BINP @ Novosibirsk, Russia
VEPP2000 Collider

Recent results from the CMD-3 at ϕ

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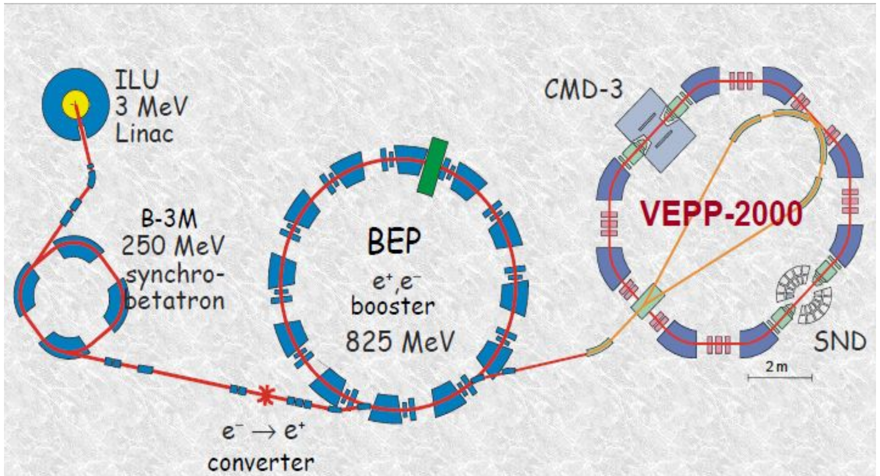
Outline

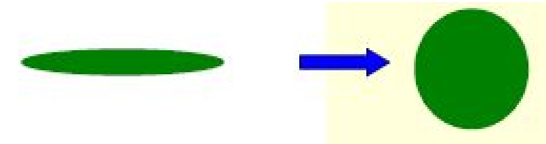
- VEPP-2000 collider and CMD-3 detector
- Study of $e^+e^- \to K_S K_L$ (published: Phys.Lett. B760 (2016) 314-319) and $e^+e^- \to K^+K^-$ processes
- Study of $e^+e^- \to 2\pi^+2\pi^-, \pi^+\pi^-2\pi^0$ processes
- Study of $e^+e^- \to \eta\gamma$ process
- Conclusion

VEPP-2000 collider

before the launch of the new injection complex:

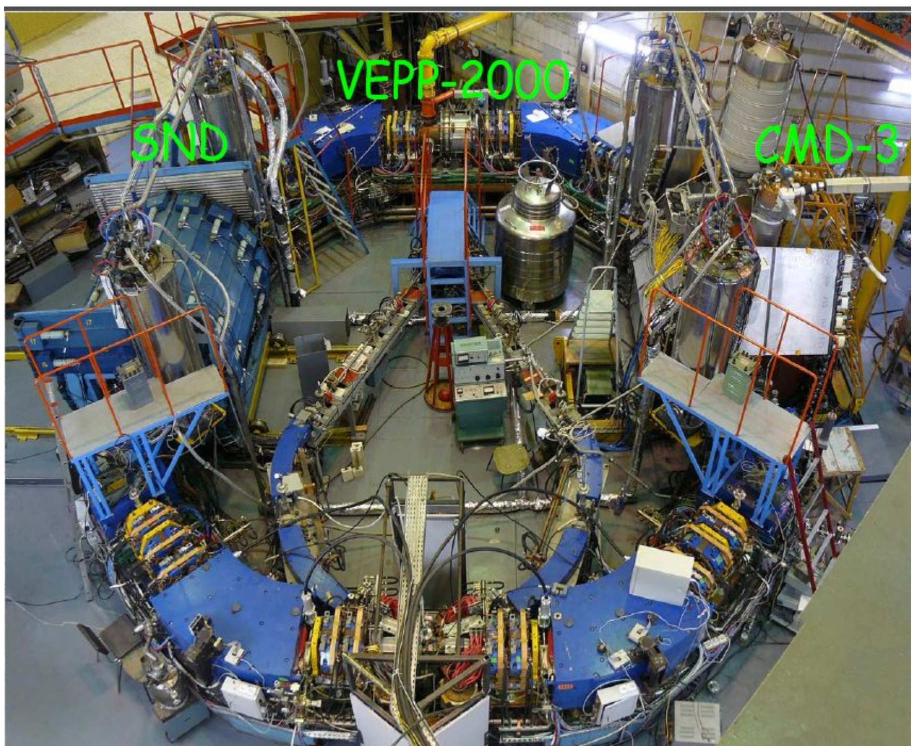


Round beams technology is used:

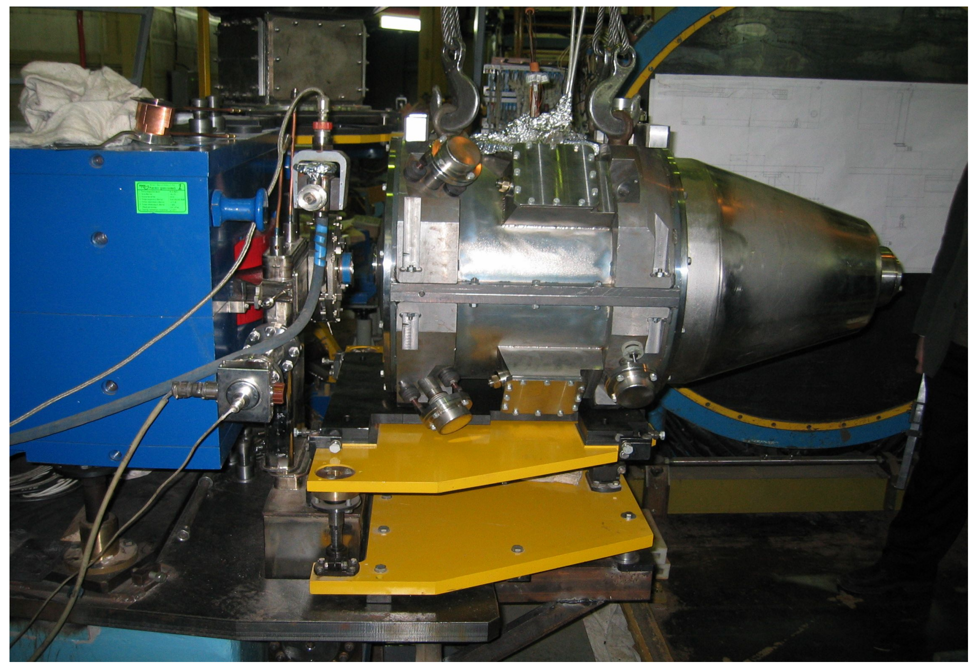


$$L=\frac{\pi\gamma^2\xi_x\xi_y\varepsilon_x f}{r_e^2\beta_y^*}\left(1+\frac{\sigma_y}{\sigma_x}\right)^2 \quad \Longrightarrow \quad L=\frac{4\pi\gamma^2\xi^2\varepsilon f}{r_e^2\beta^*} \; (\times 4)$$

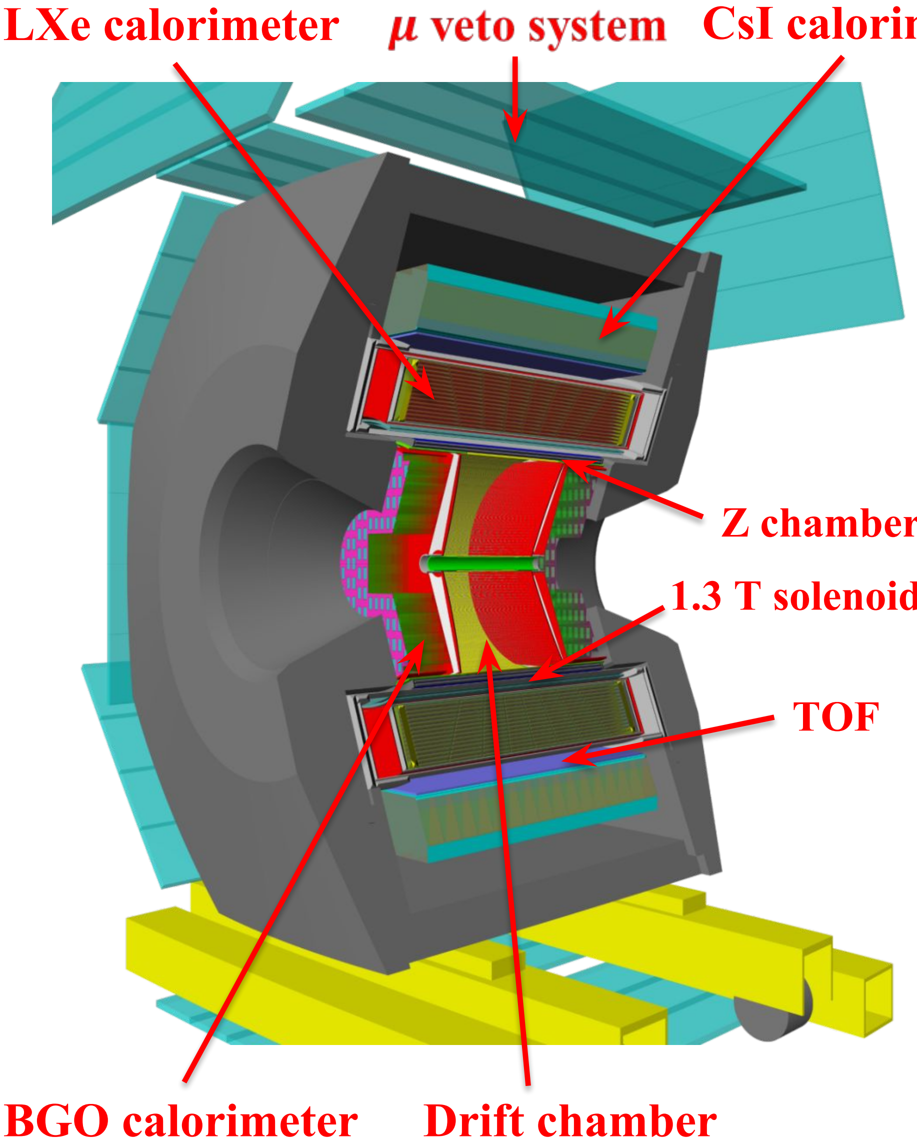
+ reduction of the beam-beam effects $(\times 4)$

