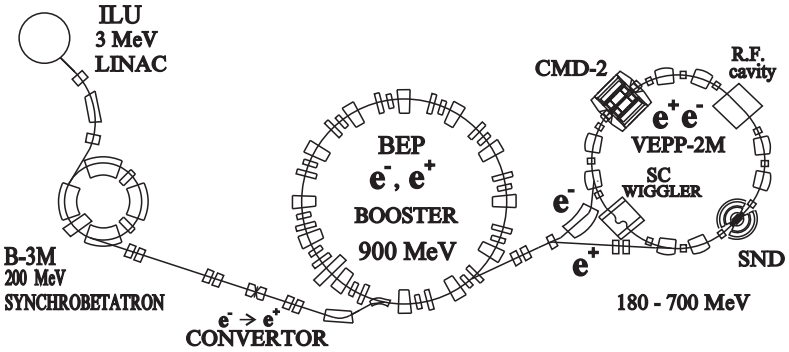
Recent results from VEPP-2M collider

- **Introduction (BINP)**
- **VEPP-2M Collider**
- **Detector(s)**
- **Runs history**
- **ρ, ω, ϕ parameters**
- **ϕ-decays study**
  - ϕ-interferometry
  - ϕ-radiative decays
  - conversion decays
- **Multihadron production study**
- **Conclusion (plans)**

– 1999 –

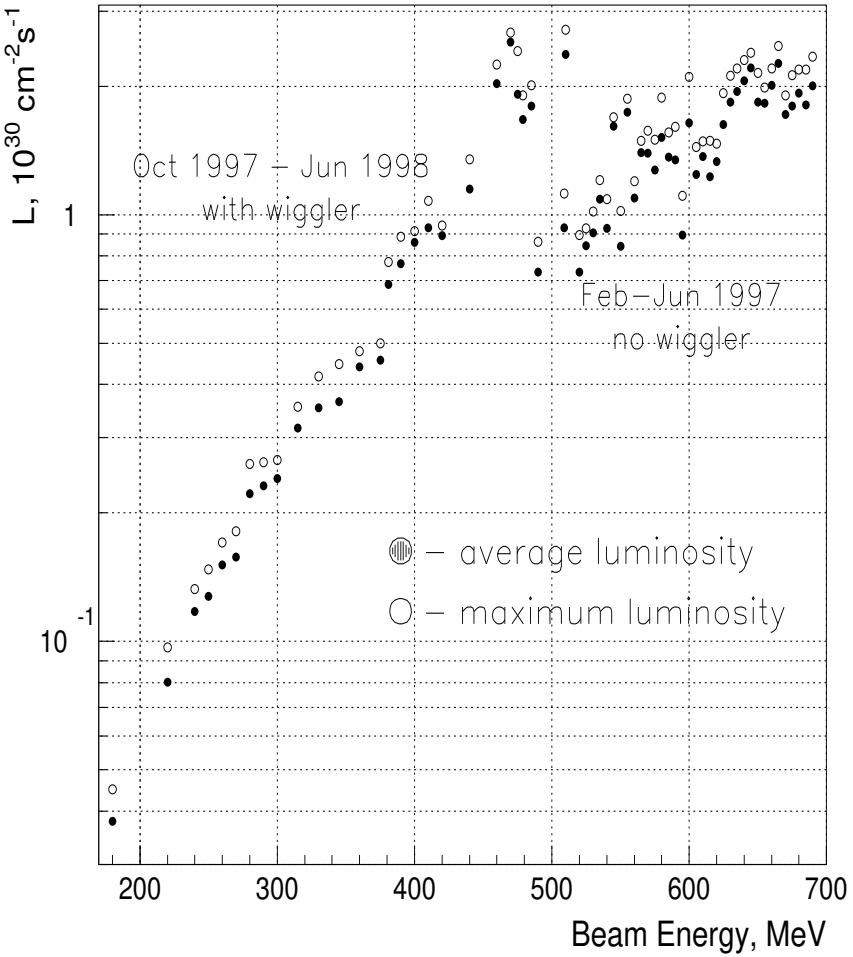
VEPP-2M collider

1974-1999

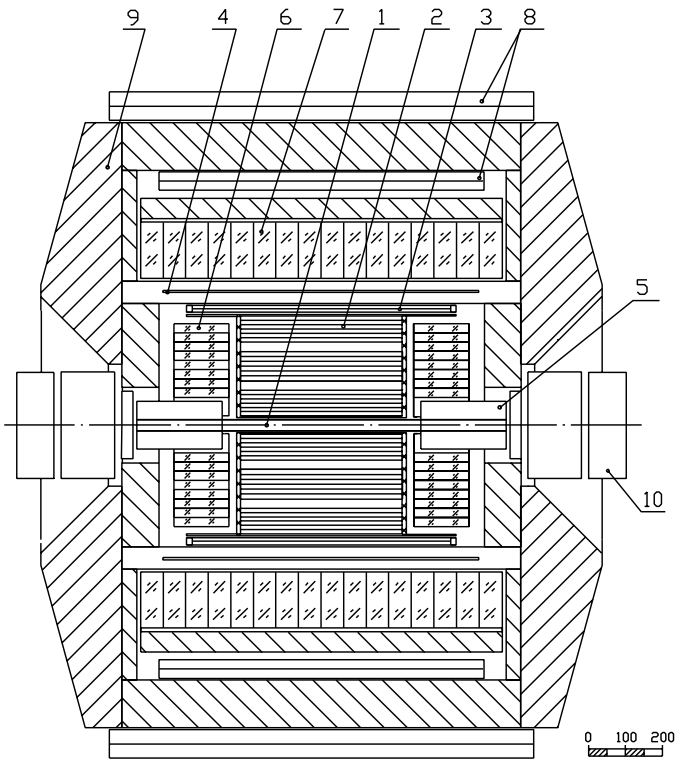


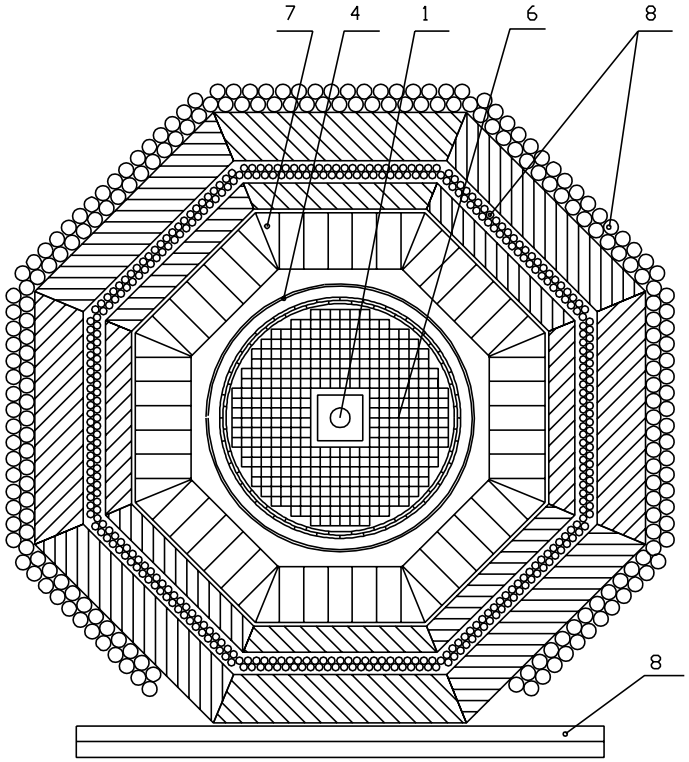
With $L_{peak} \approx 3 \cdot 10^{30} cm^{-2} sec{-}1$

VEPP-2M is a pre- ϕ-factory



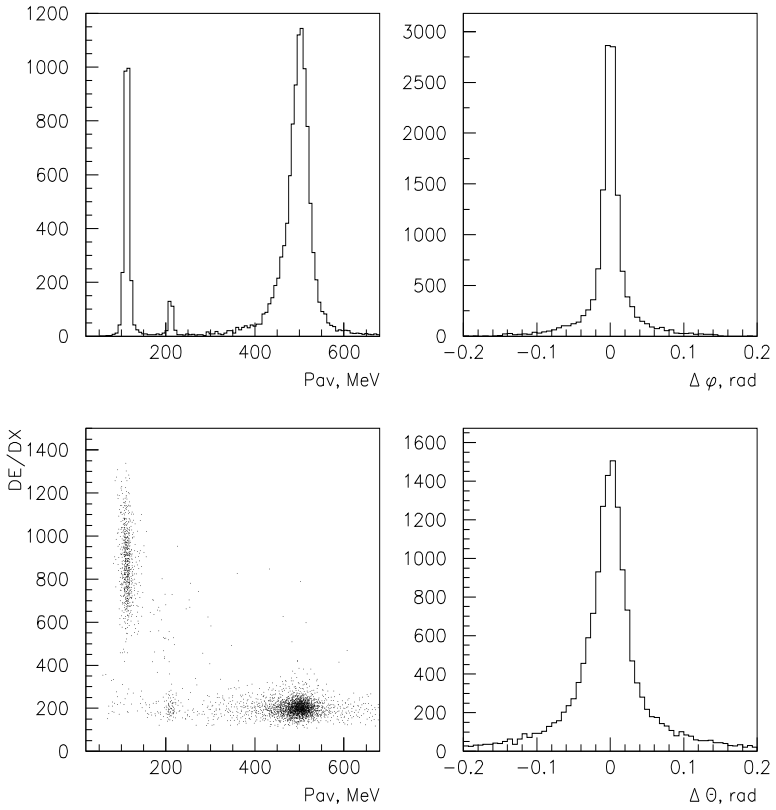
CMD-2 detector



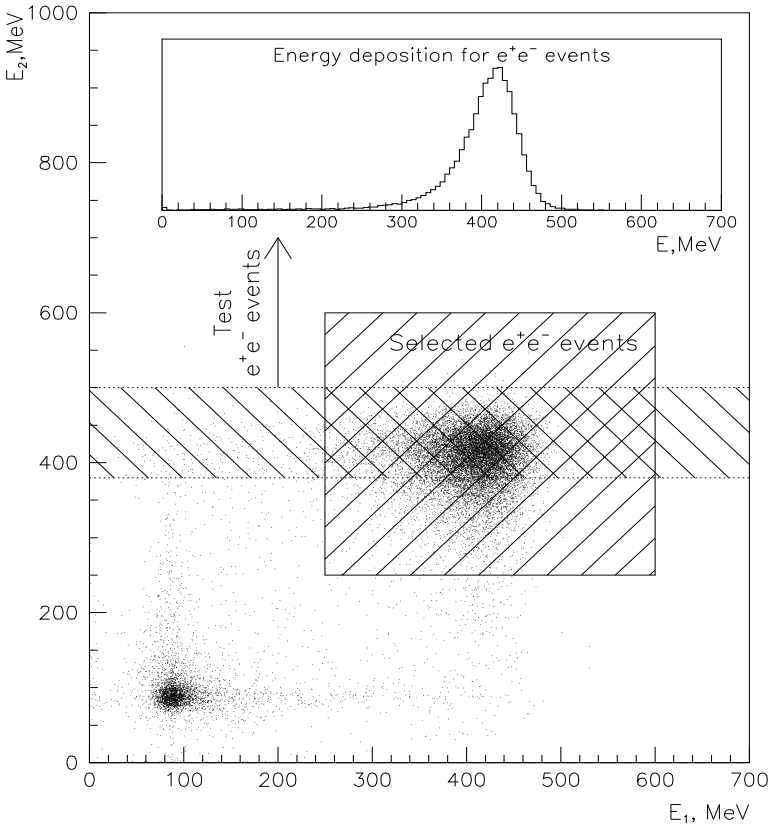


1 - beam pipe; 2 - drift chamber; 3 - Z-chamber; 4 - superconducting solenoid; 5 - compensating magnet; 6 - endcap BGO calorimeter; 7 - barrel CsI(Tl)calorimeter; 8 - muon range system; 9 - yoke; 10 - quadrupole lenses