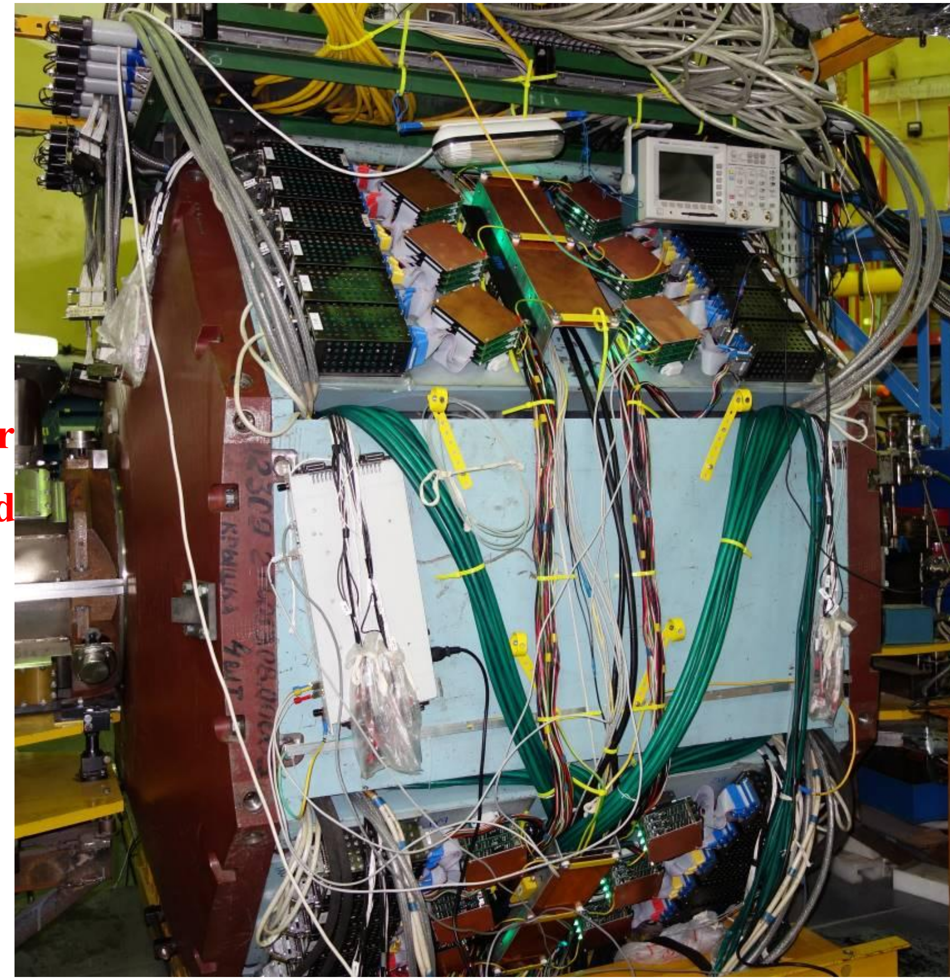


Focusing solenoid with 13.0 T field

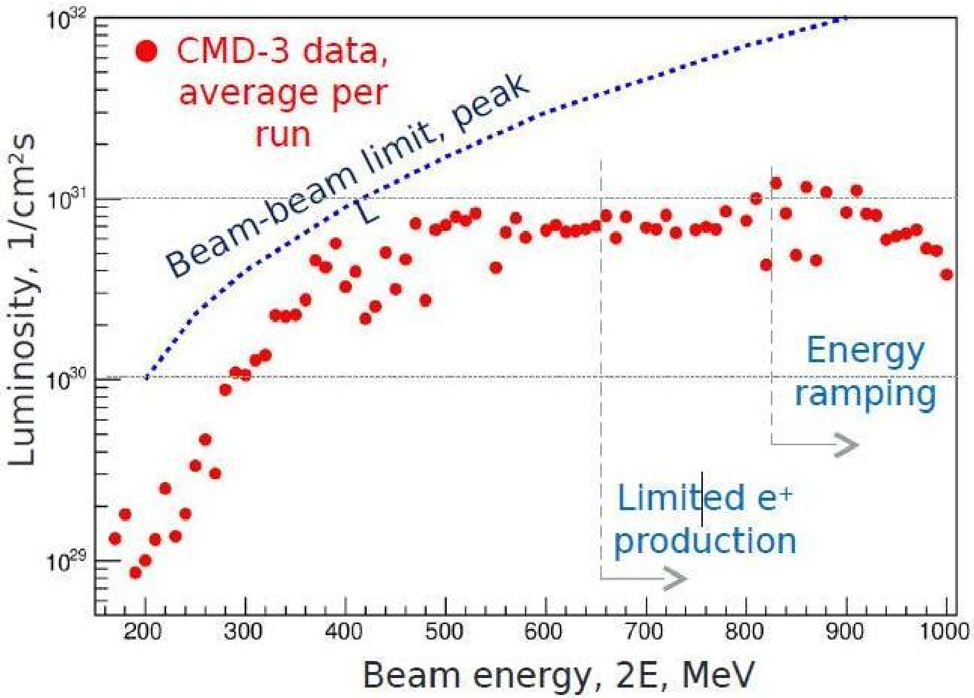


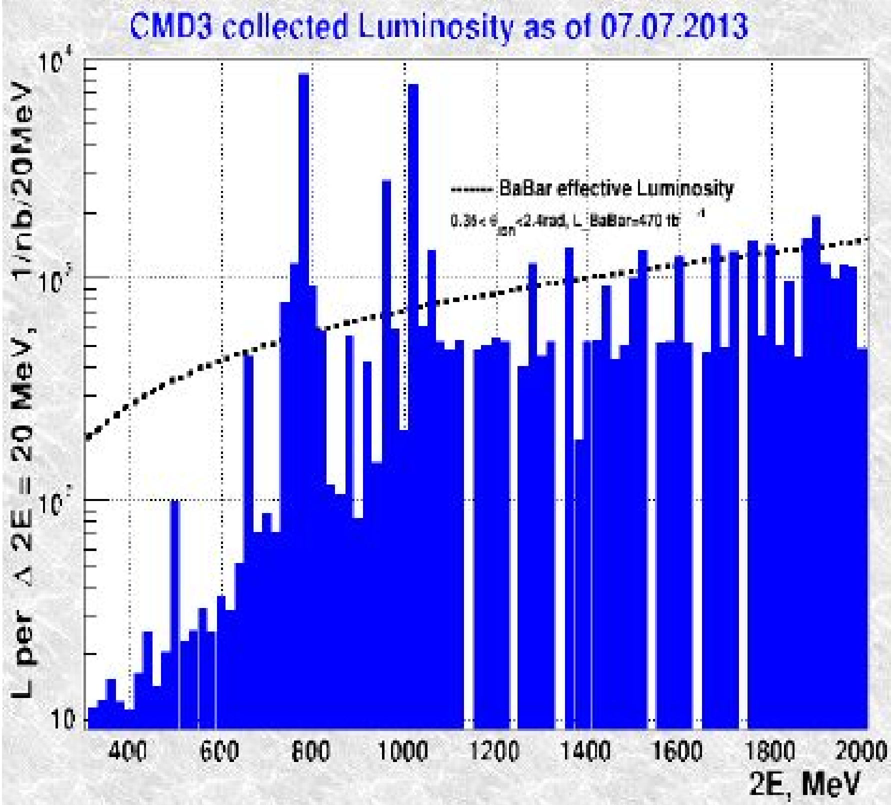
CMD-3 detector





VEPP-2000 collider: luminosity





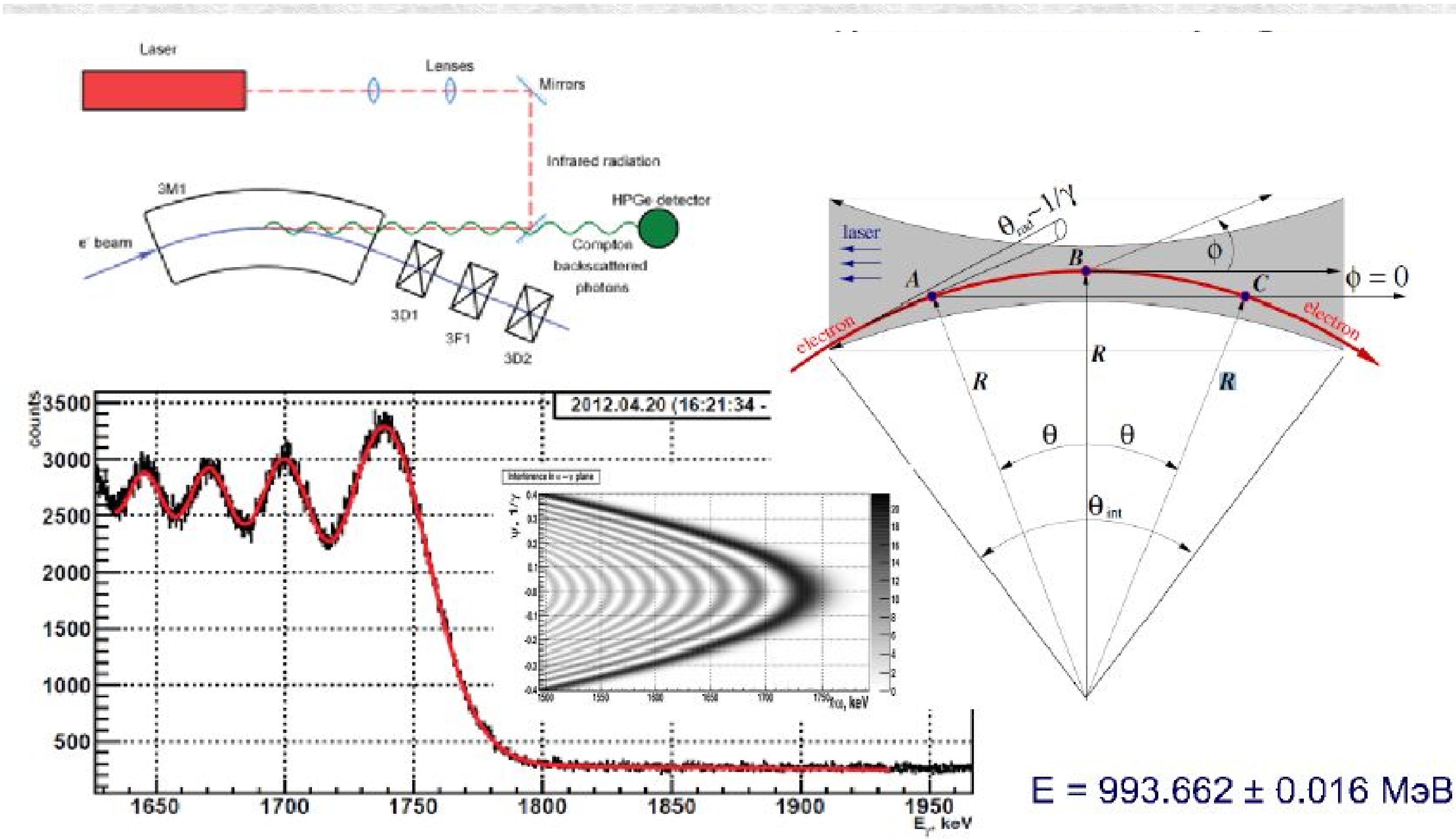
Collected L ~ 60 pb^{-1} per detector

8.3 pb^{-1}	ω - region
9.4 pb^{-1}	< 1 GeV (except ω)
8.4 pb^{-1}	φ - region
34.5 pb^{-1}	> 1.04 GeV

- The reached maximum luminosity is $2 \cdot 10^{31}\ \mathrm{cm^{-2}s^{-1}}$ at $1.7 - 1.8\ \mathrm{GeV}$, falling much slower with decreasing energy than before the round beams
- At high energies luminosity was limited by a deficit of positrons and maximum energy of the booster

Compton backscattering beam energy measurement

- Energy of electrons in the beam is measured using back-scattering compton photons with 30 keV systematic uncertainty

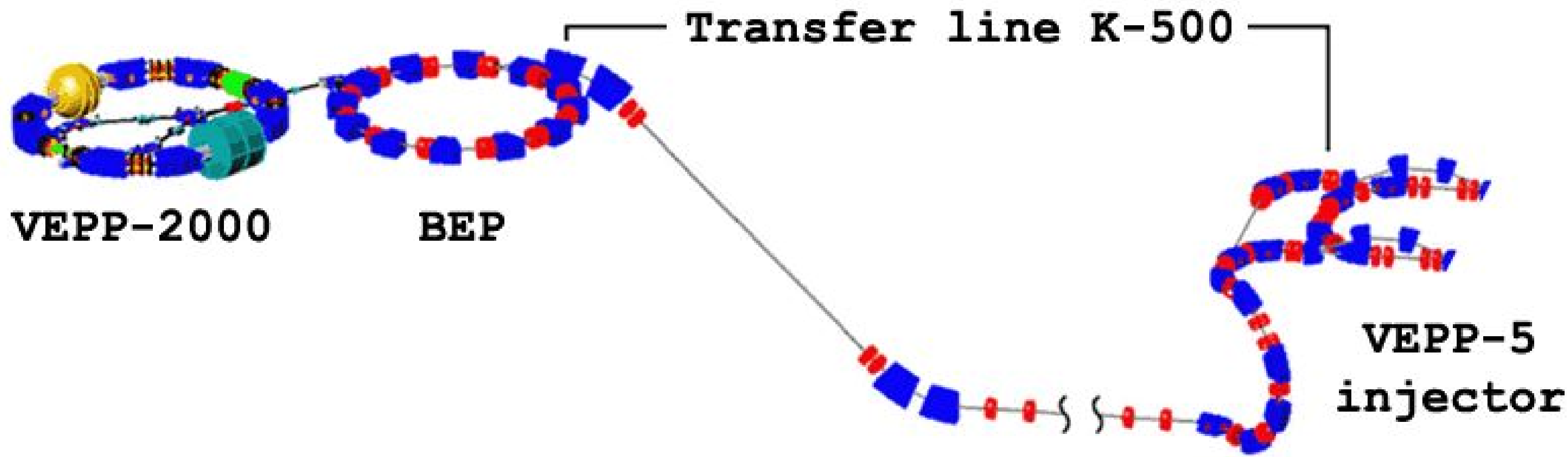


E = 993.662 ± 0.016 МэВ

E.V. Abakumova et al., Phys. Rev. Lett. 110 (2013) 14, 140402,
E.V. Abakumova et al.,Nucl.Instrum.Meth. A744 (2014) 35-40

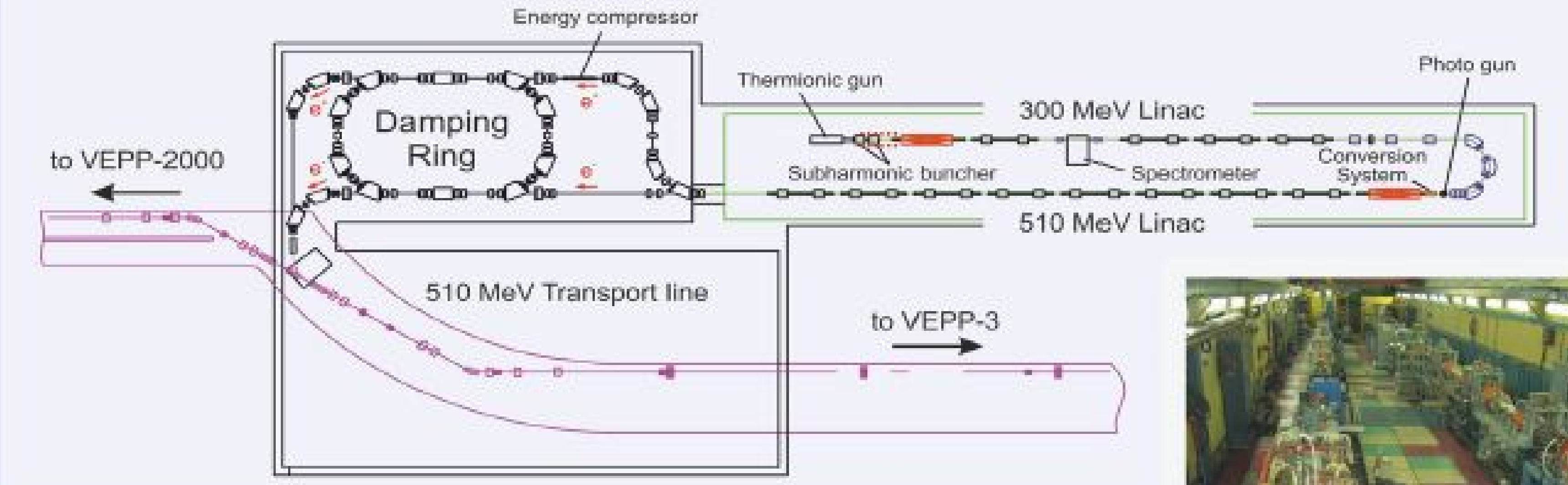
Perspectives

- The collider complex and both detectors are upgraded for next run



- VEPP-5 injection complex is operation now with x10 - 100 more positrons
- Transfer line is ready
- Maximum energy in booster BEP is increased to 1 GeV
- Additional inflectors are installed to VEPP-2000 to accept 1 GeV injection
- Both detector DAQs are upgraded to accept ×10 luminosity (background)
- The goal is to get 1 fb^{-1} in 5 – 10 years