Detector performance

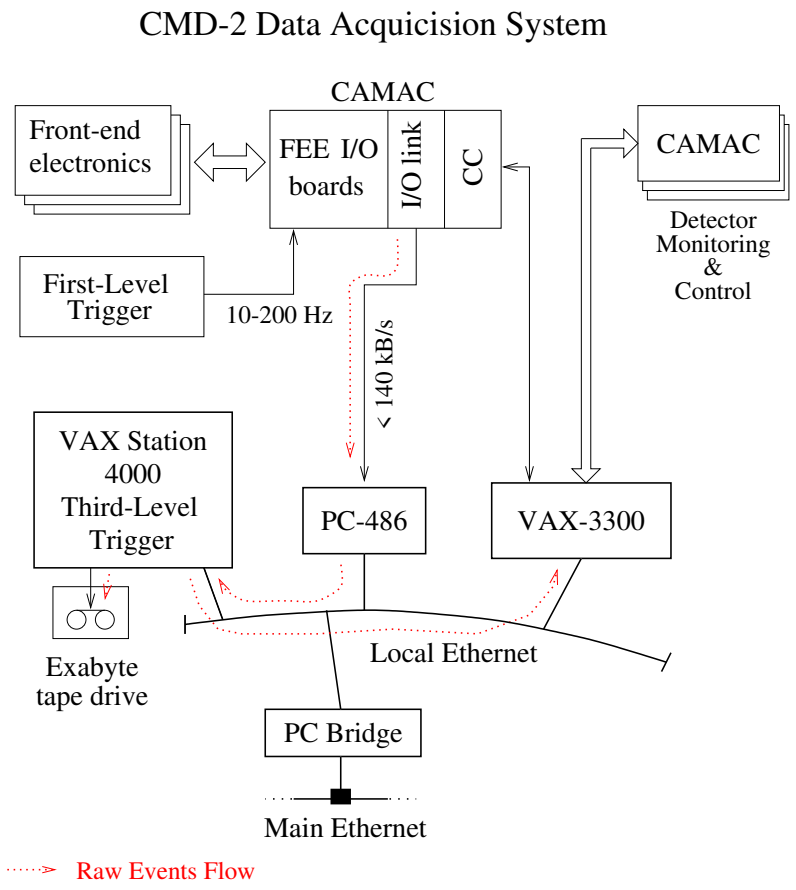


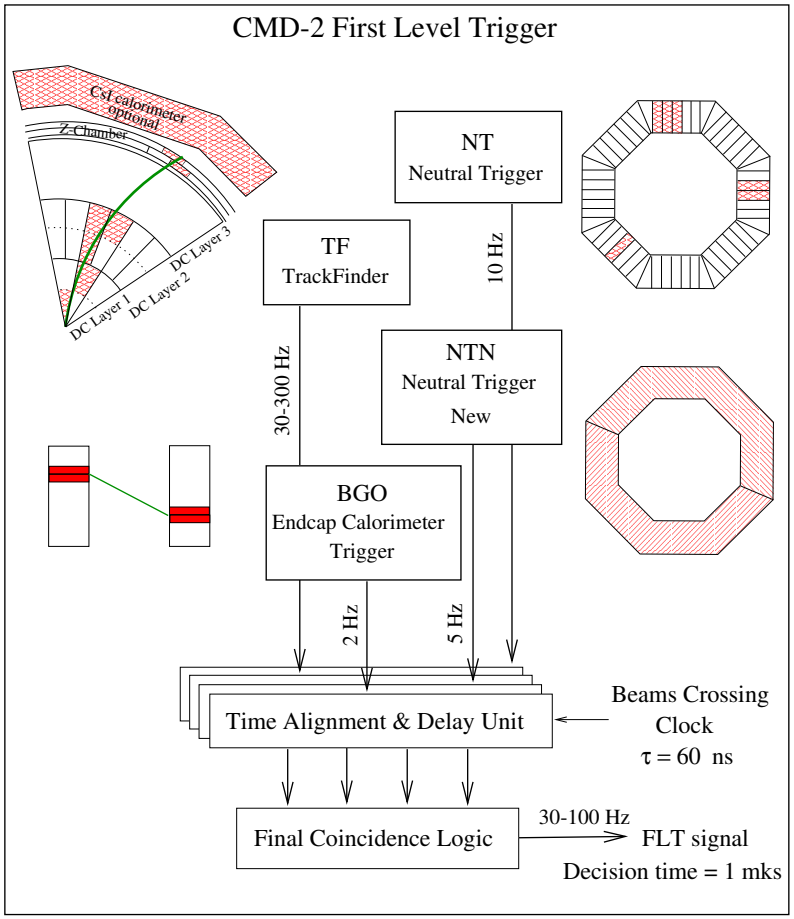
Drift Chamber



CsI Calorimeter

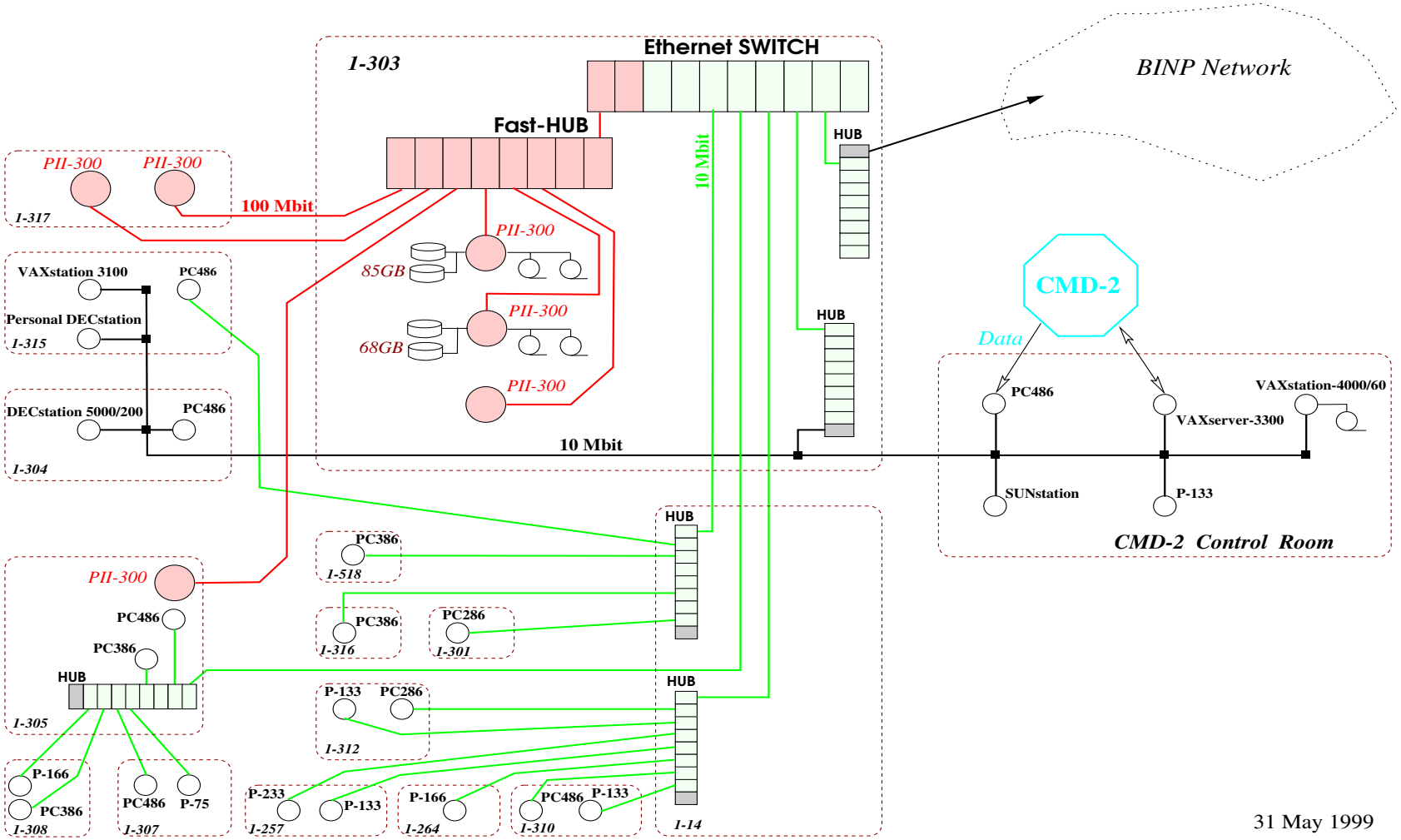
DAQ and Trigger





Recording rate 30-50 Hz

Pentium-II farm "off-line"



31 May 1999

Reconstruction speed - 100 Hz/processor

Data taking history with CMD-2

CMD-2 data taking information. Arrows show the direction of the beam energy variation during scanning

Legend	Date	C.m. energy, GeV	Run numbers	Wiggler	$\int Ldt$ pb^{-1}
PHI-93	16/02/93÷16/07/93	0.994↔1.040	2100 - 2750	Yes	1.43
PHI-94/1	24/01/94÷01/02/94	1.019→0.980	3001 - 3040	No	0.05
RHOM-94	01/02/94÷26/02/94	0.970→0.810	3041 - 3165	No	0.15
PHI-94/2	13/11/94÷26/11/94	1.018↔1.024	4038 - 4106	No	0.16
RHOM-95	30/11/94÷06/06/95	0.810→0.600	4107 - 4541	No	0.16
PHI-96	12/04/96÷14/07/96	0.984↔1.034	4545 - 5150	No	2.18
LOW-96	20/09/96÷26/10/96	0.512→0.370	5749 - 5961	No	0.10
HIGH-97	29/01/97÷16/06/97	1.040↔1.370	6115 - 7030	No	5.93
PHI-98	10/10/97÷23/03/98	0.984↔1.060	7097 - 8427	Yes	11.93
RHOM-98	24/03/98÷30/06/98	0.970→0.360	8428 - 9345	Yes	3.50
HIGH-99	09/01/99÷35/05/99	1.080→1.250	9402 - 9965	No	4.05

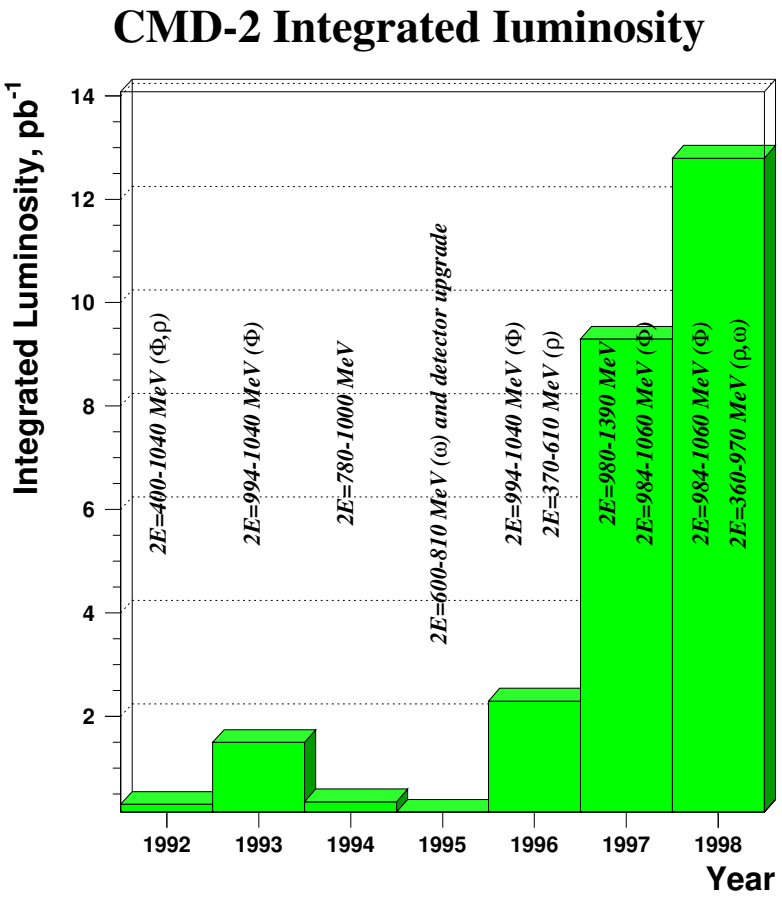
The integrated luminosity of 25 pb^{-1} has been collected so far.

The bulk of data includes: $3 \cdot 10^5$ multihadron events;

$2.1 \cdot 10^6$ $\pi^+\pi^-$ events.

About 2.0 Tbyte on tapes

Data taking with CMD-2

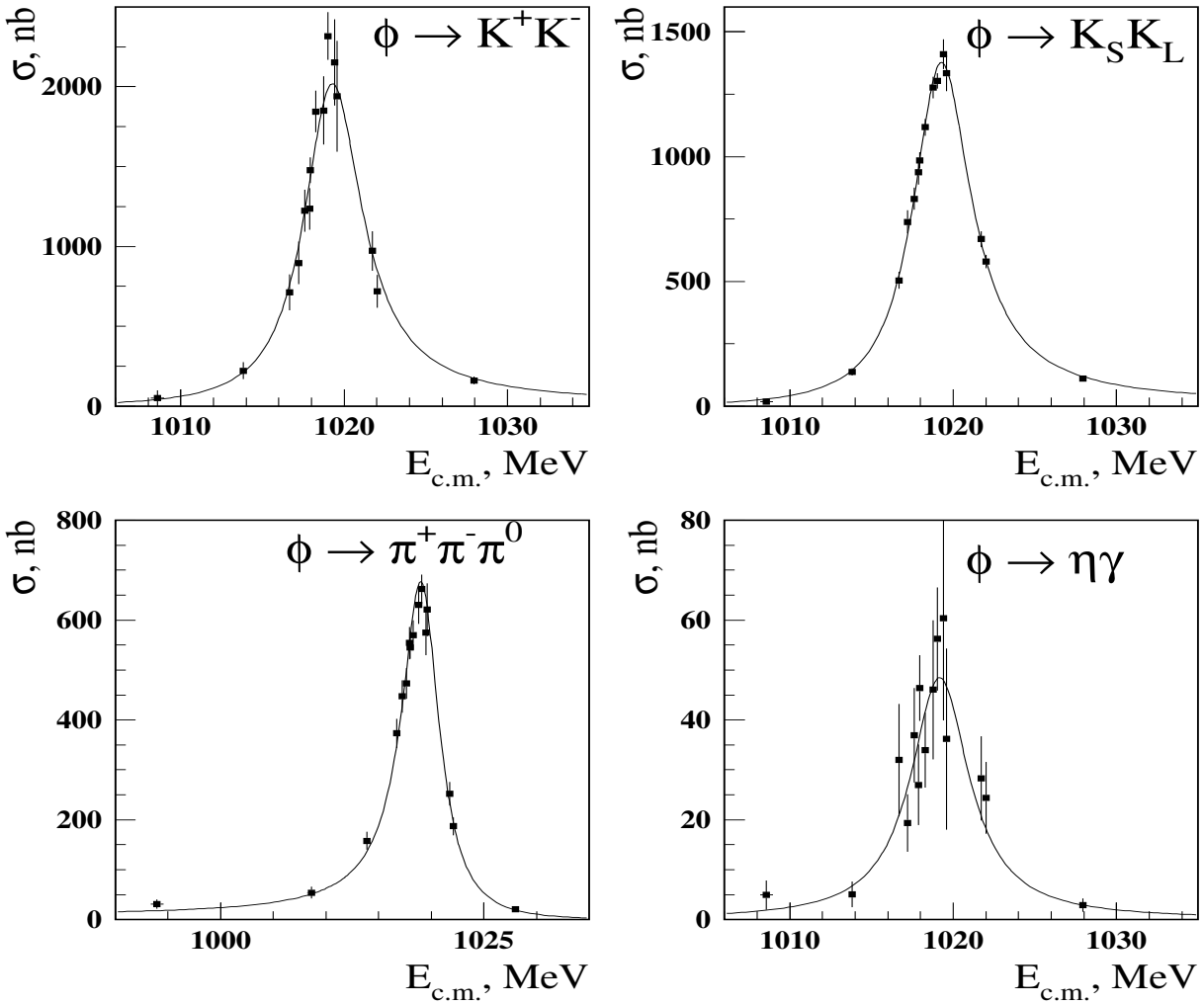


Статистика на ϕ резонансе

Год		$N_{K_S K_L}$	$N_\phi, 10^6$	L,пб$^{-1}$
1993		157362± 411	1.87 ± 0.04	1.31
1994		26464± 166	0.51 ± 0.01	0.18
1996	2-скан.	66582± 274	0.69 ± 0.02	0.46
	3-скан.	115164±403	1.21 ± 0.03	0.76
	4-скан.	88559±339	0.95 ± 0.02	0.55
	1996 г.	270305± 595	2.85 ± 0.07	1.77
1998	2-скан.	411816±691	4.46 ± 0.11	3.20
	3-скан.	476579± 742	5.34 ± 0.13	3.89
	4-скан.	521605± 748	5.88 ± 0.14	3.95
	1998 г.	$1.41 \cdot 10^6$	15.68 ± 0.38	11.04
1993-1998 гг.		$1.86 \cdot 10^6$	21.01 ± 0.39	14.3

$21 \cdot 10^6 \phi$ decays have been collected

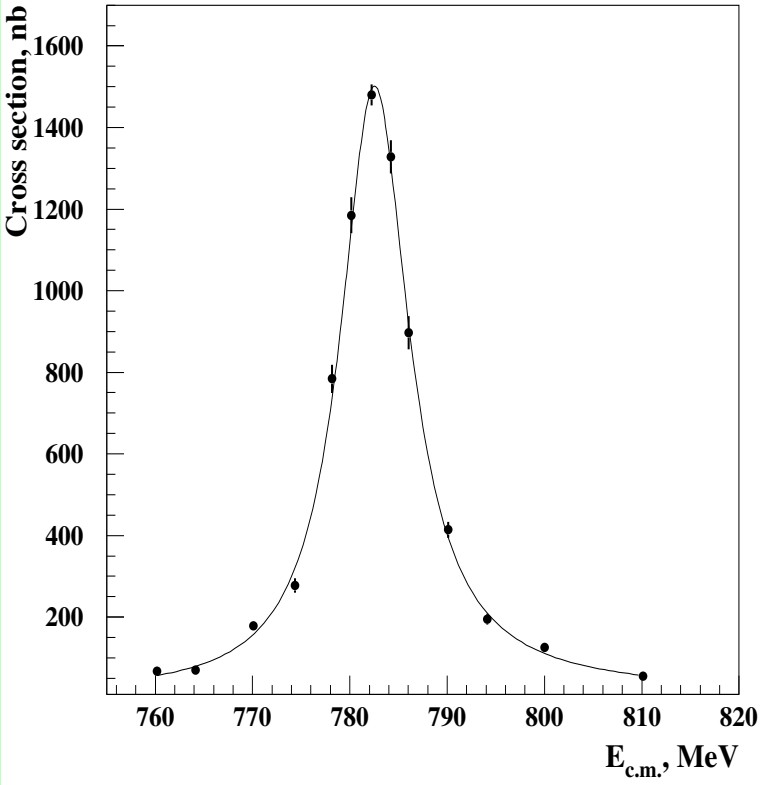
ϕ resonance in four major modes



"Mesurement of ϕ meson parameters with CMD-2 detector at VEPP-2M collider",

R.R. Akhmetshin *et al.*, Phys.Lett **B364** (1995)199-206. 1992 data, 300 nb^{-1}

ω meson parameters in $\pi^+\pi^-\pi^0$ mode



1995 data, 141 nb^{-1}

$N_{\omega\to\pi^+\pi^-\pi^0} = 1.2 \cdot 10^4$

$\sigma_0 = 1482 \pm 23 \pm 25 nb$

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

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

$\Gamma_{e^+e^-} \cdot B(\omega \to \pi^+\pi^-\pi^0) =$

$0.537 \pm 0.012 \pm 0.009 keV$

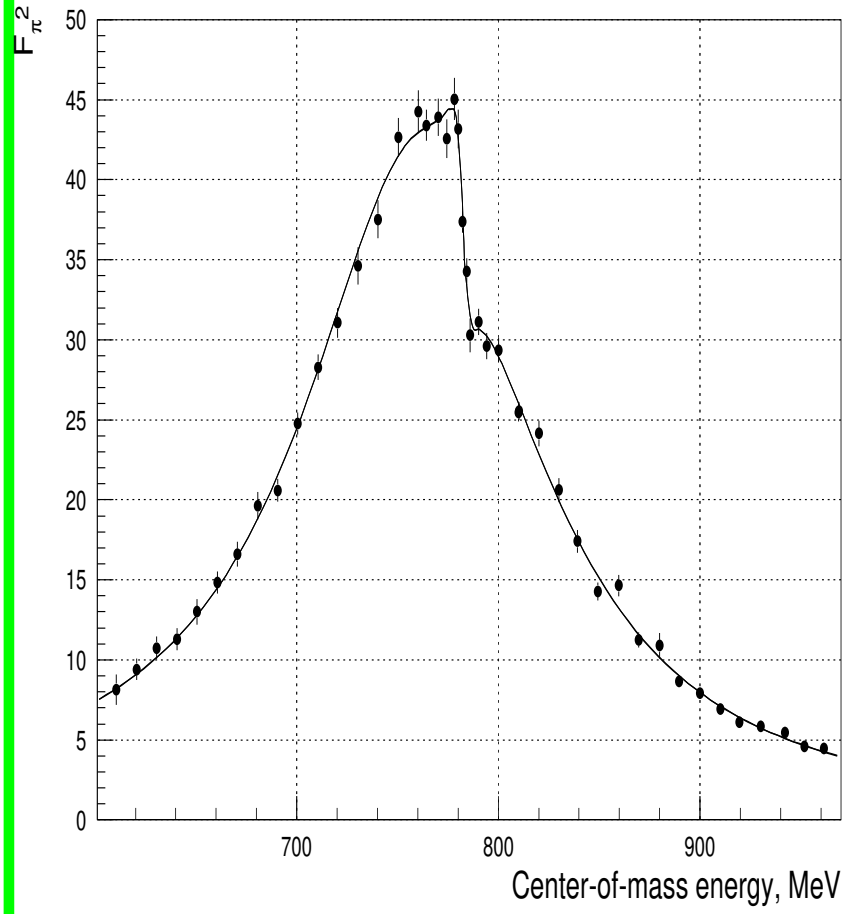
$\Gamma_{\omega\to ee} = 0.605 \pm 0.014 \pm 0.010 keV$ for

$B(\omega \to \pi^+\pi^-\pi^0) = 0.888 \pm 0.007$(PDG)

"Precision measurement of ω meson parameters with CMD-2",

R.R. Akhmetshin *et al.*, Preprint BINP 99-11, to be published in Phys.Lett.

ρ meson parameters in $\pi^+\pi^-$ mode



1995 data, 141 nb^{-1}

$N_{\rho\to\pi^+\pi^-} = 1.5 \cdot 10^5$

$m_\rho = 775.28 \pm 0.61 \pm 0.20 MeV$

$\Gamma_\rho = 147.70 \pm 1.29 \pm 0.40 MeV$

$\Gamma_{\rho\to ee} = 6.93 \pm 0.11 \pm 0.10 keV$ **for**

$B(\omega \to \pi^+\pi^-) = 1.32 \pm 0.23\%$

Systematic error about 1.0%

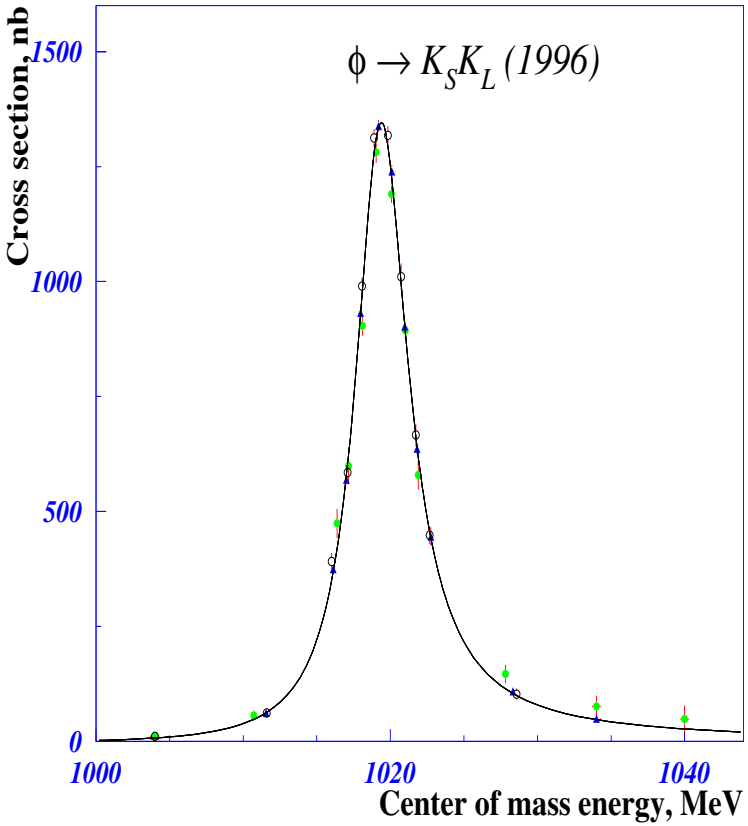
$2.1 \cdot 10^6$ $\pi^+\pi^-$ events in hand!

"Measurement of $e^+e^- \to \pi^+\pi^-$ cross section with CMD-2 around ρ meson ",

R.R. Akhmetshin *et al.*, hep-ex/9904027, to be published in Phys.Lett.

ϕ meson parameters from $K_S K_L$ mode

Resonance depolarization method for precision beam energy measurements



$\sigma E/E_{beam} = 2 - 3 \cdot 10^{-5}$

1993-1996 data, 2.37 pb^{-1}

$N_{K_S K_L} = 3.14 \cdot 10^5$

$\sigma_0 = 1367 \pm 15 \pm 21 nb$

$m_\phi = 1019.504 \pm 0.011 \pm 0.033 MeV$

$\Gamma_\phi = 4.477 \pm 0.036 \pm 0.022 MeV$

$\Gamma_{e^+e^-} \cdot B(\phi \to K_S K_L) =$

$(4.364 \pm 0.048 \pm 0.065) \cdot 10^{-4} MeV$

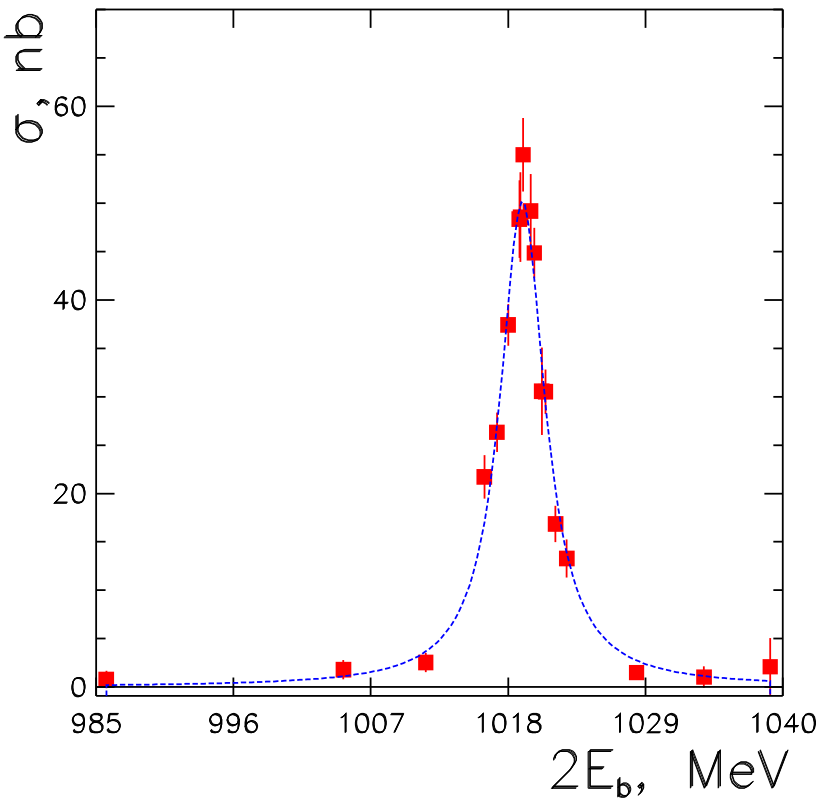
$\Gamma_{\phi \to ee} = 1.27 \pm 0.01 \pm 0.04 keV$ or

$B(\phi \to K_S K_L) = 0.329 \pm 0.002 \pm 0.013$

"Measurement of ϕ meson parameters in $K_S K_L$ decay mode",

R.R. Akhmetshin *et al.*, Phys.Lett **B466** (1999)385-391.

ϕ meson parameters from $\eta\gamma$ mode



1996 data, 1.9 pb^{-1}

$N_{\eta\gamma} = 2200$

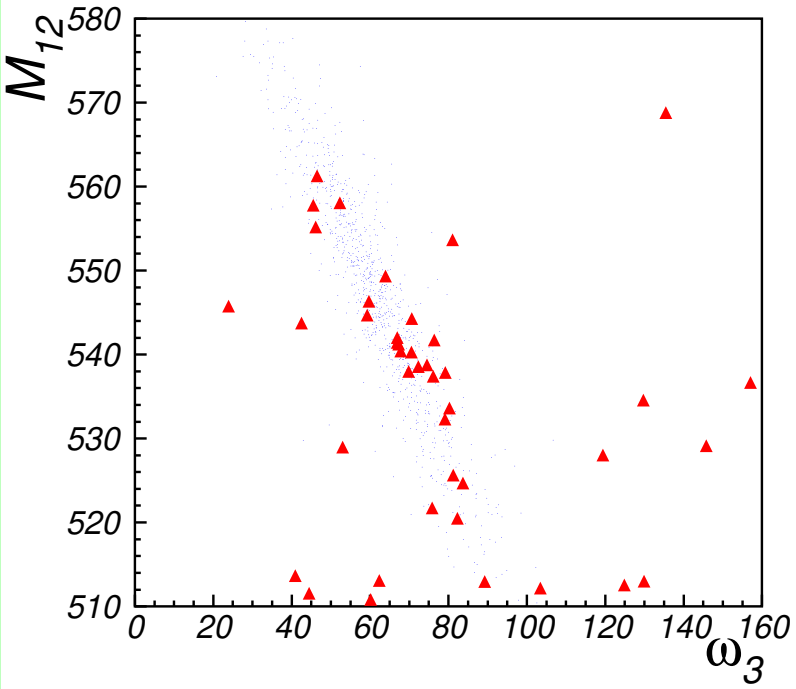
$\sigma_0 = 49.8 \pm 1.2 \pm 2.4 nb$

$m_\phi = 1019.38 \pm 0.07 \pm 0.08 MeV$

$B(\phi \to \eta\gamma) = 1.18 \pm 0.03 \pm 0.06\%$

"Study of the decay $\phi \to \eta\gamma$", R.R. Akhmetshin *et al.*, Phys.Lett **B460**(1999)242.

Search for $\phi \to \eta'\gamma$ decay



1993-1998 data, 14.5 pb^{-1}

In $\eta' \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$ mode:

$N_{\eta'\gamma} = 21.0^{+5.5}_{-4.9}$

$B(\phi \to \eta'\gamma) = (8.2^{+2.1}_{-1.9} \pm 1.1) \cdot 10^{-5}$

In $\eta' \to \eta\pi^+\pi^-$, $\eta \to \pi^+\pi^-\pi^0(\gamma)$ mode:

$N_{\eta'\gamma} = 11.6 \pm 3.6$

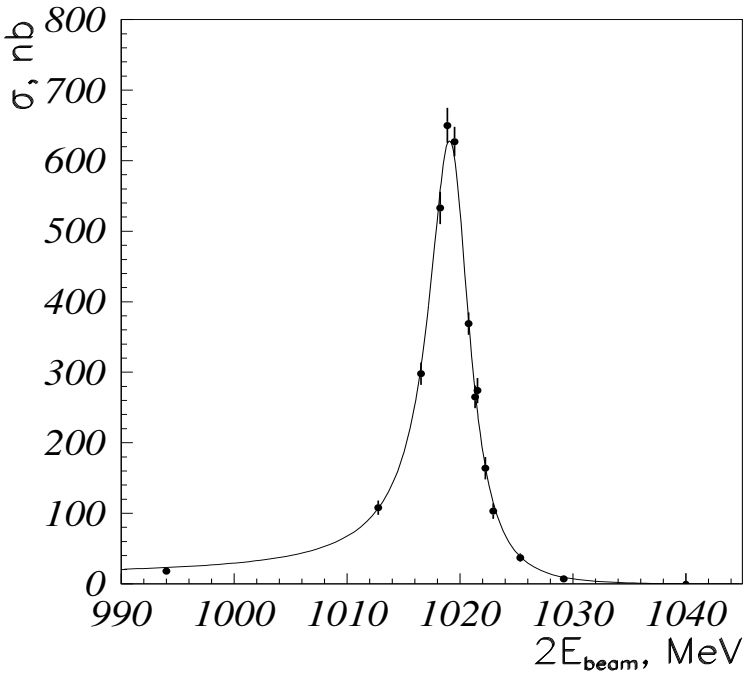
$B(\phi \to \eta'\gamma) = (5.8 \pm 1.8 \pm 1.5) \cdot 10^{-5}$.

No substantial glue component !

$B < 2 \cdot 10^{-5}$ **for glue**

"Study of the decay $\phi \to \eta'\gamma$", R.R. Akhmetshin *et al.*, hep-ex/9911036, Submitted to Phys.Lett.

ϕ meson parameters from $\pi^+\pi^-\pi^0$ mode



1993 data, 1.425 pb^{-1}

$N_{\pi^+\pi^-\pi^0} = 10794$

$\sigma_0 = 619 \pm 39 \pm 12nb$

$\delta_{\phi-\omega} = 162 \pm 17^0$

$m_\phi = 1019.51 \pm 0.07 \pm 0.10MeV$

$B(\phi \to \pi^+\pi^-\pi^0) = 0.145 \pm 0.009 \pm 0.003$

$\phi \to \rho\pi$ **mechanism dominates**

"Study of the dynamics of $\phi \to \pi^+\pi^-\pi^0$ decay with CMD-2 detector",

R.R. Akhmetshin *et al.*, Phys.Lett **B434**(1998)426.

$Br(\phi \to e^+e^-)$ independent measurement

No $\phi \to e^+e^-$ events observed. $Br(\phi \to \mu^+\mu^-) = (2.5 \pm 0.4) \cdot 10^{-4}$

In e^+e^- experiments the measured values are σ^f_{peak}, Γ^{tot}_ϕ, m^2_ϕ and

$$Br(\phi \to f) \cdot \Gamma_{\phi ee} = \frac{\sigma^f_{peak} \Gamma^{tot}_\phi m^2_\phi}{12\pi}$$

By measuring σ^f_{peak} for four major ϕ decay modes $(K^+K^-, K_SK_L, \pi^+\pi^-\pi^0, \eta\gamma)$ and assuming $\Sigma Br(\phi \to f) = 1$ (all the rest gives $\approx 10^{-3}$):

$$\Gamma_{\phi ee} = \frac{\Sigma\sigma^f_{peak} \Gamma^{tot}_\phi m^2_\phi}{12\pi}, \; Br(\phi \to e^+e^-) = \frac{\Sigma\sigma^f_{peak} m^2_\phi}{12\pi}$$

CMD-2 data only: $\Gamma_{\phi ee} = 1.286 \pm 0.024 \pm 0.028 keV$

$$Br(\phi \to e^+e^-) = (2.87 \pm 0.05 \pm 0.06) \cdot 10^{-4}$$

PDG'98: $Br(\phi \to e^+e^-) = (2.99 \pm 0.08) \cdot 10^{-4}$

CMD-2 - step to ϕ - factory experiments

$21 \cdot 10^6$ of ϕ decays allow:

- **to study rare ϕ decays to $10^{-4} - 10^{-5}$**
- **to observe $K_S K_L$ couple decays**
- **to study background for $K_L \to \pi^+\pi^-$:**
  - regenerstion of K_L in detector material
  - admixture of $K_S K_S$ due to $\phi \to f_0(980)\gamma$ (SND - HADRON'97)
- **to study $\phi \to f_0(980)\gamma$:**
  - $f_0(980) \to K_S K_S$ is small (10^{-6}?), $f_0(980) \to \pi^+\pi^-, \pi^0\pi^0$ - are observable
  - what is the structure of $f_0(980)$? (N.N.Achasov, V.N.Ivanchenko, 1989)
    - qqqq - BR($\phi \to f_0(980)\gamma$) $\approx 2 - 3 \cdot 10^{-4}$
    - qq - BR($\phi \to f_0(980)\gamma$) $\approx 5 \cdot 10^{-5}$
    - $K\bar{K}$ molecule - BR($\phi \to f_0(980)\gamma$) $\approx 1 - 2 \cdot 10^{-5}$

Search for $\phi \to \pi^+\pi^-\gamma$

N.N.Achasov *et al.* Phys.Rev.**D55**(1997)2672,
Phys.Rev.**D57**(1998)1987.

$$\frac{d\sigma(s,E_\gamma)}{dE_\gamma} \approx |A^{in}_{br}(s,E_\gamma)|^2 + |A^{f}_{br}(s,E_\gamma) + A_\phi(s,E_\gamma) \pm e^{i\Psi}\cdot A_{f_0}(s,E_\gamma)|^2.$$

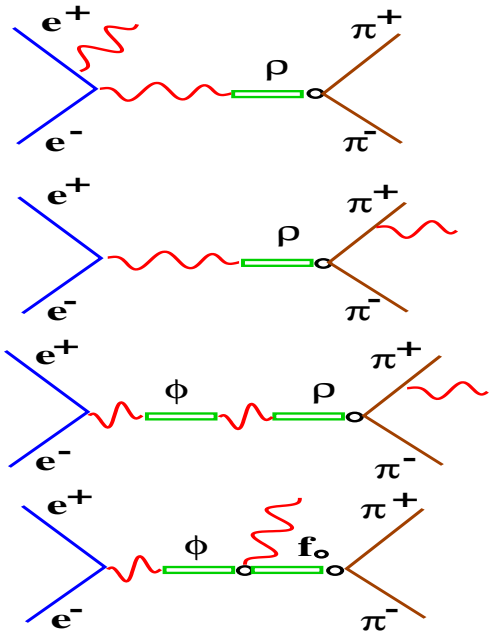
$A^{in}_{br}(s,E_\gamma)$ – initial e^+e^- bremsstrahlung

$A^{f}_{br}(s,E_\gamma)$ – final pions bremsstrahlung

$A_\phi(s,E_\gamma)$ – vacuum polirization by ϕ

$A_{f_0}(s,E_\gamma)$ – $\phi \to f_0(\sigma)\gamma \to \pi^+\pi^-\gamma$ decay

f_0 – qqqq, qq or $K\bar{K}$ molecule



$e^{i\Psi}$ – $\pi\pi$ interaction (σ) in final state

Ψ_{theor} ≈1.2-1.4 rad.