VEPP-5 INJECTION COMPLEX



Parameters at E_{beam} = 510 MeV

Number of electrons per bunch	$2 \cdot 10^{10}$
Number of positrons per bunch	$2 \cdot 10^{10}$
Repetition rate	1 Hz
Electron bunch energy spread	0.07%
Positron bunch energy spread	0.07%
Vertical emittance	$5 \cdot 10^{-9}$ m·rad
Horizontal emittance	$23 \cdot 10^{-9}$ m·rad

Physics program at VEPP-2000

- Precise measurement of $R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$ - the goal is to achieve <1% systematic for major channels
- Study of exclusive hadronic channels of e^+e^- annihilation
- Study of the "excited" vector mesons: $\rho', \rho'', \omega', \phi'$ ...
- CVC tests: comparison of isovector part of $\sigma(e^+e^- \to hadrons)$ with τ −decay spectra
- Study of the nucleon electromagnetic form factor
- Diphoton physics

CMD-3 detector and ϕ-meson energy range

- The study of ϕ energy range is not a priority of CMD-3, but ϕ is very important for us from the point of view:

1. Study of the photon detection efficiency $\varepsilon_\gamma(E_\gamma, \theta_\gamma)$ in MC and experiment ($\phi \to \pi^+\pi^-\pi^0$ mode is used)
2. Study of the energy depositions of $\pi^\pm$ in the calorimeters, which is necessary for proper π/μ separation
3. Study of the $\pi^\pm$ and $K^\pm$ detection efficiencies $\varepsilon(p, \theta)$ in MC and experiment

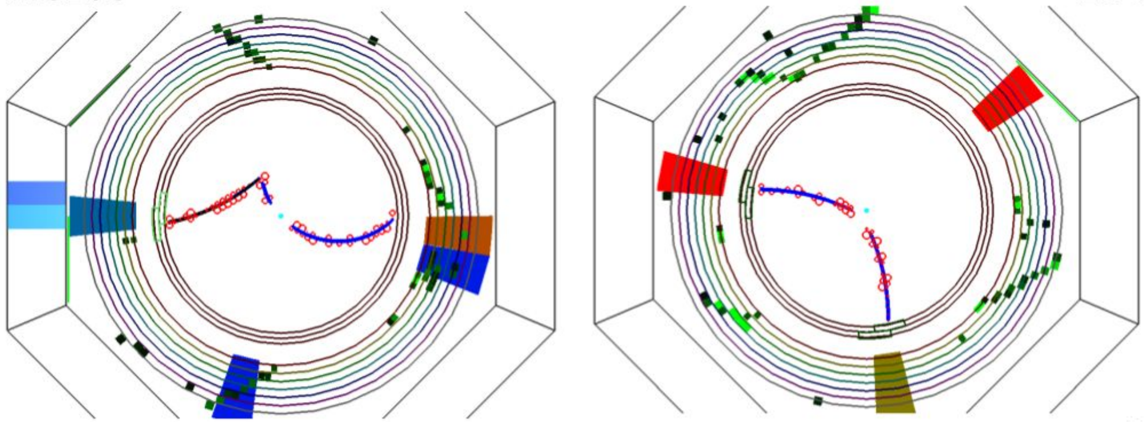
- CMD-3 can not compete with the KLOE-2's statistics, but it can provide interesting results on some problems where the systematic uncertainty is decisive

Study of the $e^+e^- \to K_SK_L, K^+K^-$ processes

$70 < p(K^{\pm}) < 190$ МэВ/с
$\sigma_p/p \sim 3\%$

$130 < p(\pi^{\pm}) < 320$ МэВ/с
$\sigma_p/p \sim 1.4\ \%$

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



$e^+e^- \to K_S^0K_L^0$

$B(\phi \to K^+K^-) = 49.3$

The visualisation of typical events

$B(\phi \to K_SK_L) = 33.6$

Motivation

According to isospin invariance of u- and d- quarks there is expectation for coupling constants relationship with electromagnetic correction

$$Z(m_\phi) = \frac{\pi\alpha/\beta}{1-e^{-\pi\alpha/\beta}}\left(1+\frac{\alpha^2}{4\beta^2}\right) = 1.046$$

- Sommerfeld-Gamow-Sakharov factor taking into account the Coulomb interaction of charged kaons in final state

Experimentally: $R = \frac{g_{\phi K^+K^-}}{g_{\phi K_SK_L}\sqrt{Z(m_\phi)}} = \sqrt{\frac{B(\phi\to K^+K^-)p^3_{K_SK_L}}{B(\phi\to K_SK_L)p^3_{K^+K^-}}\frac{1}{Z(m_\phi)}}$

- $R_{SND} = 0.92 \pm 0.03 (2.6\sigma)$
- $R_{CMD-2} = 0.943 \pm 0.013 (4.4\sigma)$
- $R_{BaBar} = 0.972 \pm 0.017 (1.5\sigma)$
- $R_{BaBar}^{\Upsilon(4S)\to B\overline{B}} = 0.84 \pm 0.04 (4\sigma)$

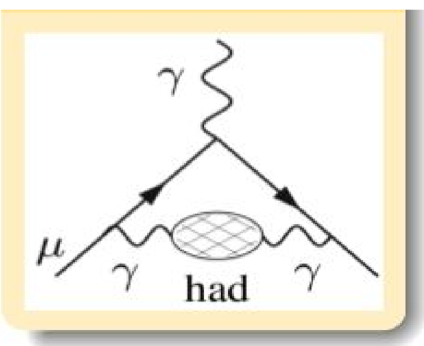
Motivation

- It is way to measure the parameters of intermediate vector resonances
- It is important for the improvement of the knowledge of hadronic vacuum polarisation

"muon g-2 puzzle" $a_\mu = \frac{g_\mu - 2}{2}$: $\bar{\mu} = g_\mu \frac{e}{2m} \bar{s}$

$$a_\mu = \frac{\alpha}{\pi} \int_0^\infty \frac{ds}{s} \frac{1}{\pi} \mathrm{Im}\Pi_\gamma^{hadr}(s) K(s)$$

$$\sigma(s)_{e^+e^- \to \gamma^* \to hadrons} = \frac{4\pi^2\alpha}{s} \frac{1}{\pi} \mathrm{Im}\Pi_\gamma^{hadr}(s)$$



$a_\mu^{theory} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$

BNL E821	11 659 208.9	±6.4
QED	11 658 471.895	±0.008
weak	15.4	±0.2
had	693.0	±4.9
BNL−SM	28.7	±8.0

a_μ units in 10^{-10}

$$a_\mu^{SM} - a_\mu^{E821} = 28.7 \pm 8.0 \times 10^{-10} (3.6\sigma)$$ [ar-v:1010.1480]

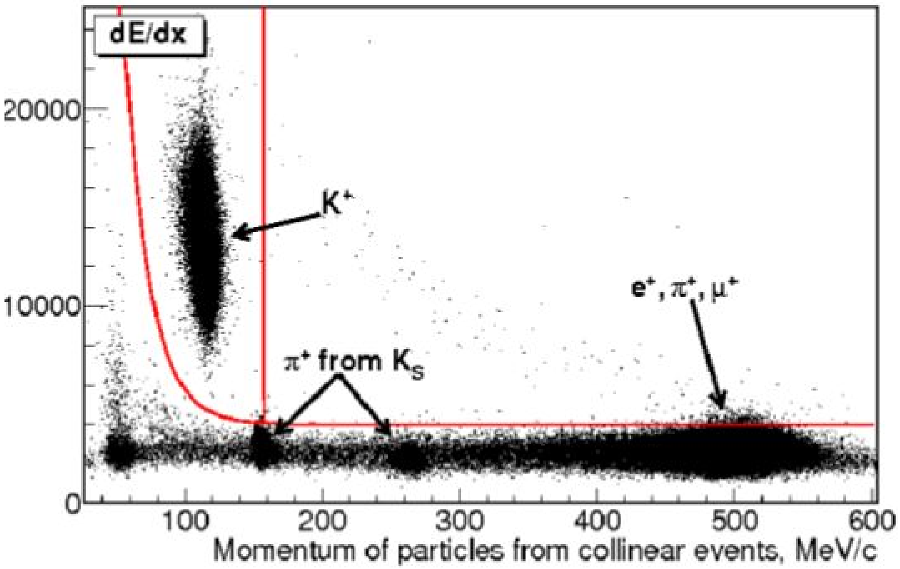
$$a_\mu^{K^+K^-,LO} = 21.63 \pm 0.73 \times 10^{-10}$$ [Eur.Phys.J.C71,1515]

$$a_\mu^{K^+K^-,LO} = 22.93 \pm 0.28 \times 10^{-10}$$ [Phys.Rev.D88 032013]