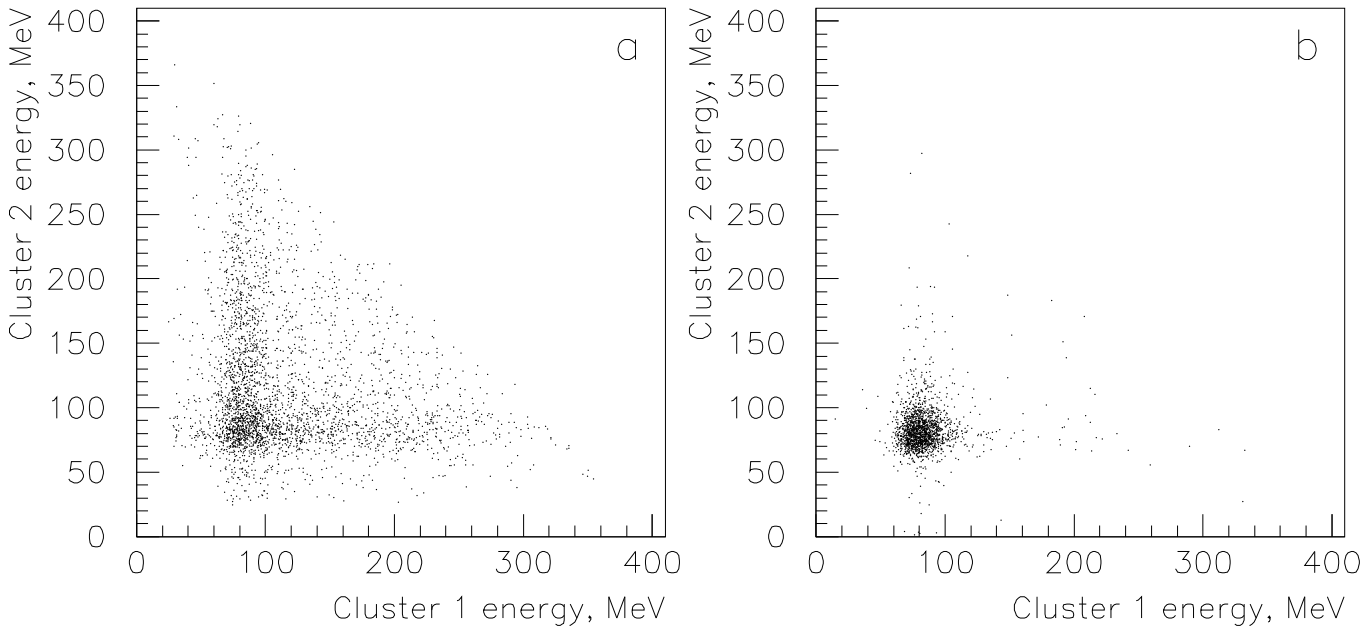
Selection of $e^+e^- \to \pi^+\pi^-\gamma$ events

- 2 charged tracks and 1 or 2 photons found;
- $(P^+ + P^-)/2 > 240$ МэВ/c - removes backgnd from $K_S \to \pi^+\pi^-$;
- $R_{min} < 0.15$ cm;
- $|Z| < 10$ cm - suppress cosmic backgnd;
- $1.05 < \theta_{1,2} < \pi - 1.05$ rad.;
- $(E^1_{CsI} + E^2_{CsI}) < 450$ МэВ - removes Bhabha events;
- $0.85 < \theta_\gamma < \pi - 0.85$ rad. suppress $e^+e^-(\gamma) \to \pi^+\pi^-$;
- $|m_{\gamma\gamma} - m_{\pi^0}| > 40$ MeV - suppress backgnd from $\phi \to \pi^+\pi^-\pi^0$;

  Remained backgnd for $\pi^+\pi^-\gamma$ final state:

  - $e^+e^- \to \mu^+\mu^-\gamma$ - muon system + calorimeter
  - $\phi \to \pi^+\pi^-\pi^0$ (one photon lost) - constrained fit
  - $e^+e^- \to \mu^+\mu^-, \pi^+\pi^-$ with backgnd cluster

Pion - muon separation



Additional cuts:

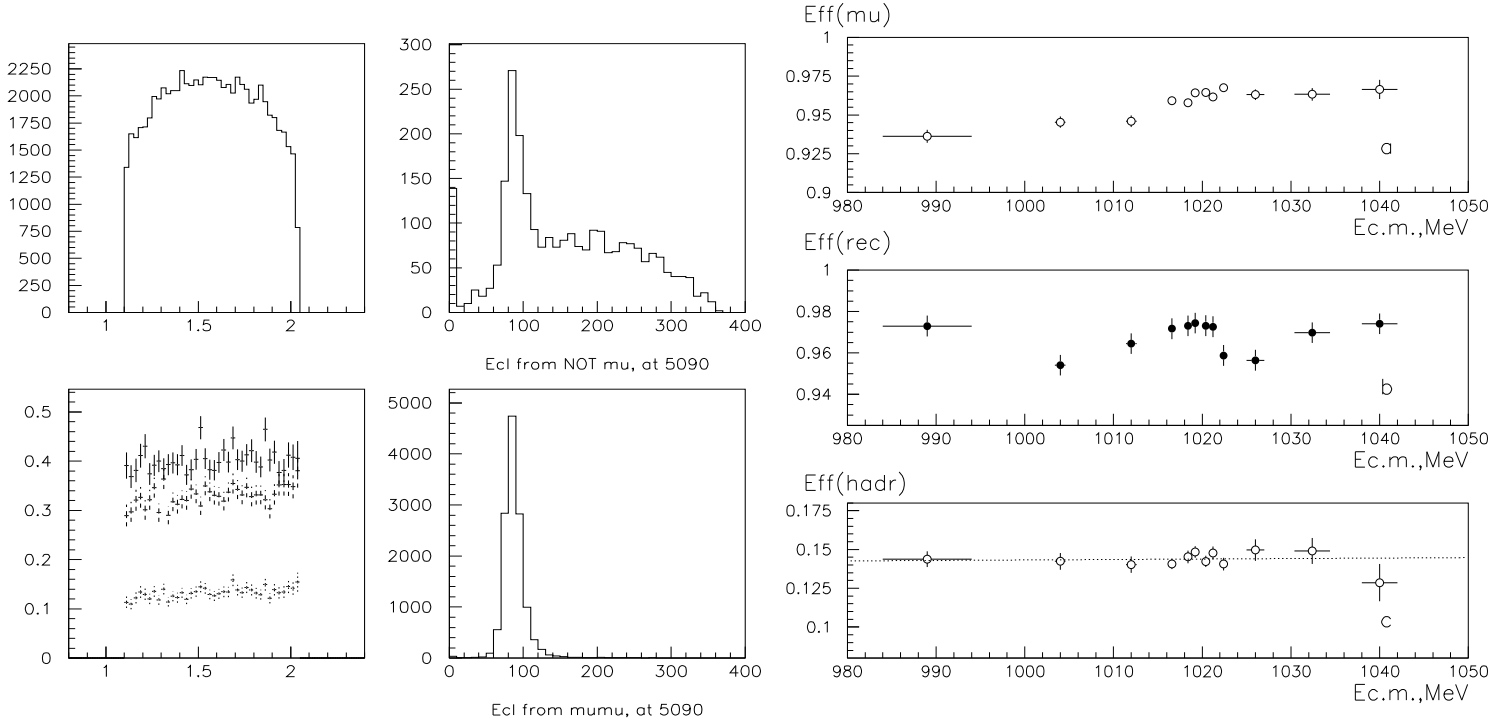
"Muons" - both tracks $50 < E_{CsI} < 150$ MeV + signal in μ-system

"Pions" - all the rest

Pion - muon separation

$N_{\pi\pi\gamma} = (1-\epsilon_\mu)\cdot N^0_{\mu\mu\gamma} + (1-\epsilon_\pi)\cdot N^0_{\pi\pi\gamma}$, ϵ_μ– muon system efficiency,

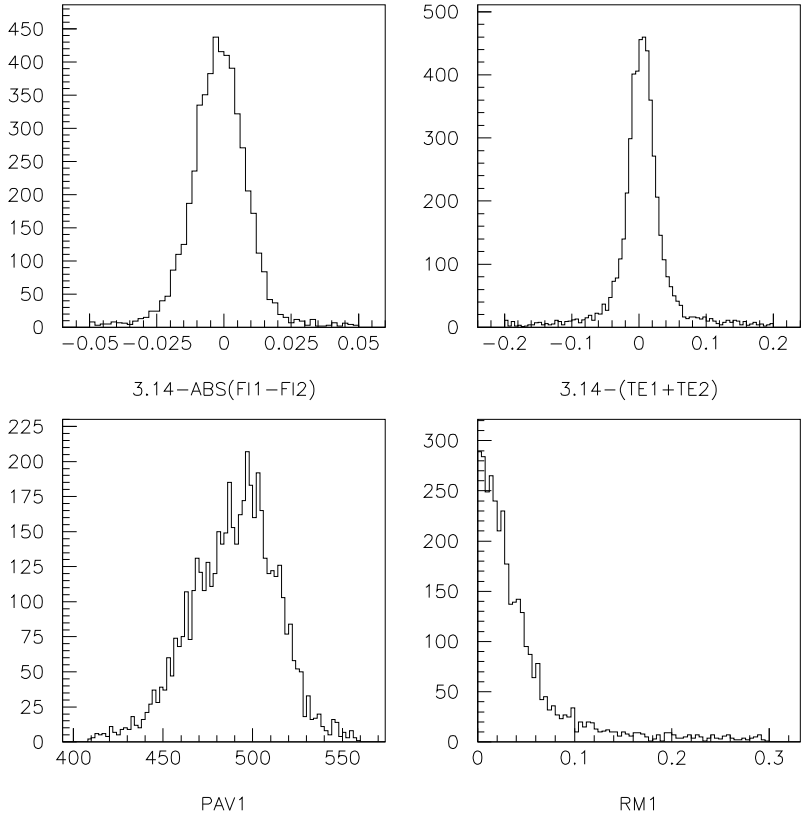
$N_{\mu\mu\gamma} = \epsilon_\mu \cdot N^0_{\mu\mu\gamma} + \epsilon_\pi \cdot N^0_{\pi\pi\gamma}$, ϵ_π– probability for $\pi\pi\gamma$ to be selected as muons.



Processes $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \pi^+\pi^-$

Event selection:

- $P_{av} > (E_{beam} - 100)$ MeV/c
- $|\Delta\varphi| < 0.05, \quad |\Delta\theta| < 0.2$
- $|Z| < 10$ cm
- R_{min} <0.15 cm - signal, 0.15< R_{min} <0.3 - backgnd.
- 1.1< θ < π-1.1
- $E^1_{clus} + E^2_{clus} < 450$ MeV

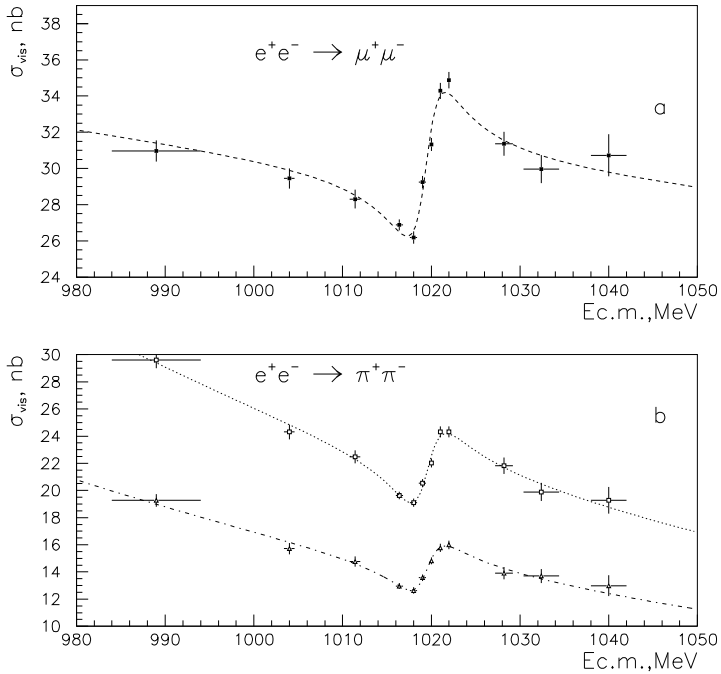


$+ \pi - \mu$ separation

+ Pion selection without muon system information:

$50 > E^{1,2}_{clus} \cdot sin(\theta_{1,2}) > 150$ – $N_{\pi\pi}$(strong).

Visible cross section for $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \pi^+\pi^-$



Approximation according:

$$\sigma(s) = \sigma_0(s) \cdot \frac{1}{|1-\prod -0.013|^2 \cdot (1+\delta)},$$

$$\sigma_0(s) = \sigma_0 \cdot (m_\phi/\sqrt{s})^k, \quad \prod = Z \cdot \frac{\Gamma_\phi \cdot s}{m_\phi \cdot \Delta_\phi}$$

$$\Delta_\phi = s - m_\phi^2 + i\Gamma_\phi(s)\sqrt{s}.$$

$$|Z| = \sqrt{\frac{36 \cdot B_{ee} \cdot B_{\pi\pi}}{\alpha^2 \cdot \beta_\pi^3 |F_\pi|^2}} \quad \text{for } \pi^+\pi^-,$$

$$|F_\pi(s = m_\phi^2)|^2 = 2.58$$

$$|Z| = \sqrt{\frac{9 \cdot B_{ee} \cdot B_{\mu\mu}}{\alpha^2 \cdot \beta_\mu \cdot (1+(1-\beta_\mu^2)/2)}} \quad \text{for } \mu^+\mu^-.$$

	muons	pions	pions(strong cut)
$\sigma_0(m_\phi^2)$, нб	30.09 ± 0.23	21.49 ± 0.24	14.08 ± 0.18
$\sigma_0^{th}(m_\phi^2)$, нб	30.83	31.22	-
k	2 (fixed)	9.89 ± 0.65	9.39 ± 0.79
Re(Z)	$0.134 \pm 0.006 \pm 0.007$	$0.137 \pm 0.008 \pm 0.010$	0.132 ± 0.009
Im(Z)	$0.007 \pm 0.006 \pm 0.007$	$-0.017 \pm 0.008 \pm 0.008$	-0.011 ± 0.010

Branching ratios $\phi \to \mu^+\mu^-$, $\phi \to \pi^+\pi^-$

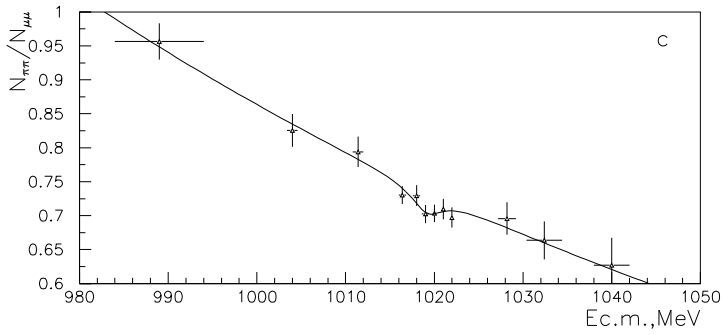
$$\sqrt{Br_{\phi\to\mu^+\mu^-} \cdot Br_{\phi\to e^+e^-}} = Br_{\phi\to l^+l^-} = (3.26 \pm 0.14 \pm 0.17) \times 10^{-4},$$

$$\sqrt{Br_{\phi\to\pi^+\pi^-} \cdot Br_{\phi\to e^+e^-}} = (2.56 \pm 0.15 \pm 0.17) \times 10^{-4},$$

$$Br_{\phi\to\mu^+\mu^-} = (3.54 \pm 0.32 \pm 0.37) \times 10^{-4},$$

$$Br_{\phi\to\pi^+\pi^-} = (2.20 \pm 0.25 \pm 0.30) \times 10^{-4}.$$

Ratio of number of pions to number of muons vs. energy.



$Re(Z) = 0.002 \pm 0.010 \pm 0.003$,
$Im(Z) = -0.0224 \pm 0.0107 \pm 0.0030$

$\sqrt{Br(\phi \to \pi^+\pi^-)_{direct} \cdot Br_{\phi\to e^+e^-}} = (4.19 \pm 2.03) \times 10^{-5}$,

$Br(\phi \to \pi^+\pi^-)_{direct} = (0.59 \pm 0.55) \times 10^{-5}$.

Can be presented as upper limit:

Br $(\phi \to \pi^+\pi^-)_{direct} < 0.13 \times 10^{-4}$ **at 90% CL.**

Constrained fit for $e^+e^- \to \mu^+\mu^-\gamma, \pi^+\pi^-\gamma$

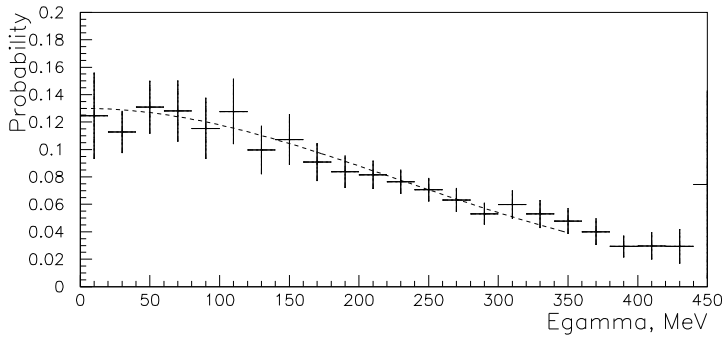
Conservation laws:

$$\bar{P}_1 + \bar{P}_2 + \bar{P}_\gamma = 0.$$
$$E_1 + E_2 + E_\gamma = 2 \cdot E_{beam}$$

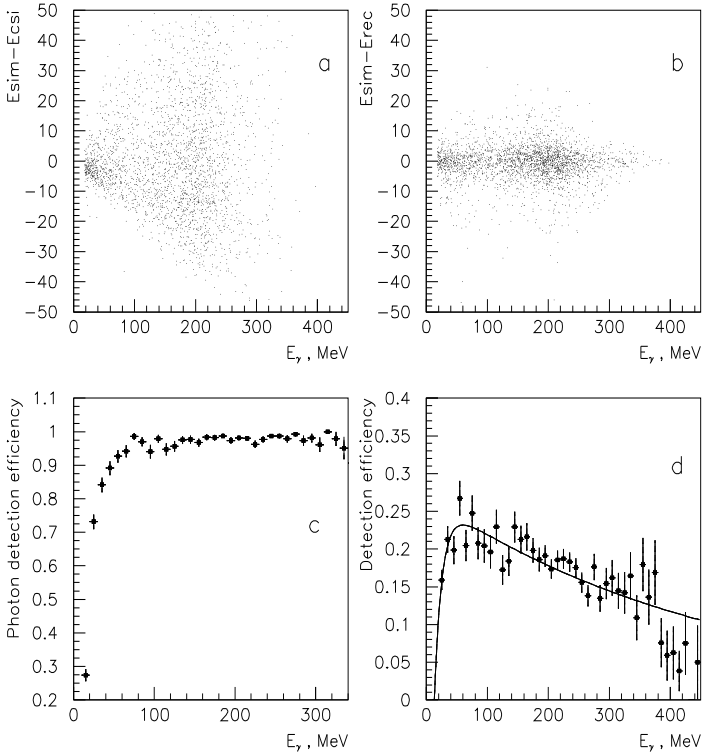
calorimeter resolution:

$\sigma(E_\gamma) = 8\% \cdot E_\gamma$ МэВ - **before**

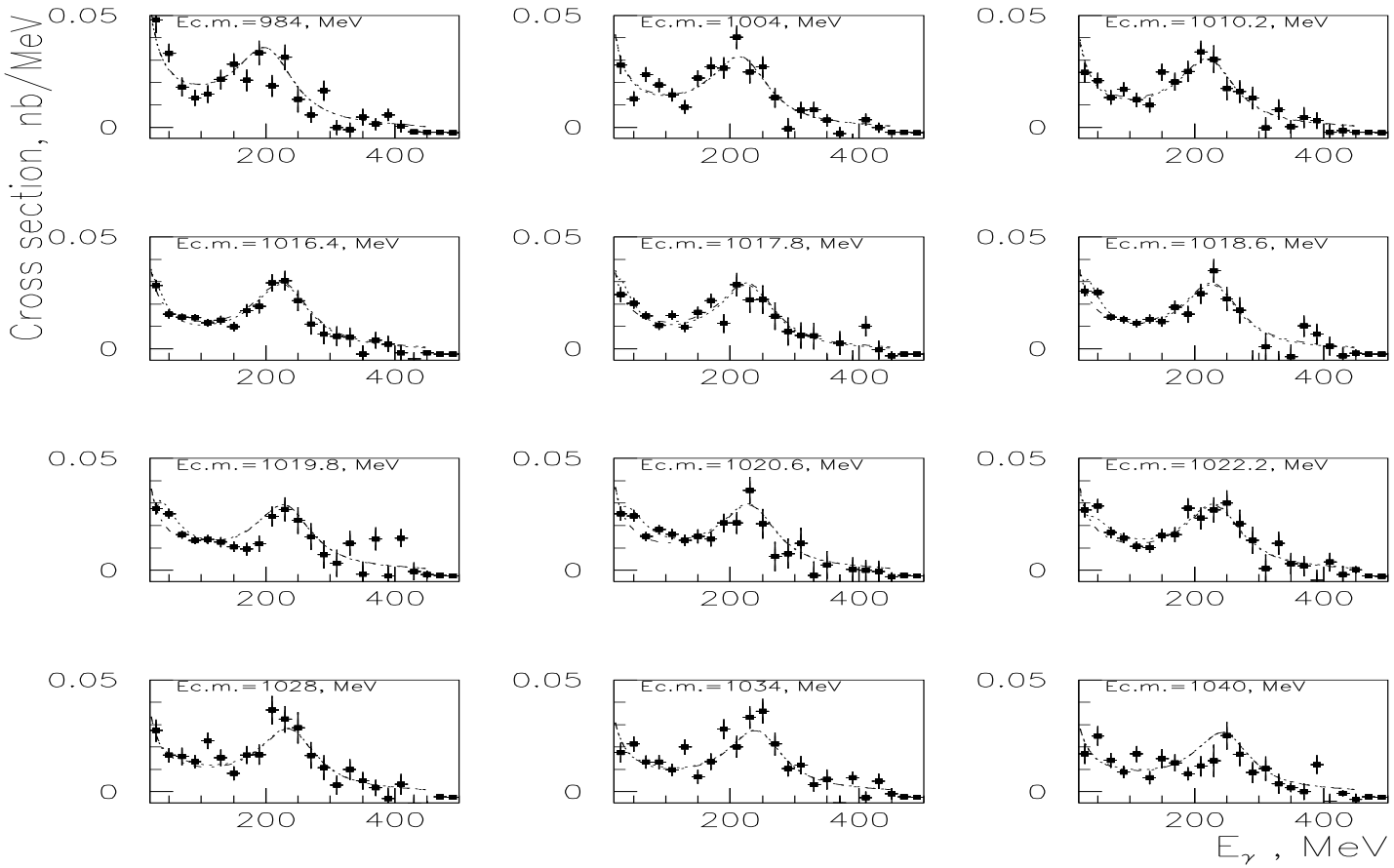
$\sigma(E_\gamma) = 5$ МэВ - **after fit**



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



Photon spectra for $e^+e^- \to \pi^+\pi^-\gamma$

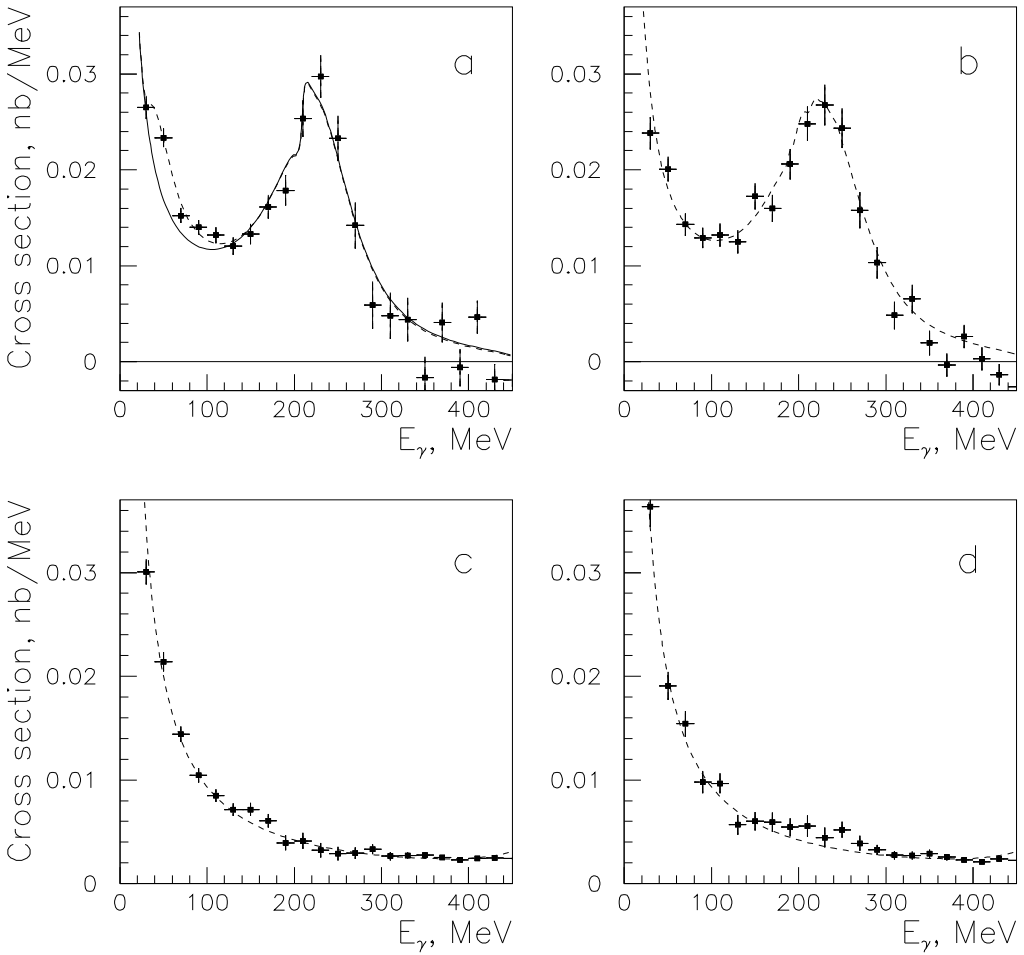


ϕ

Photon spectra for 12 energy points for $\pi^+\pi^-\gamma$ events.

Photon spectra for $e^+e^- \to \pi^+\pi^-\gamma$, $\mu^+\mu^-\gamma$

At ϕ **Out of ϕ**



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

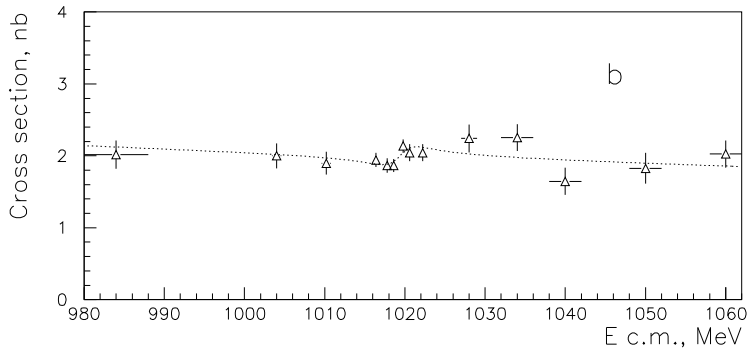
$N_{\pi\pi\gamma} = 13335$

$e^+e^- \to \mu^+\mu^-\gamma$

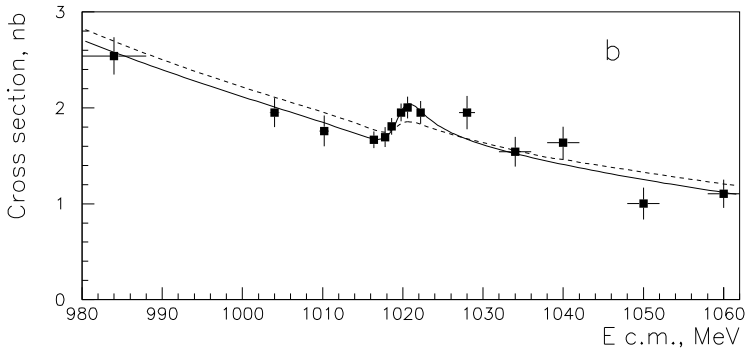
$N_{\mu\mu\gamma} = 9852$

Cross section vs. energy for $\pi^+\pi^-\gamma$, $\mu^+\mu^-\gamma$

Photons in $20 < E_\gamma < 120$ MeV range



Cross section for $e^+e^- \to \mu^+\mu^-\gamma$



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

$$\sigma(s) = \sigma^{in}_{br}(s) + \sigma^{f}_{br}(s) \cdot |1 - e^{i\psi} \cdot A_\phi \frac{m_\phi \Gamma_\phi}{\Delta_\phi}|^2, \quad \Delta_\phi = s - m^2_\phi + i\sqrt{s}\Gamma_\phi(s).$$

$\sigma^{exp}(m^2_\phi)/\sigma^{th}_{\mu\mu\gamma} = 0.97 \pm 0.03 \pm 0.05$ и $\sigma^{exp}(m^2_\phi)/\sigma^{th}_{\pi\pi\gamma} = 1.04 \pm 0.02 \pm 0.05$

$\psi = (0.2 \pm 0.4)$ rad. for muons and $\psi = (0.56 \pm 0.17)$ rad. for pions.

$$\sigma(\phi \to \pi\pi\gamma) = |A_\phi|^2 \cdot \sigma^{f}_{br}(m^2_\phi), \qquad Br(\phi \to \pi\pi\gamma) = \sigma(\phi \to \pi\pi\gamma)/\sigma^{\phi}_{tot}$$

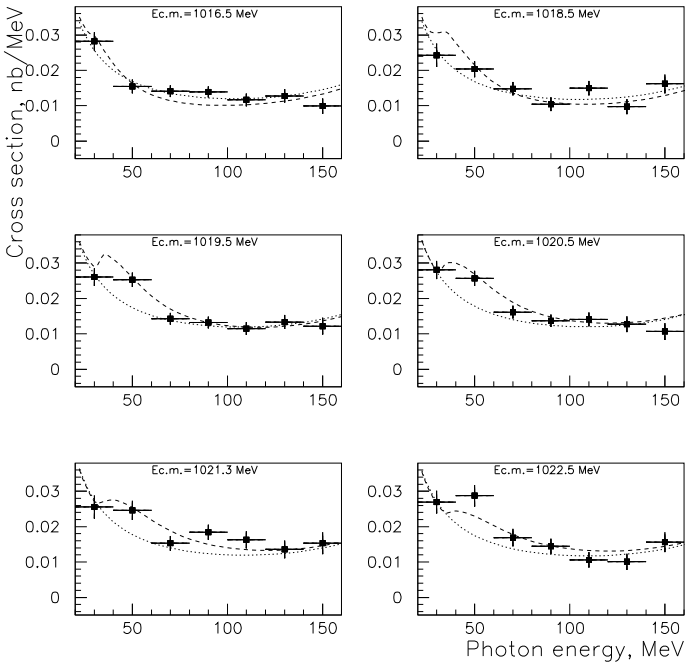
$Br(\phi \to \mu^+\mu^-\gamma) = (1.43 \pm 0.45 \pm 0.14) \times 10^{-5}$ $Br^{th}_{\phi\to\mu\mu\gamma} = 1.15 \times 10^{-5}$

$Br(\phi \to \pi^+\pi^-\gamma) = (0.41 \pm 0.12 \pm 0.04) \times 10^{-4}$ $Br^{th}_{\phi\to\pi\pi\gamma} = 0.047 \times 10^{-4}$!

The hadron $\phi \to \pi^+\pi^-\gamma$ decay has been observed !

Photon spectra from $e^+e^- \to \pi^+\pi^-\gamma$

6 energy points at ϕ resonance



N.N.Achasov model fit:

$Br(\phi \to f_0\gamma) = (1.93 \pm 0.46 \pm 0.50) \times 10^{-4}$

$m_{f_0} = 976 \pm 5 \pm 6$ MeV

$W_{f_0} = 40(70)$ MeV (fixed)

$\psi = 1.55 \pm 0.22$ radians

χ^2/d.f.=51/39

χ^2/d.f.=131/39 bremsstrahlung only.

In $\phi \to \pi^+\pi^-\gamma$ there is a resonance with m≈980 MeV

Obtained Br value points to qqqq structure of f_0

Selection of $e^+e^- \to \pi^0\pi^0\gamma$ events

Decay $\phi \to \pi^0\pi^0\gamma$ has no bremsstrahlung background

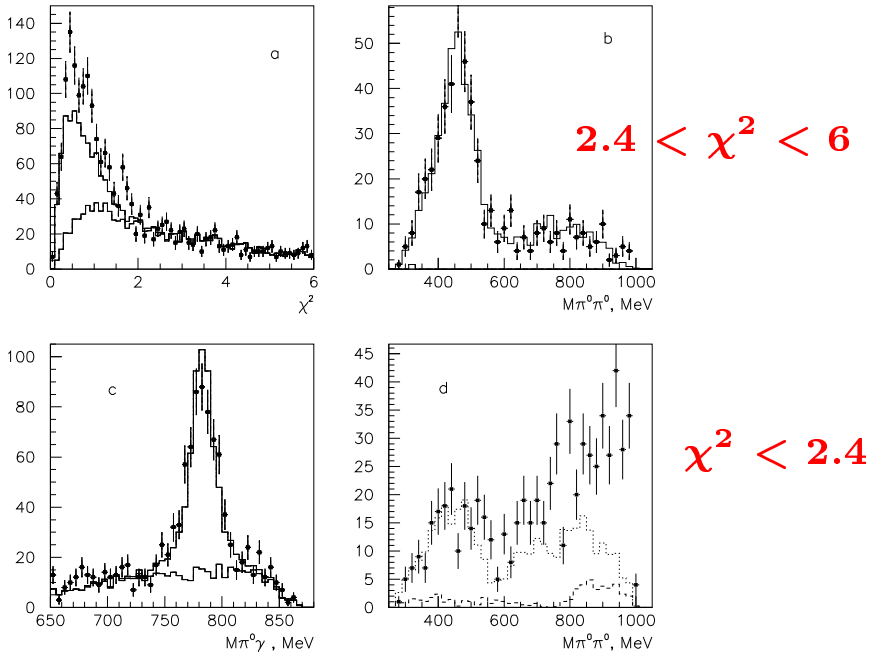
Selection criteria:

– **5 photons in CsI(3) and in BGO with $E_{tot} > 1.75 \cdot E_{beam}$ MeV**

– **threshould: $E_\gamma^{CsI} > 25$ MeV, $E_\gamma^{BGO} > 40$ MeV**

– **Constrained fit $+ 2\pi^0 + \chi^2 < 6$**

– **pion momenta:**
$|(P^1_{\pi^0} - P^2_{\pi^0})/(P^1_{\pi^0} + P^2_{\pi^0})| < 0.8$