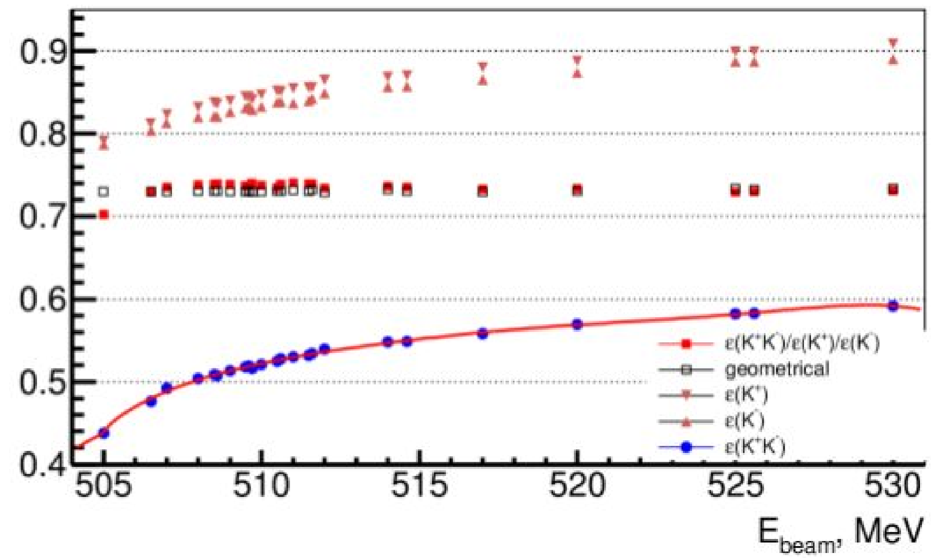
$$a_\mu^{K_SK_L,LO} = 12.96 \pm 0.39 \times 10^{-10}$$ [ar-v:1010.1480]

$K^{\pm}$ selection

We select two "good" tracks passing from the beams interaction region and which satisfy the collinearity conditions: $\Delta\varphi < 0.3$, $\Delta\theta < 0.3$ rad



The ionisation losses in DC vs momentum at energy $E_{c.m.}$ = 508 MeV. Red lines correspond to applied requirements.



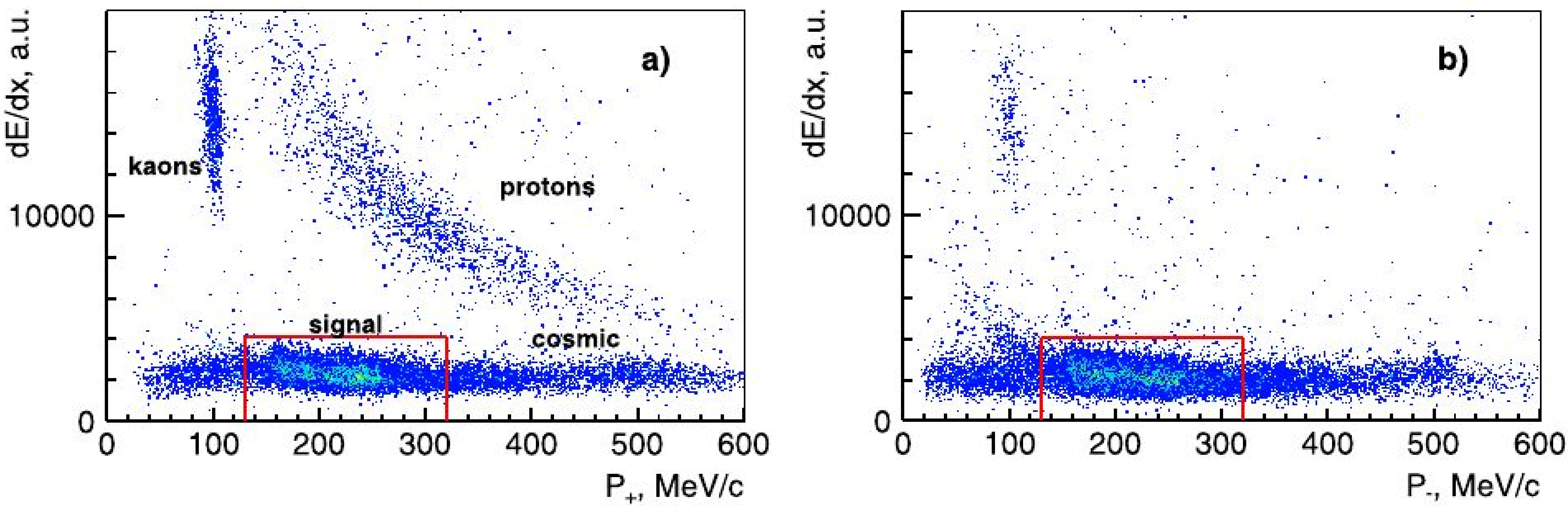
The energy dependence of detection efficiencies: for individuals tracks, geometrical, for both tracks

K_S selection

• Signal identification is based on detection of two pions from the $K^0_S \rightarrow \pi^+\pi^-$ decay

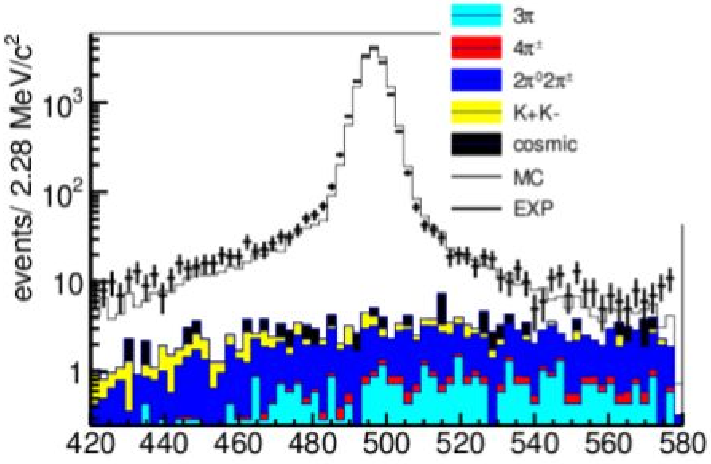
• The longitudinal distance and the transverse coordinate of the vertex should have $|Z_v|<10$ cm and $|\rho_V| < 6$ cm, respectively

• Pions from K^0_S decay are required to have polar angles $1<\theta_{\pi+,\pi-}<\pi-1$ radians

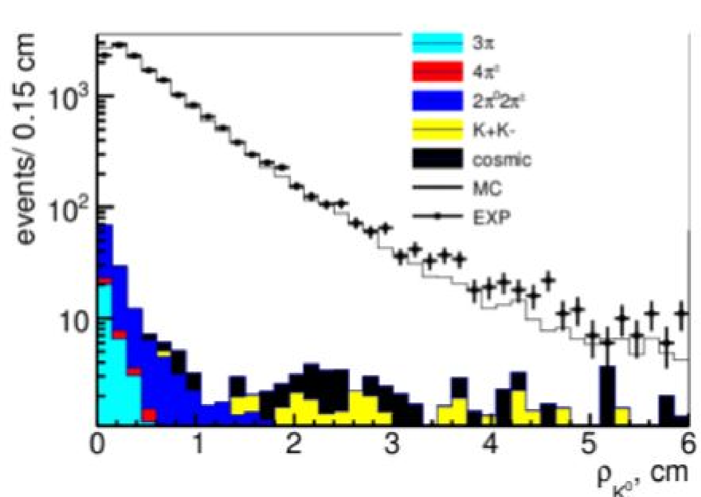


Ionization losses vs momentum for positive (a) and negative (b) tracks for data at E_{beam}=505 MeV. The lines show selections of pions from the K^0_S decay.

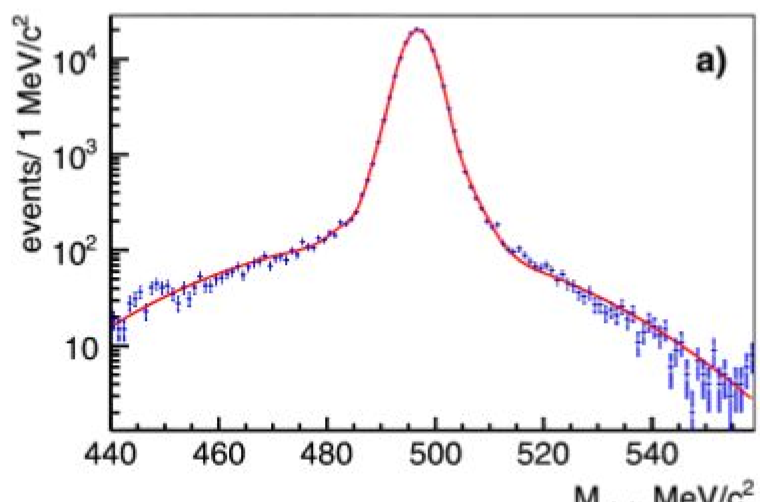
K_S selection

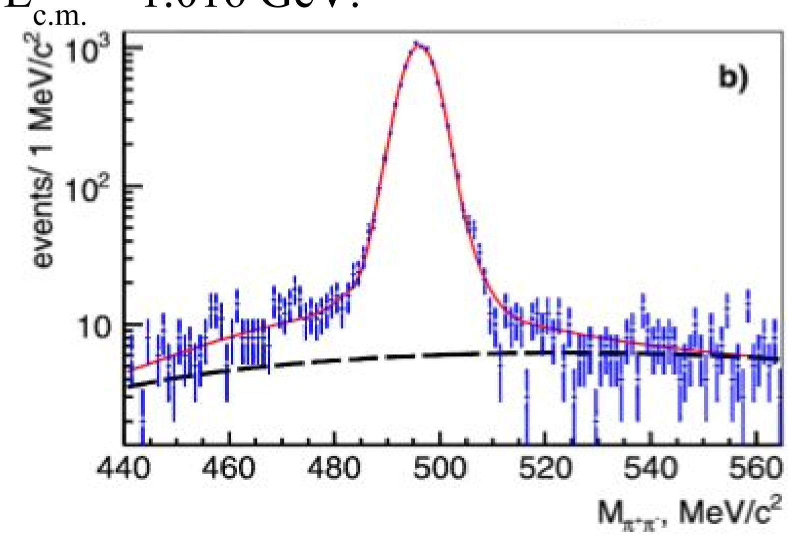


Two pion invariant mass at $E_{c.m.} = 1.016$ GeV. The main background is $e^+e^- \to 2\pi^0 2\pi^\pm$.