$2.4 < \chi^2 < 6$

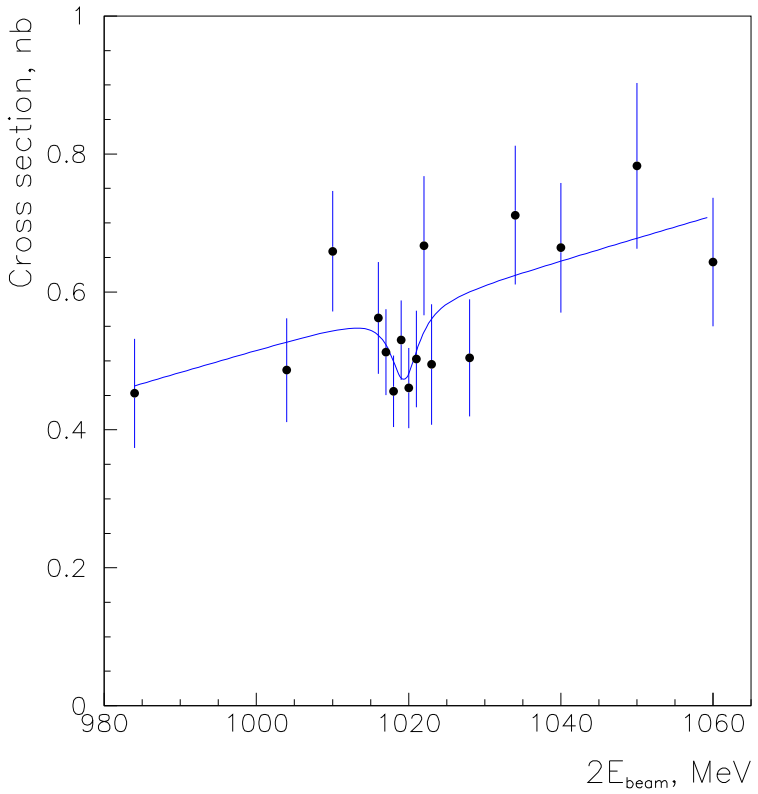
$\chi^2 < 2.4$

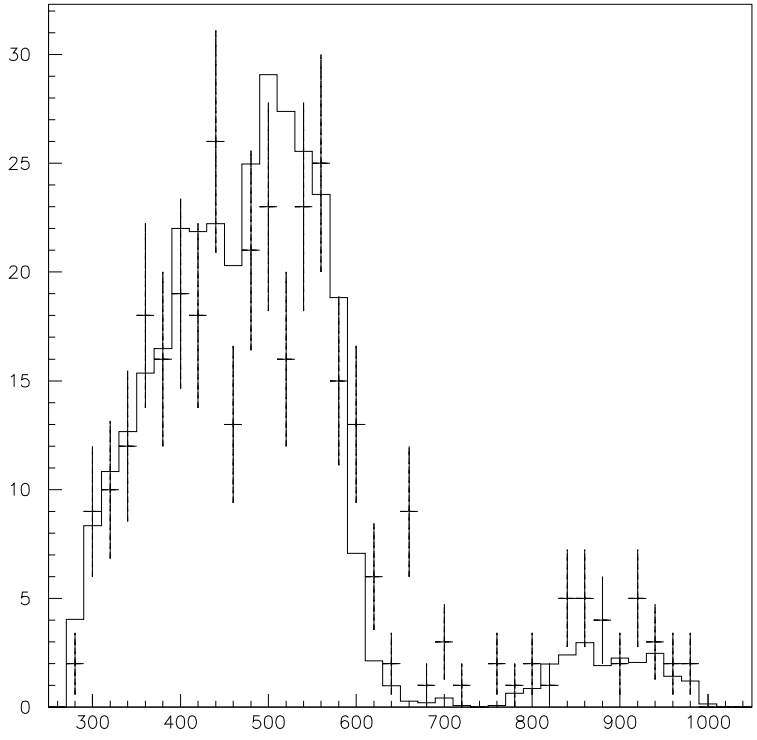
Remain background for $\pi^0\pi^0\gamma$ final state:
(histograms - simulation)

- $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$ - (nonresonant process)
- $\phi \to \eta\gamma \to \pi^0\pi^0\pi^0\gamma$ - (two photons are lost)

Selection of $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$ events

$N_{\omega\pi^0} = 506 \pm 28$, $m_\omega = (782.0 \pm 0.9)$ MeV





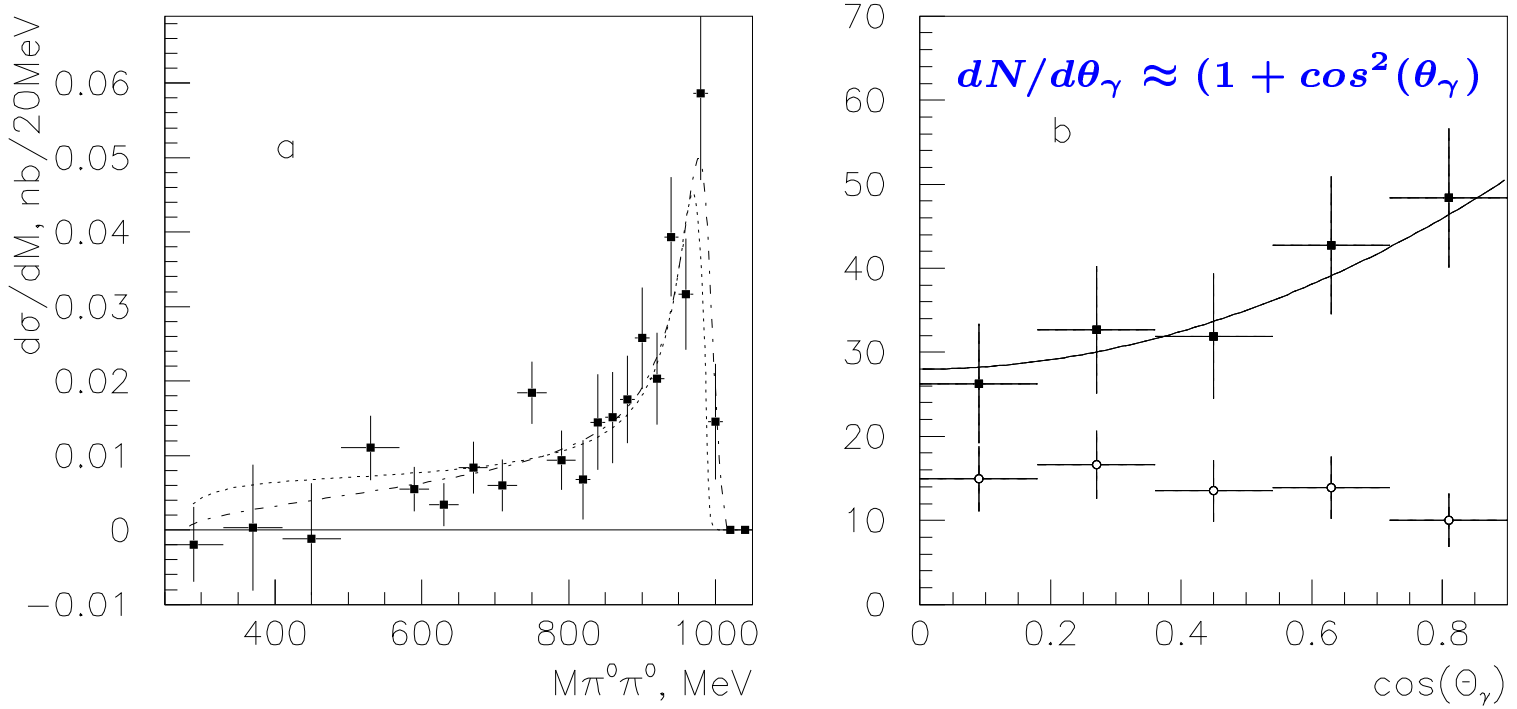
$\sigma_{\omega\pi^0}(E = m_\phi) = 0.58 \pm 0.02 \pm 0.04$

SND: $\sigma_{\omega\pi^0} = 0.65 \pm 0.05$

$m_{\pi^0\pi^0}$ out of ϕ resonance, check of incorrect combinations

Process $e^+e^- \to \phi \to \pi^0\pi^0\gamma$

$N_{\phi\to\pi^0\pi^0\gamma} = 268 \pm 27$



$Br(\phi \to \pi^0\pi^0\gamma) = (1.08 \pm 0.17 \pm 0.09) \times 10^{-4}$

$Br(\phi \to \pi^0\pi^0\gamma) = (1.06 \pm 0.09 \pm 0.06) \times 10^{-4}$ для $M_{\pi^0\pi^0} > 550$ MeV;

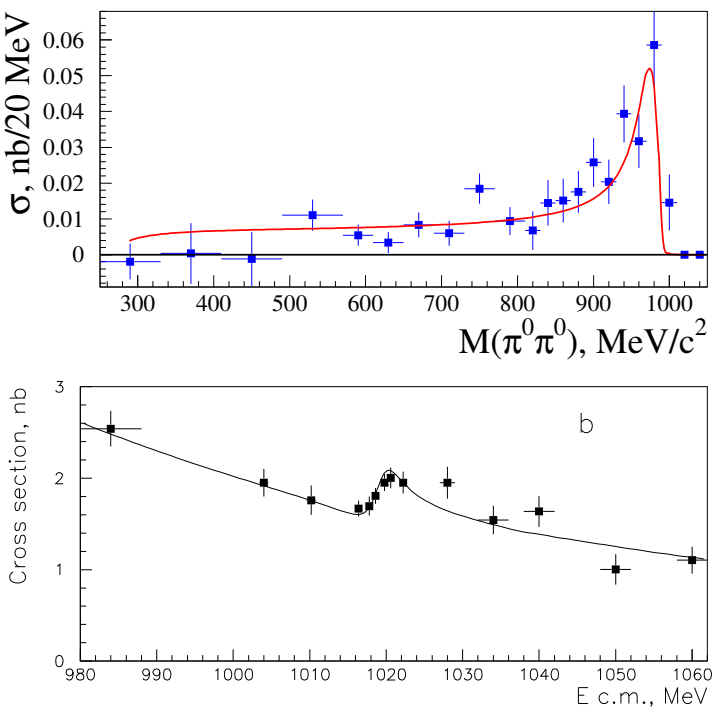
$Br(\phi \to \pi^0\pi^0\gamma) = (0.92 \pm 0.08 \pm 0.06) \times 10^{-4}$ для $M_{\pi^0\pi^0} > 700$ MeV;

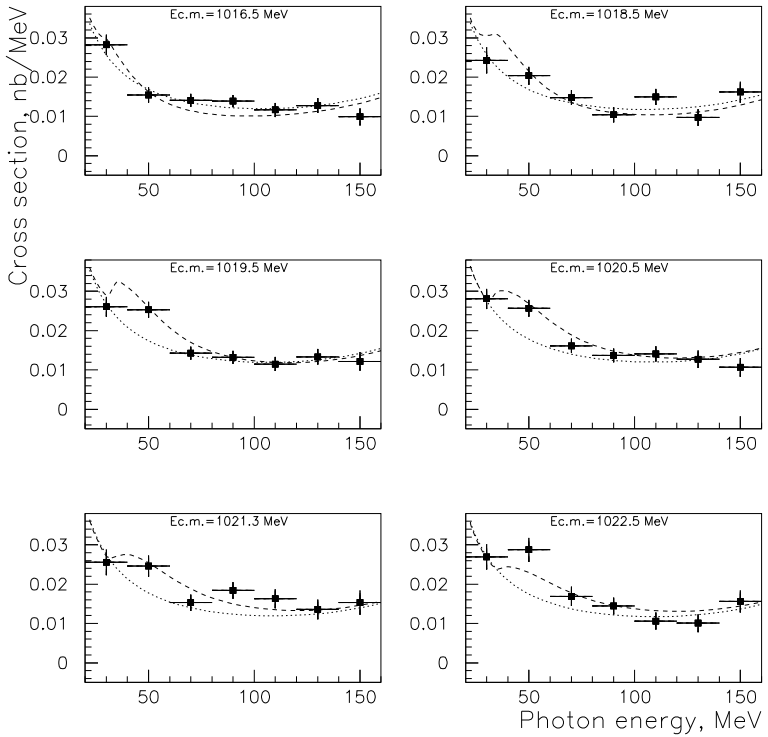
$Br(\phi \to \pi^0\pi^0\gamma) = (0.57 \pm 0.06 \pm 0.04) \times 10^{-4}$ для $M_{\pi^0\pi^0} > 900$ MeV.

The resonance with $M_{\pi^0\pi^0}$ ≈980 MeV.

Combined analysis of $\phi \to \pi^0\pi^0\gamma$ and $\phi \to \pi^+\pi^-\gamma$

N.N.Achasov model - $\phi \to f_0(980)\gamma$ only





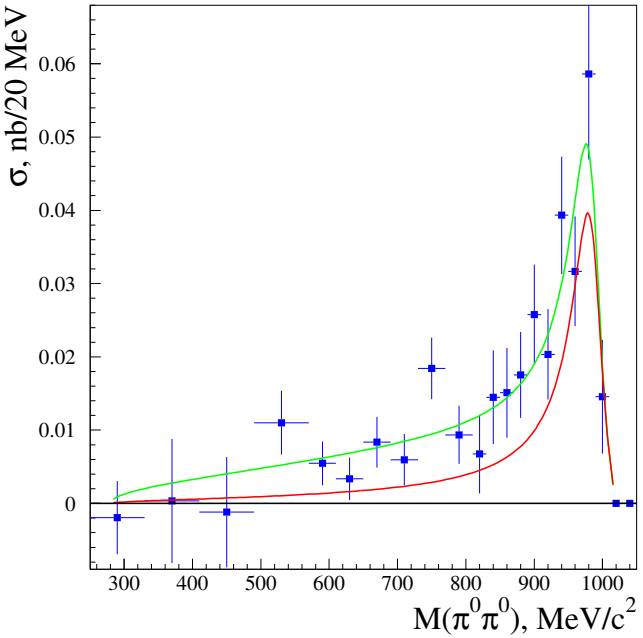
$m_{f_0} = 974 \pm 4 \pm 6$ MeV/c², $g^2_{KK}/4\pi = (1.48 \pm 0.32)$ GeV², $\Psi = (1.47 \pm 0.19)$ радиан, $g^2_{\pi\pi}/4\pi = (0.41 \pm 0.06)$ GeV², χ^2/d.f.=1.5

$Br(\phi \to f_0\gamma) = (2.90 \pm 0.21 \pm 0.65) \cdot 10^{-4}$, R=3.61±0.62

How big is $\phi \to f_0(980)\gamma$?

Two narrow resonance fit $\phi \to (f_0 + \sigma)\gamma$

$$\frac{d\sigma}{dM_{\pi\pi}} \sim 2M_{\pi\pi} \cdot (1 - \frac{M^2_{\pi\pi}}{4E^2_{beam}}) \cdot \sqrt{1 - \frac{4m^2_\pi}{M^2_{\pi\pi}}} \cdot |\frac{m_f \Gamma_f}{\Delta_f} + \frac{A e^{i\psi} m_\sigma \Gamma_\sigma}{\Delta_\sigma}|^2$$



$m_{f_0} = 987 \pm 7$ MeV/c^2

$\Gamma_{f_0} = 56 \pm 20$ MeV

A=0.22±0.09, χ^2/d.f.=0.96

$Br(\phi \to f_0(980)\gamma) = (1.5 \pm 0.5) \cdot 10^{-4}$

Big contribution of qqqq-component!

With theoretical uncertainty from CMD-2 data:

$$Br(\phi \to f_0(980)\gamma) = (2.90 \pm 0.21 \pm 1.54) \cdot 10^{-4}$$

$$m_{f_0} = (978 \pm 4 \pm 6) \text{ MeV}$$

$$\Gamma_{f_0} = (56 \pm 20 \pm 10) \text{ MeV}.$$

Study of $e^+e^- \to \phi \to \eta\pi^0\gamma \to 5\gamma$

Selection: – 5 photons
in CsI(3) and in BGO with

$$E_{tot} > 1.75 \cdot E_{beam}$$

– Threshold: $E_\gamma^{CsI} > 25$ MeV,

$$E_\gamma^{BGO} > 40 \text{ MeV}$$

– Constrained fit + π^0 + χ^2 <2.4

– Photon energies from π^0:

$|(E_\gamma^1 - E_\gamma^2)/(E_\gamma^1 + E_\gamma^2)| < 0.8$

– anti-ω and anti-$\pi^0\pi^0\gamma$

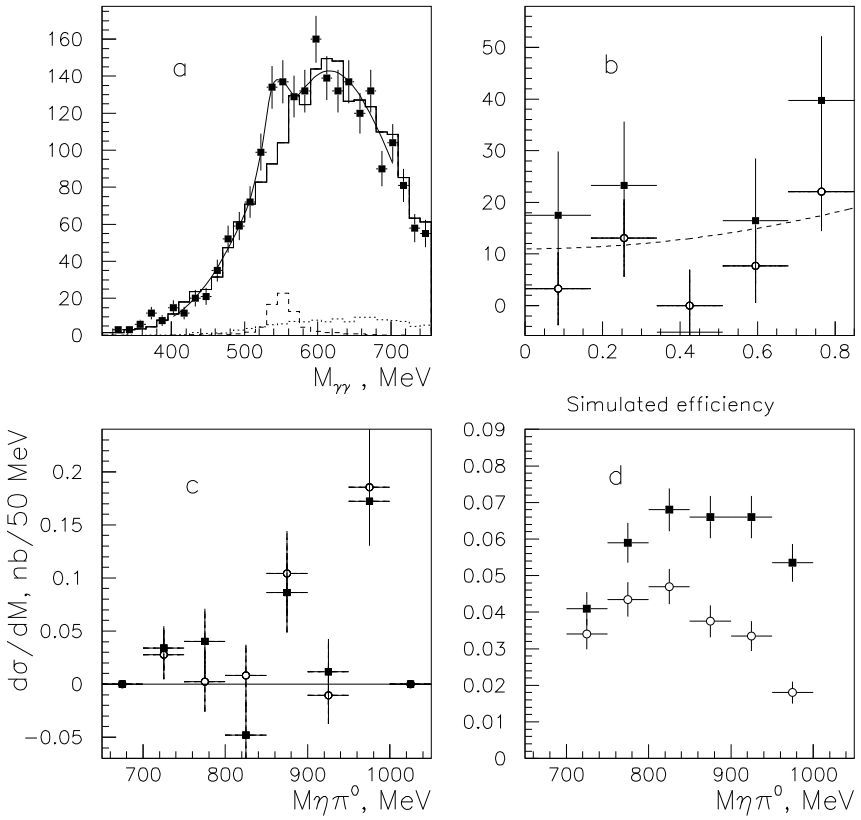
– "Strong" cuts

$$E_\gamma^{max}/E_{beam} < 0.75$$

Background (from simulation):

$e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$,

$\phi \to \eta\gamma \to \pi^0\pi^0\pi^0\gamma$



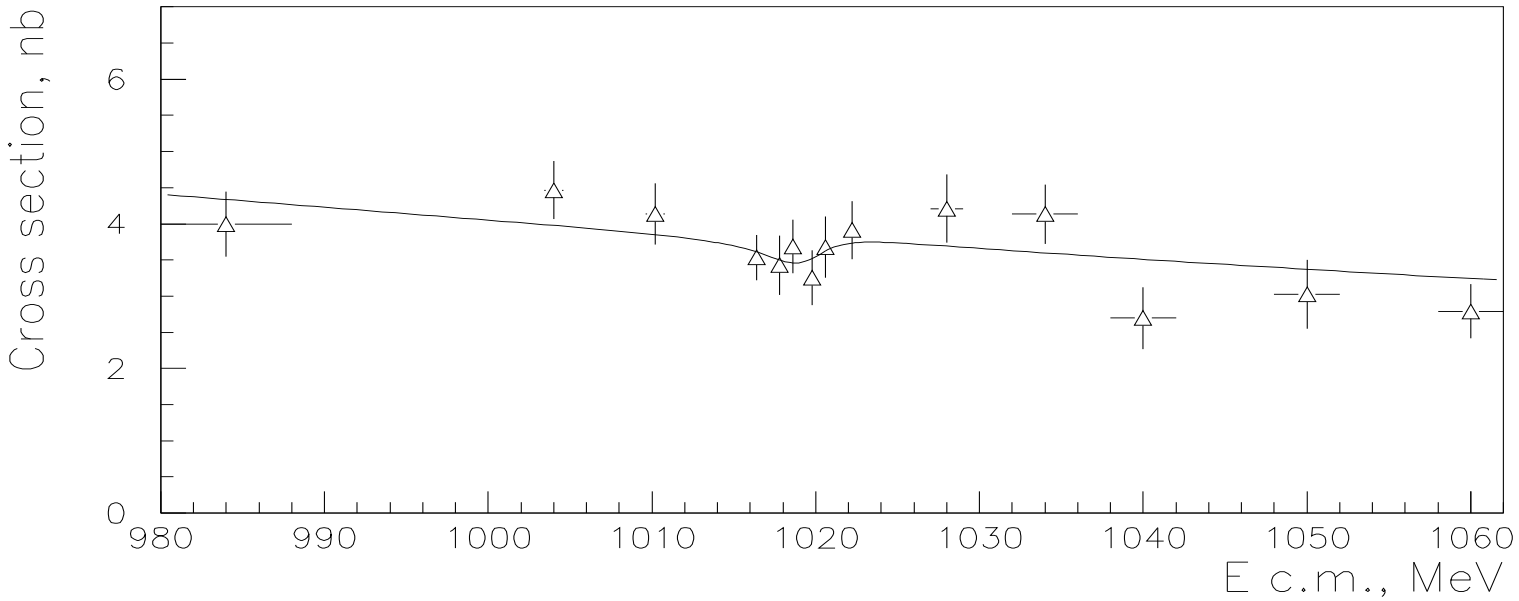
$N_{\eta\pi^0\gamma} = 80 \pm 22$ (37 ± 12), $m_{\gamma\gamma} = (545 \pm 4)$ MeV

$Br(\phi \to \eta\pi^0\gamma) = (0.90 \pm 0.24 \pm 0.10) \times 10^{-4}$ $(\phi \to a_0(980)\gamma$?)

Experimental situation with radiative ϕ decays

Decay	SND	CMD-2	PDG, 1998
$\phi \to \pi^0\gamma$	$(1.23 \pm 0.10)10^{-3}$		$(1.31 \pm 0.13)10^{-3}$
$\phi \to \eta\gamma$	(1.246 ± 0.062) % (1.338 ± 0.053) %	(1.18 ± 0.07) % (1.24 ± 0.06) %	(1.26 ± 0.06) %
$\phi \to \eta'\gamma$	$(6.7^{+3.4}_{-2.9}) \cdot 10^{-5}$	$(8.2^{+2.3}_{-2.1}) \cdot 10^{-5}$ $(5.8 \pm 2.3) \cdot 10^{-5}$	$(12^{+7}_{-5}) \cdot 10^{-5}$
$\phi \to \pi^0\pi^0\gamma$ $m_{\pi^0\pi^0} > 700$ MeV	$(1.14 \pm 0.16) \cdot 10^{-4}$ $(1.00 \pm 0.14) \cdot 10^{-4}$	$(1.08 \pm 0.19) \cdot 10^{-4}$ $(0.92 \pm 0.10) \cdot 10^{-4}$	$< 10^{-3}$
$\phi \to \eta\pi^0\gamma$	$(0.83 \pm 0.23) \cdot 10^{-4}$ $(0.88 \pm 0.21) \cdot 10^{-4}$	$(0.90 \pm 0.26) \cdot 10^{-4}$	$< 2.5 \cdot 10^{-3}$

Search for $\phi \to \rho\gamma$ decay (C-violation)



Cross section for $\pi^+\pi^-\gamma$ events with photons in 100-300 MeV range.

For C violation $\sigma(s) = \sigma_{br}^{in}(s) \cdot |1 - e^{i\psi} \cdot \sqrt{\frac{\sigma(\phi\to\rho\gamma)}{\sigma_{br}^{in}(s)}} \cdot \frac{m_\phi \Gamma_\phi}{\Delta_\phi}|^2$, $\sigma_{br}^{in}(s) = \sigma_0 \cdot (m_\phi^2/s)$

$Br(\phi \to \rho\gamma) = \sigma(\phi \to \rho\gamma)/\sigma_{tot}^{\phi} = (0.3 \pm 0.5) \times 10^{-5}$ **and** $\psi = -0.9 \pm 1.0$ **radians**

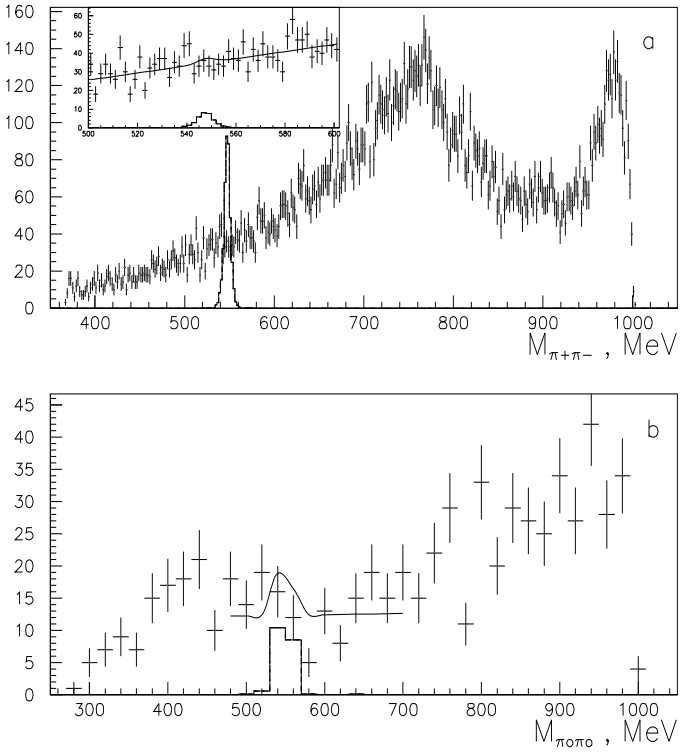
$$\boldsymbol{Br(\phi \to \rho\gamma) < 1.2 \times 10^{-5}\text{, for 90\% C.L.}}$$

$$\boldsymbol{Br(\phi \to \rho\gamma) < 2 \times 10^{-2}\text{ - PDG'96}}$$

Search for $\eta \to \pi^+\pi^-$, $\eta \to \pi^0\pi^0$

(P and CP-violation)

about 240000 $\phi \to \eta\gamma$ decays used for search



Theory:

SM - $< 2 \times 10^{-27}$

Shabalin et al. - $10^{-15} - 10^{-16}$

Experiment:

CMD-2(97) - $< 9 \times 10^{-4} (\pi^+\pi^-)$

SND(98) - $< 7 \times 10^{-4} (\pi^0\pi^0)$

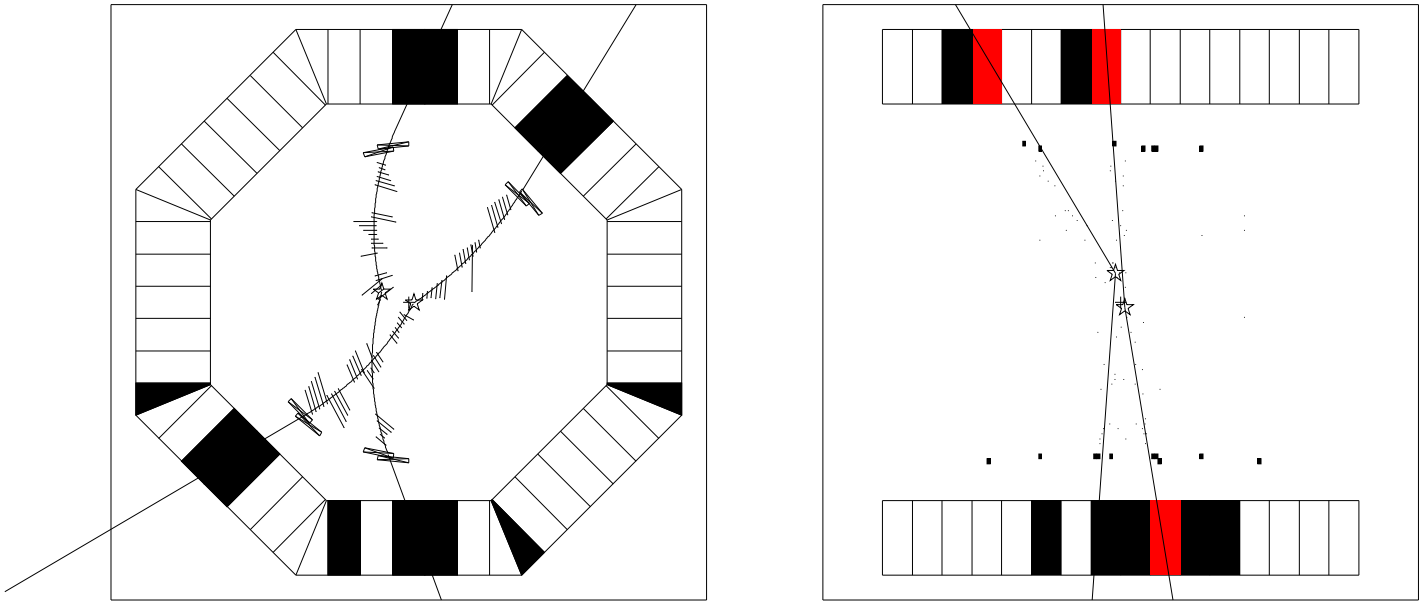
$\mathbf{N(\eta \to \pi^+\pi^-) < 10}$,

$\mathbf{N(\eta \to \pi^0\pi^0) < 11}$,

Efficiency - 12.4%, 10.8%

$\mathrm{Br}(\eta \to \pi^+\pi^-) < \mathbf{3.3 \times 10^{-4}}$, $\mathrm{Br}(\eta \to \pi^0\pi^0) < \mathbf{4.3 \times 10^{-4}}$.

Study of $K_S K_L$ couple decays



$\phi \to K_S K_L$ event with kaons couple decays.

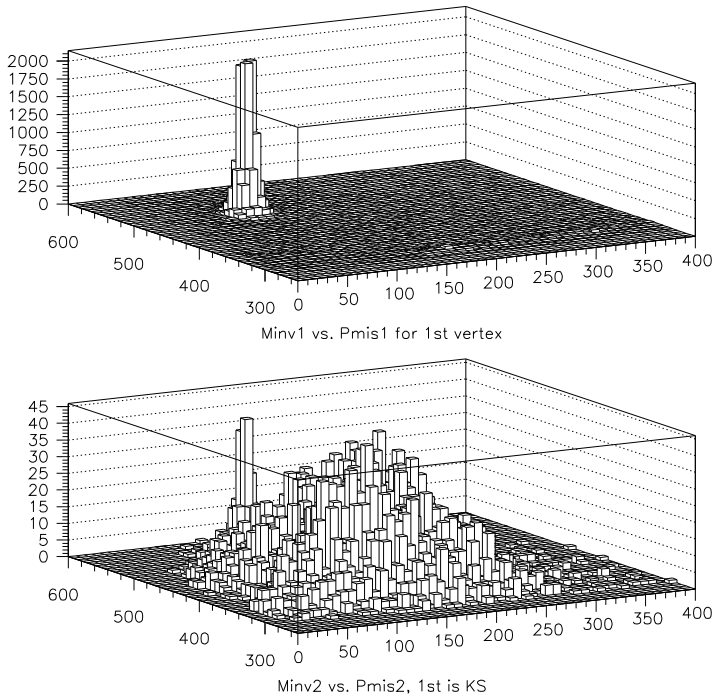
Selection: – Two verteces with two tracks,

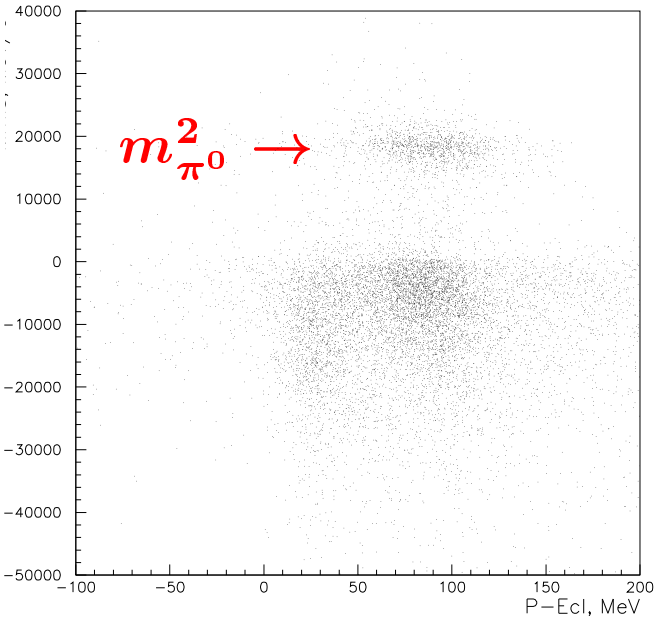
– all momenta $<$ **300** MeV/c.

About $\mathbf{20 \cdot 10^6}$ decays of ϕ; efficiency about 3%,

Detected $N_{K_S K_L}$=14000

Decay $K_S \to \pi^+\pi^-$ as a tag for K_L



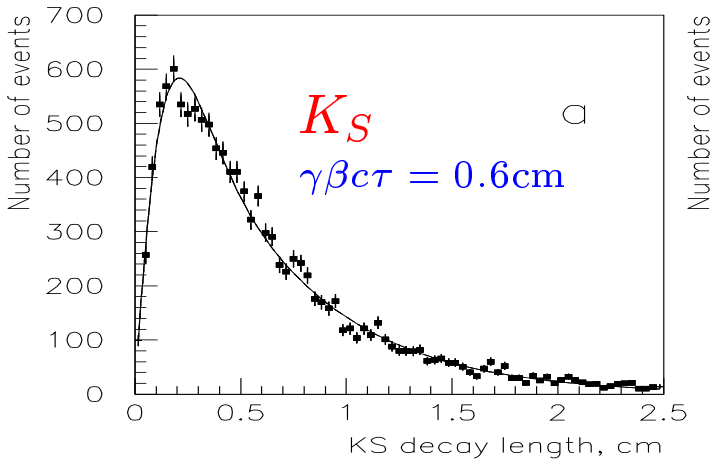


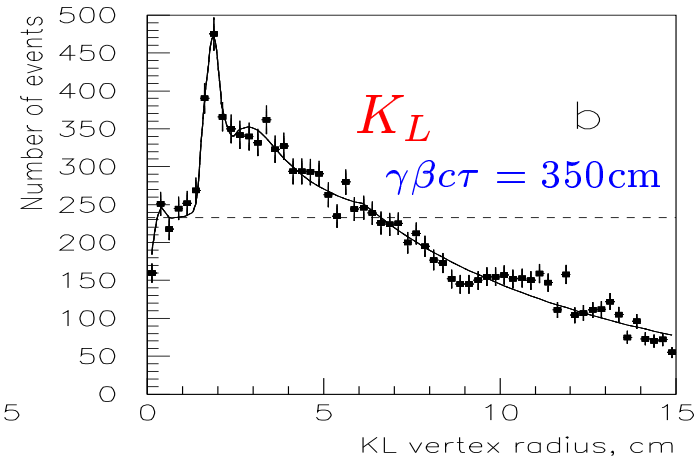
Missing mass for 2-nd vertex vs. P-Ecal.