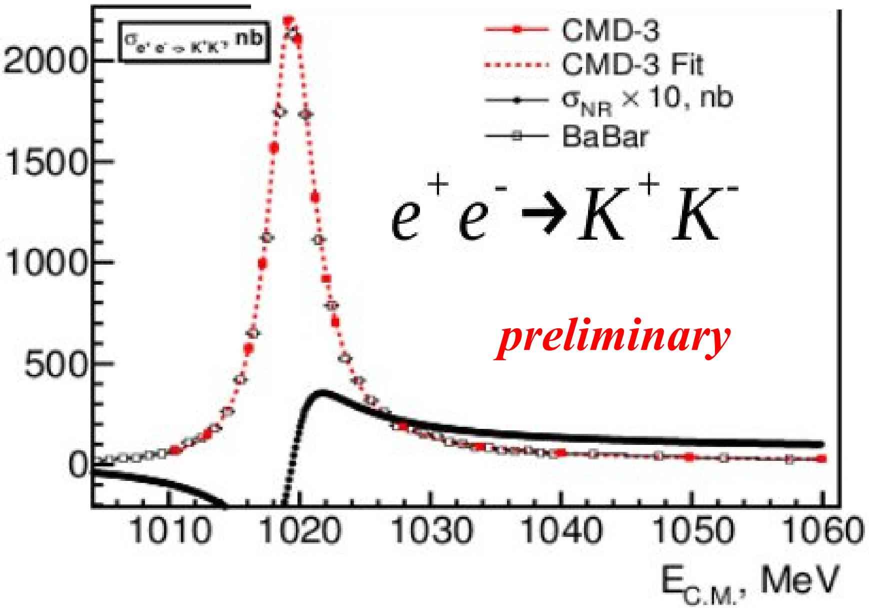
Transverse coordinate of the K^0_Svertex at $E_{c.m.} = 1.016$ GeV.

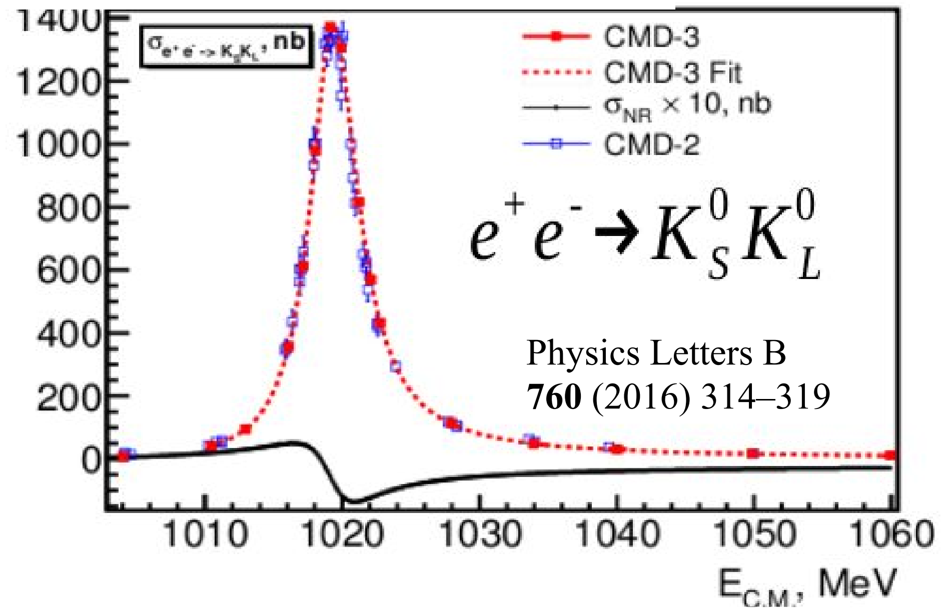




Approximation of the invariant mass of two pions at E_{beam}=505 MeV for simulation (a) and data (b). The solid line corresponds to the signal, the long-dotted line to the background. The efficiency of registration **$\varepsilon_{reg} \sim 35\%$.**

Cross sections of $e^+e^- \to K^+K^-, K_SK_L$ processes





Systematic uncertainty is estimated to be 3% in charged channel and 1.8% in neutral channel

Obtained cross sections were approximated according to Vector Dominance Model

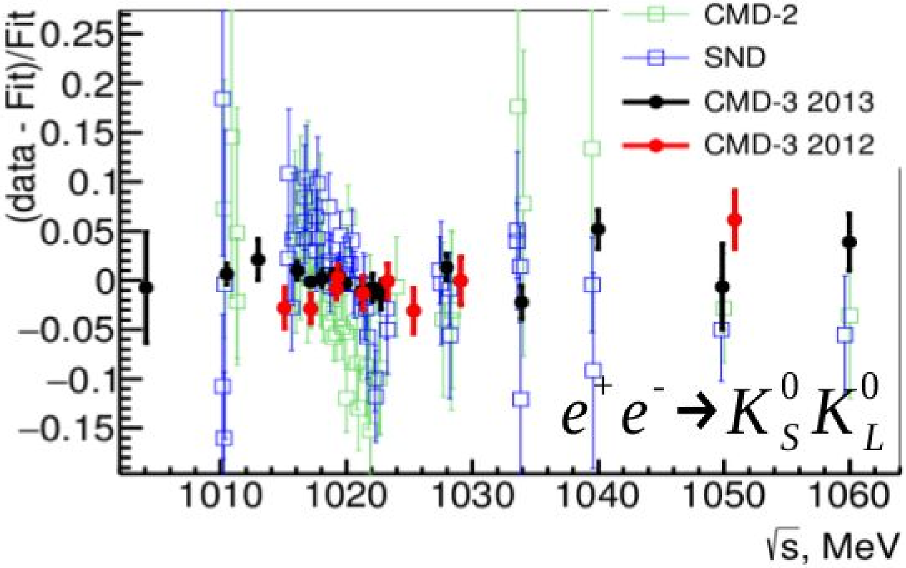
$$\sigma = \frac{8\pi\alpha}{3s^{5/2}} p^3 \left| \frac{g_{\phi\gamma} g_{\phi KK}}{D_\phi(s)} \pm^c_n A_\rho + A_\omega + A \right|^2 ; \quad g_{V\gamma} = \sqrt{\frac{3 m_V^3 \Gamma_V B_{Vee}}{4\pi\alpha}} ; \quad g_{VKK} = \sqrt{\frac{6\pi m_V^2 \Gamma_V B_{VKK}}{p_K^3(m_V)}}$$

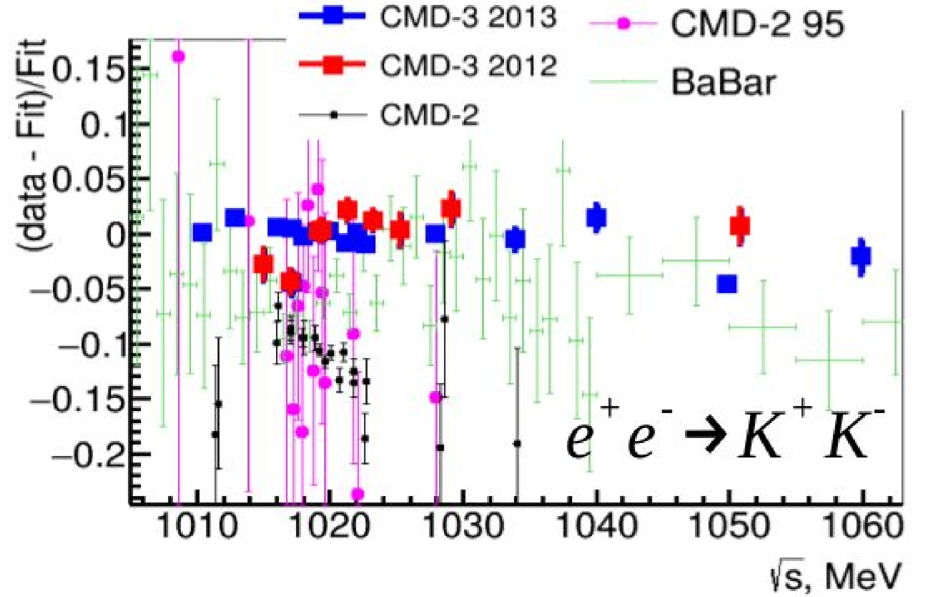
$$\sigma_{e^+e^- \to K\overline{K}} \equiv \sigma_\phi + \sigma_{NR}$$

The contribution from ρ and ω is fixed from quark model and SU(3) symmetry of u-,d-,s- quarks as follows:

$$g_{\phi K_S K_L} : g_{\omega K_S K_L} : g_{\rho K_S K_L} = -1 : 1/\sqrt{2} : -1/\sqrt{2} \qquad g_{\phi K^+K^-} : g_{\omega K^+K^-} : g_{\rho K^+K^-} = -1 : 1/\sqrt{2} : 1/\sqrt{2}$$

Fit results





Relative difference between the data and fit. Comparison with other experimental data is shown. Only statistical uncertainties are shown.

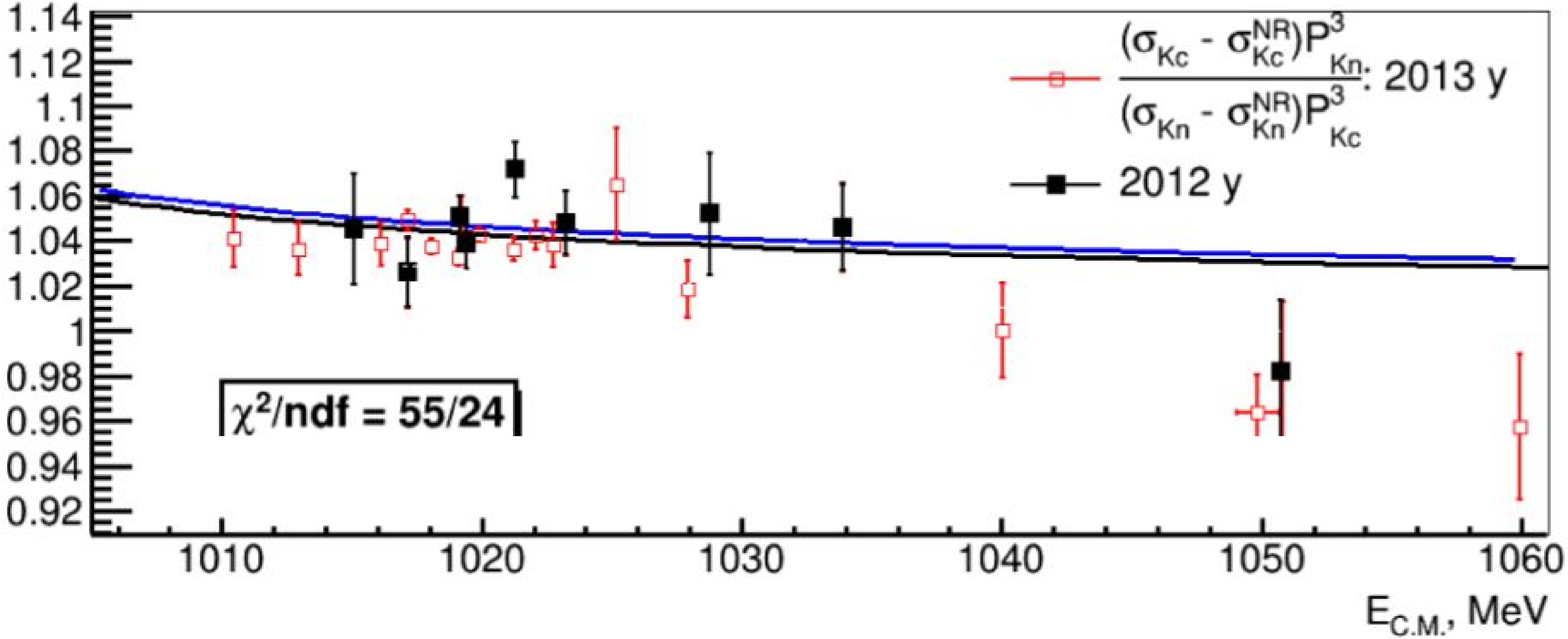
	CMD-3	PDG
m_ϕ, MeV	$1019.468 \pm 0.005 \pm 0.060 \pm 0.020$	1019.461 ± 0.019
Γ_ϕ, MeV	$4.254 \pm 0.009 \pm 0.016 \pm 0.012$	4.266 ± 0.031
$B_{\phi\to ee}B_{\phi\to K_S^0K_L^0} \times 10^{-5}$	$10.06 \pm 0.03 \pm 0.22 \pm 0.02$	10.10 ± 0.13
$B_{\phi\to ee}B_{\phi\to K^+K^-} \times 10^{-5}$	$15.83 \pm 0.04 \pm 0.47 \pm 0.10$	14.46 ± 0.23
$\Gamma_{\phi\to ee}B_{\phi\to K^+K^-} \times 10^{-1}$, keV	$6.735 \pm 0.014 \pm 0.199 \pm 0.042$	6.340 ± 0.08

The results of the approximation procedure in comparison with previous experiments. Uncertainties dominate by systematic errors - still working on improvements

Fit results

We obtain the ratio of coupling constants with ϕ-meson consistent with isospin symmetry:

$$R = \frac{g_{\phi K^+K^-}}{g_{\phi K_S K_L}\sqrt{Z(m_\phi)}} = \frac{R_{c/n}}{R_{phase\ space} \cdot R_{coulomb}} = 0.984 \pm 0.029$$

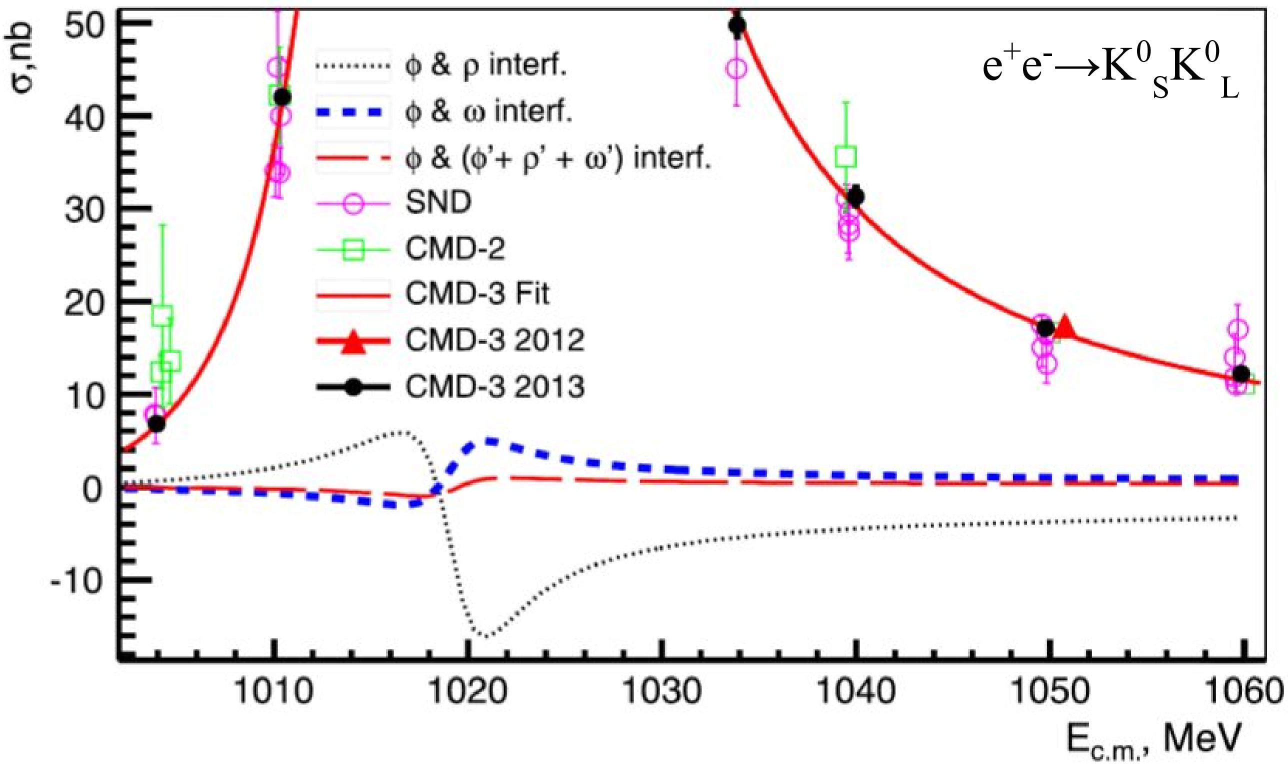


Fit results

In previous approximation the contribution from ρ and ω is fixed from quark model and SU(3) symmetry of u,d,s quarks as follows:

$$g_{\phi K_S K_L} : g_{\omega K_S K_L} : g_{\rho K_S K_L} = -1 : 1/\sqrt{2} : -1/\sqrt{2} \quad g_{\phi K^+K^-} : g_{\omega K^+K^-} : g_{\rho K^+K^-} = -1 : 1/\sqrt{2} : 1/\sqrt{2}$$