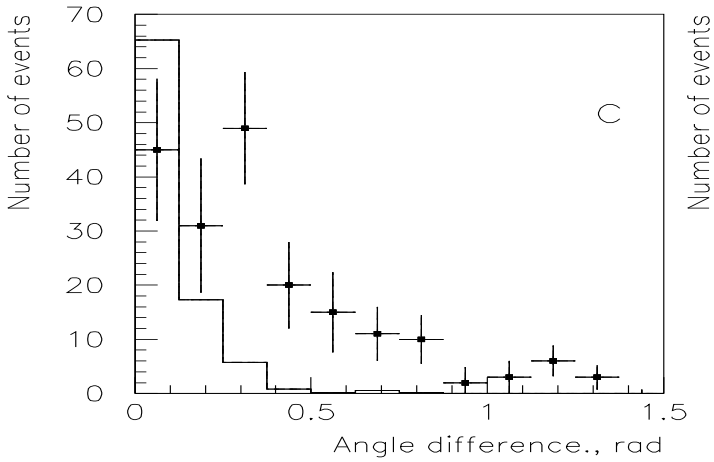
$K_L \to \pi^+\pi^-\pi^0, \pi e\nu, \pi\mu\nu$

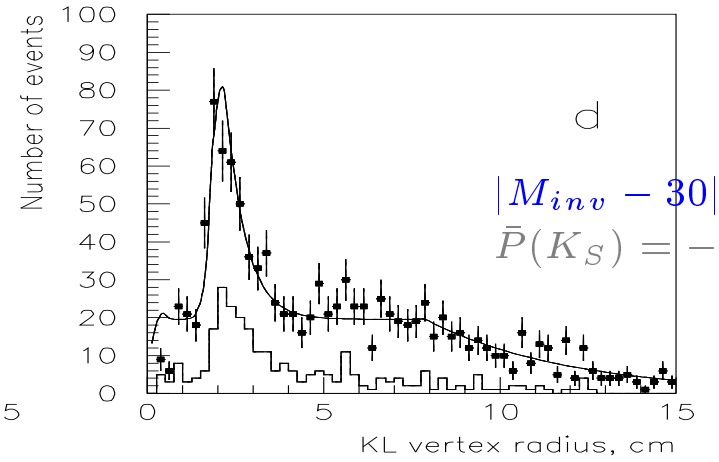
Invariant mass vs. missing mimentum for 1st vertex (a) and for 2nd vertex (b) if $K_S \to \pi^+\pi^-$ decay selected in 1st.

Study of the decay lenght of K_S and K_L









$|M_{inv} - 30| < M_{K^0}$

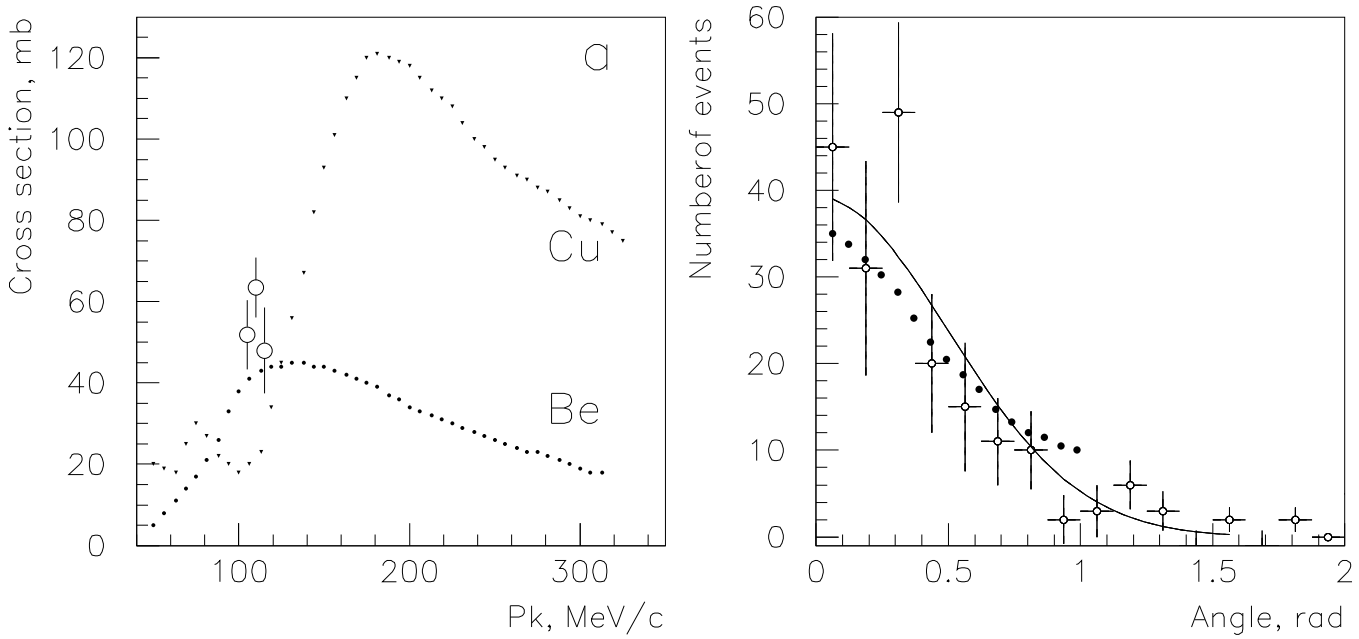
$\bar{P}(K_S) = -\bar{P}(K_L)$

N_{nucl}=562±48 , N_{reg}=238±20, $N_{K_L} \cdot \epsilon_{rec} = 418205 \pm 10769$,

$P_{nucl} = (0.74 \pm 0.09) \cdot 10^{-3}$, $P_{reg} = (0.68 \pm 0.07) \cdot 10^{-3}$

Regeneration cross section of slow kaons at Be

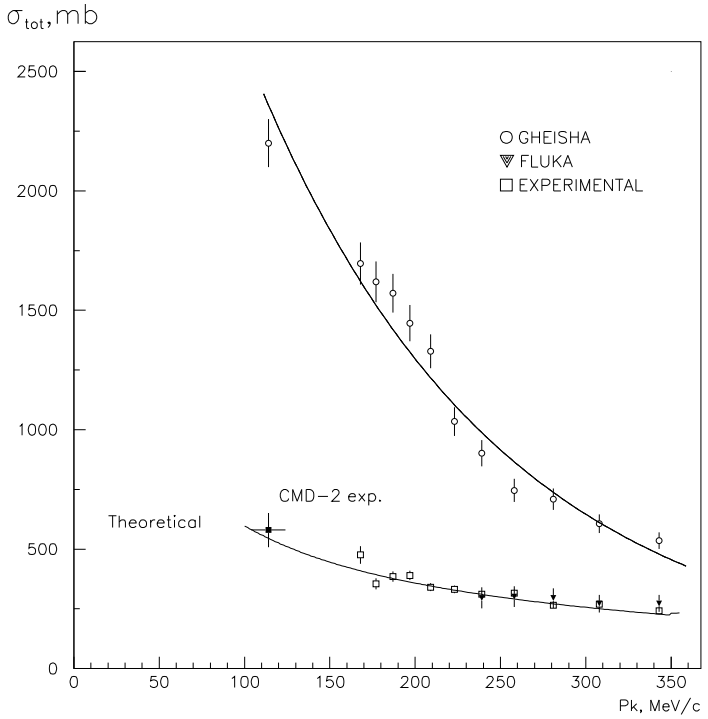
$$\sigma = \frac{P \cdot A}{N_A \cdot \rho \cdot t}, \qquad \sigma_{reg}^{Be} = (55.1 \pm 5.9 \pm 5.0)\ \text{mb}.$$



a. Experimental cross sections and theoretical calculations for Be and Cu; b. Angular distributions of reconstructed K_S with exponential fit (solid line) and theoretical prediction (points).

Total nuclear cross section of slow kaons

$$\sigma = \frac{P \cdot A}{N_A \cdot \rho \cdot t}, \qquad \sigma_{inel}^{vis} = (72 \pm 9)\ \text{mb}, \qquad \sigma_{tot}^{Be} = (508 \pm 72 \pm 174)\ \text{mb}$$



Reactions, contributed into visible cross section:

$K_L + p \to \Lambda^0 + \pi^+, \Lambda^0 \to p + \pi^-$;

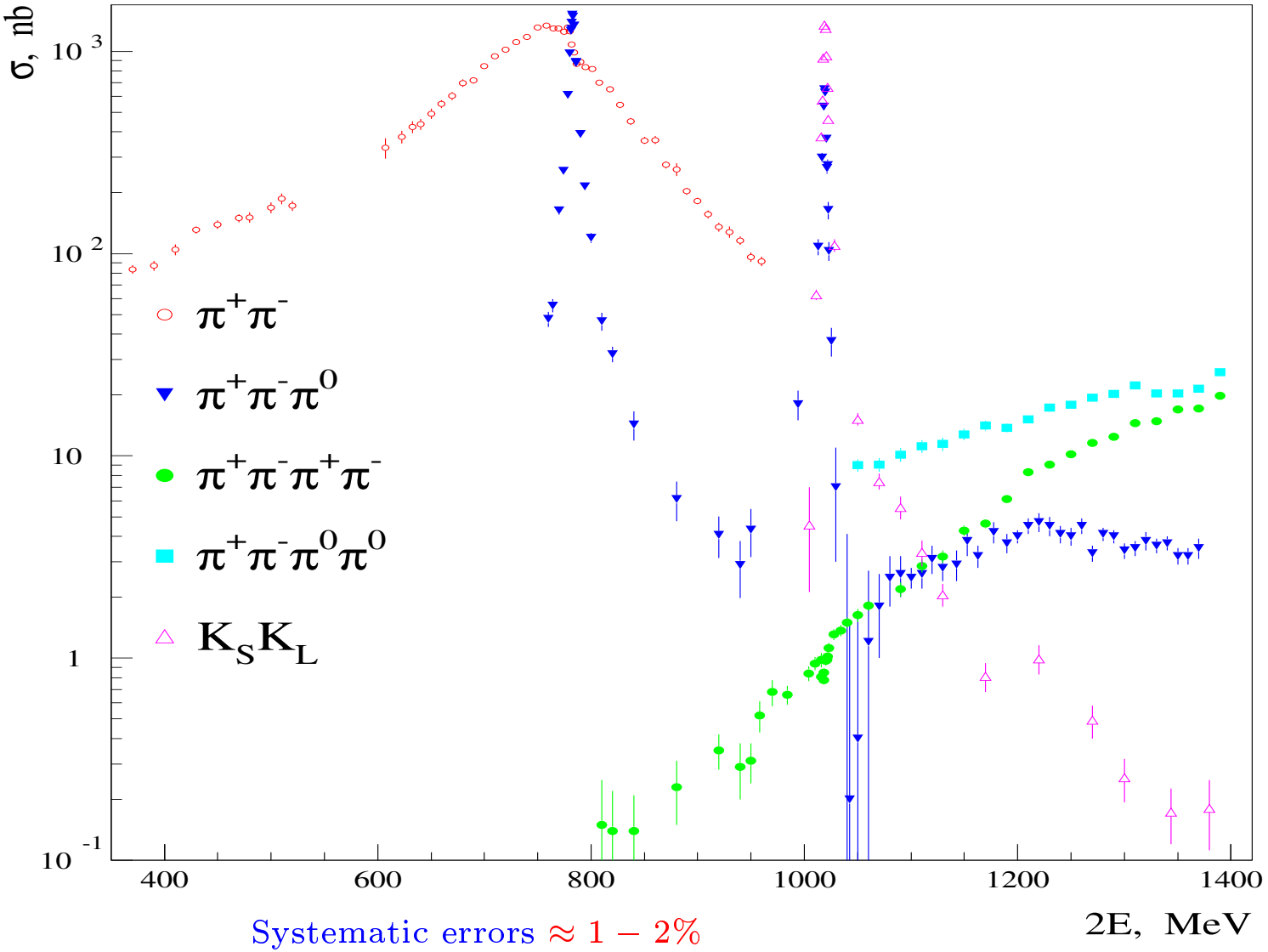
$K_L + p \to \Sigma^0 + \pi^+, \Sigma^0 \to \Lambda^0 + \gamma, \Lambda^0 \to p + \pi^-$;

$K_L + n \to \Sigma^- + \pi^+, \Sigma^- \to n + \pi^-$;

$K_L + n \to \Sigma^+ + \pi^-, \Sigma^+ \to n + \pi^+$.

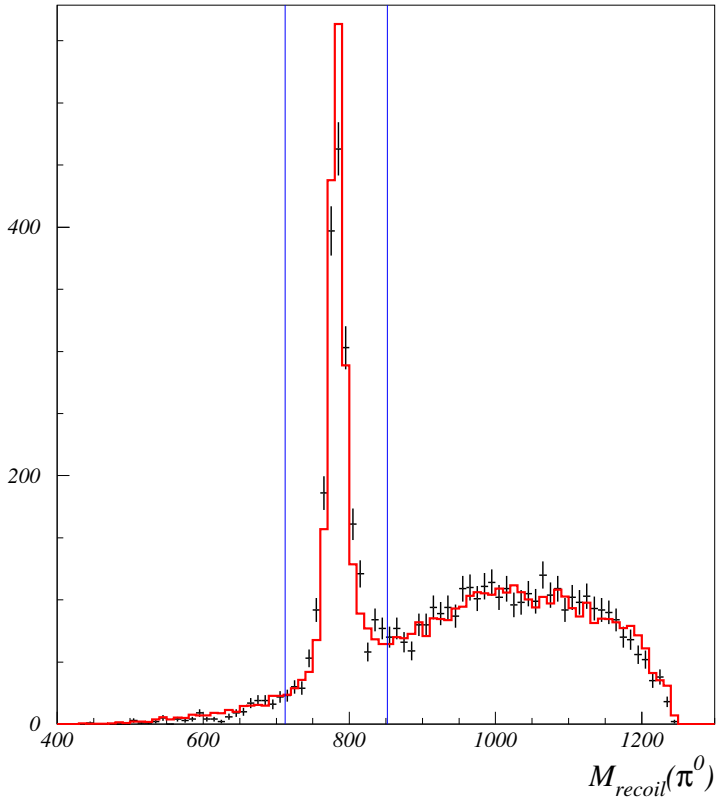
Comparison of experimental total cross section of K_L with theoretical calculations and simulation by different packages. Experimental cross section at higher momenta are shown.

Hadron cross section measurements at VEPP-2M

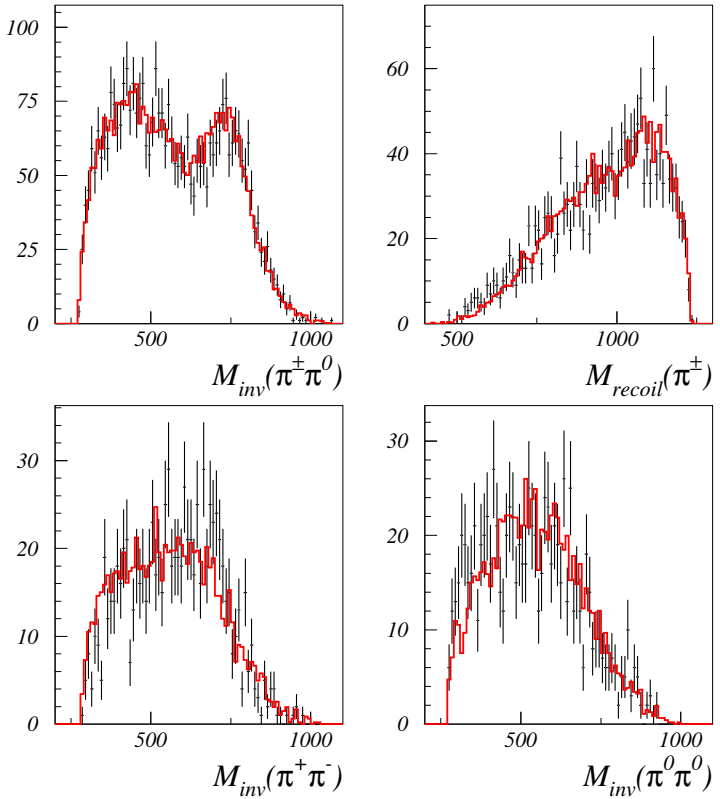


Systematic errors $\approx 1 - 2\%$

Study of the dynamics of $e^+e^- \to \pi^+\pi^-\pi^+\pi^-, \pi^+\pi^-\pi^0\pi^0$



Distribution over π^0 recoil mass for $\pi^+\pi^-2\pi^0$



Distributions over $M_{\pi^\pm\pi^0}$, $M_{recoil}(\pi^\pm)$, $M_{\pi^+\pi^-}$ and $M_{\pi^0\pi^0}$ for $\pi^+\pi^-2\pi^0$ (no ω).

Only $\omega\pi^0$ and $a_1(1260)\pi$ dominate!