This statement is needed to be checked. We multiply ρ and ω coupling constants to float parameter ($r_{\rho/\omega}$*$g_{\rho/\omega KK}$), as a result we obtain: **$r_{\rho/\omega}$= 0.76±0.11**

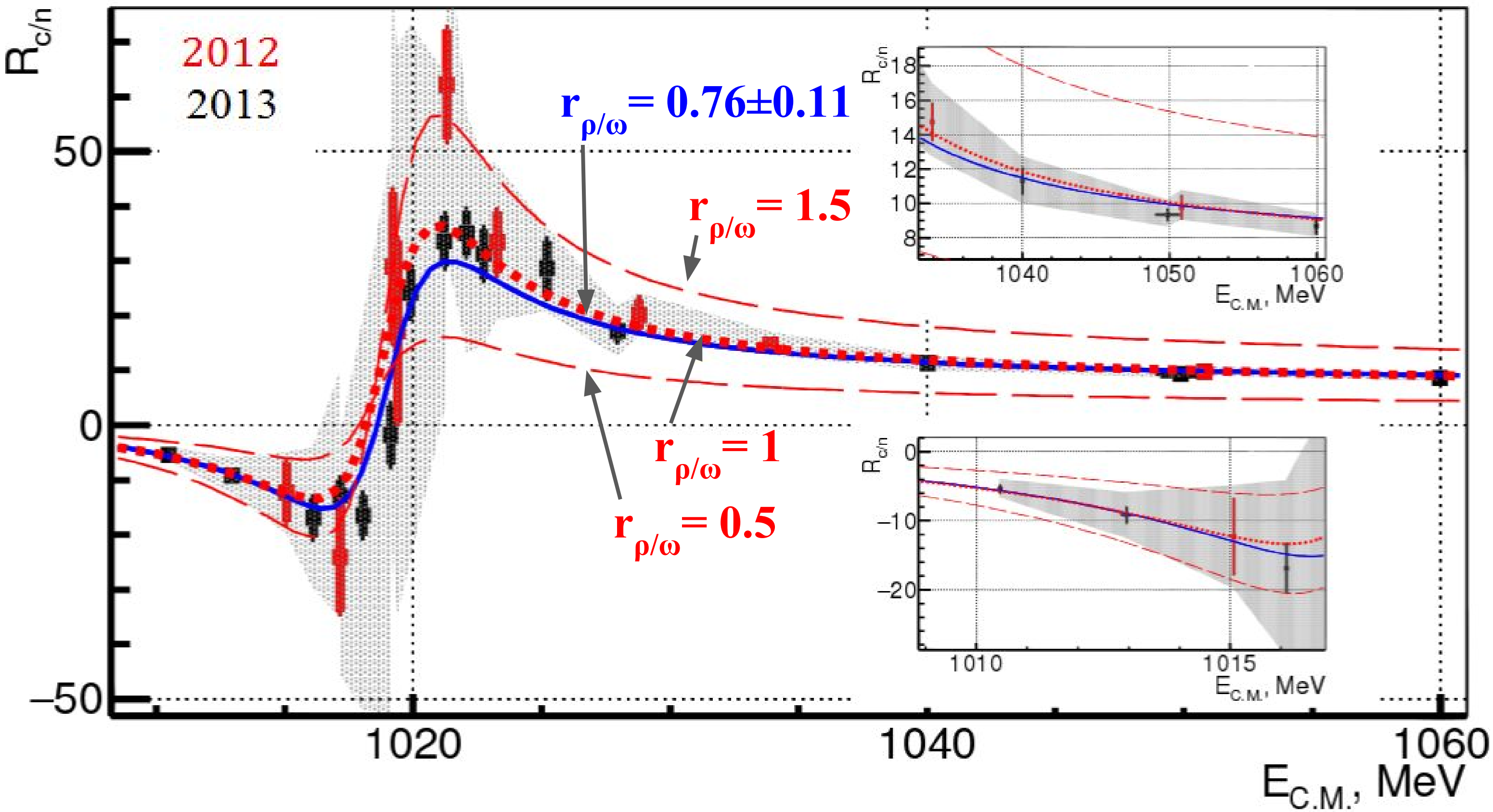


Contribution of lower- and higher-mass resonances to the fit of the $e^+e^-\rightarrow K^0_S K^0_L$ cross section in the studied energy range.

Fit results

The difference of charged and neutral cross sections at ϕ region (corrected for the phase space and coulomb effects) gives model independent contribution of isovector amplitude (interference term) to ϕ resonance signal

$$R_{c/n} = \sigma_{e^+e^- \to K^+K^-} \times \frac{p^3_{K^0}(s)}{p^3_{K^\pm}(s)} \times \frac{1}{Z(s)} - \sigma_{e^+e^- \to K^0_S K^0_L}.$$

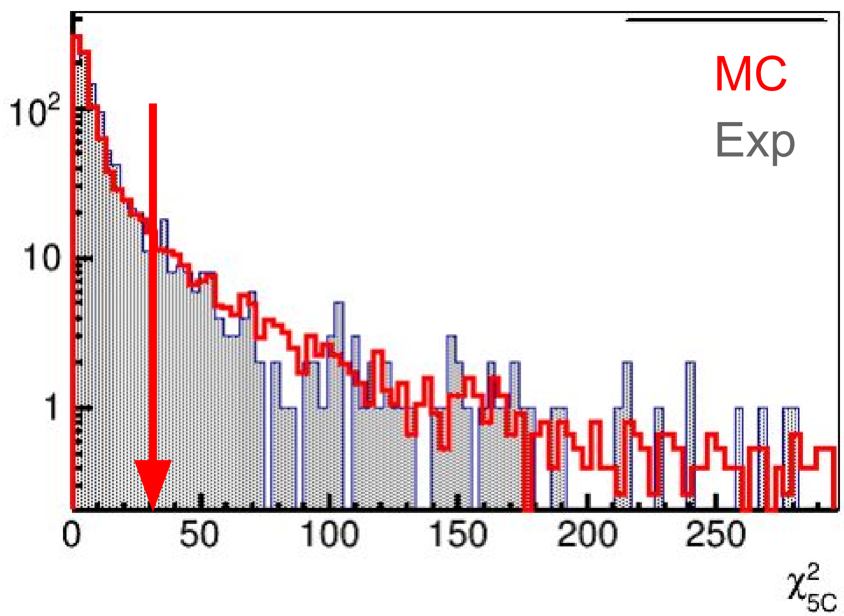


Shaded area corresponds to systematic uncertainties in data, solid line - to fit of data, short dotted line - to theoretical prediction with $A_{\phi',\rho',\omega'} = 0$, $g_{V\to K^+K^-}/g_{V\to K^0_S K^0_L} = 1$ and $r_{\rho/\omega} = 1$ while long dotted lines - to the same theoretical prediction with $r_{\rho/\omega} = 0.5$ (1.5).

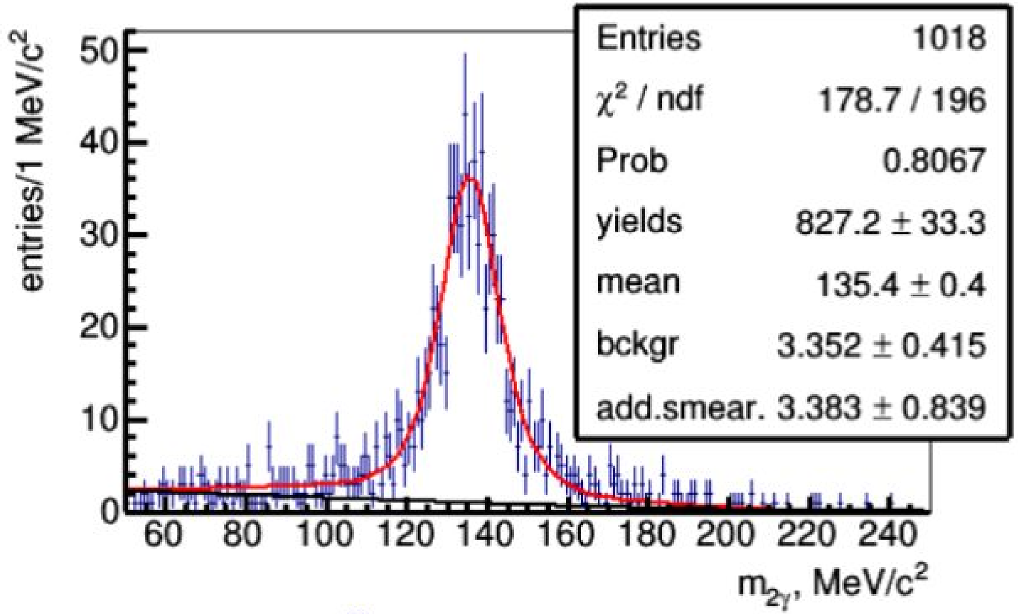
Study of $e^+e^- \to \pi^+\pi^-2\pi^0$ process

All combinations of 4 photons and 2 tracks were involved into 5C kinematic fit with the following constraints:

1. energy-momentum conservation
2. the invariant mass of one photon pair is fixed at π^0 mass

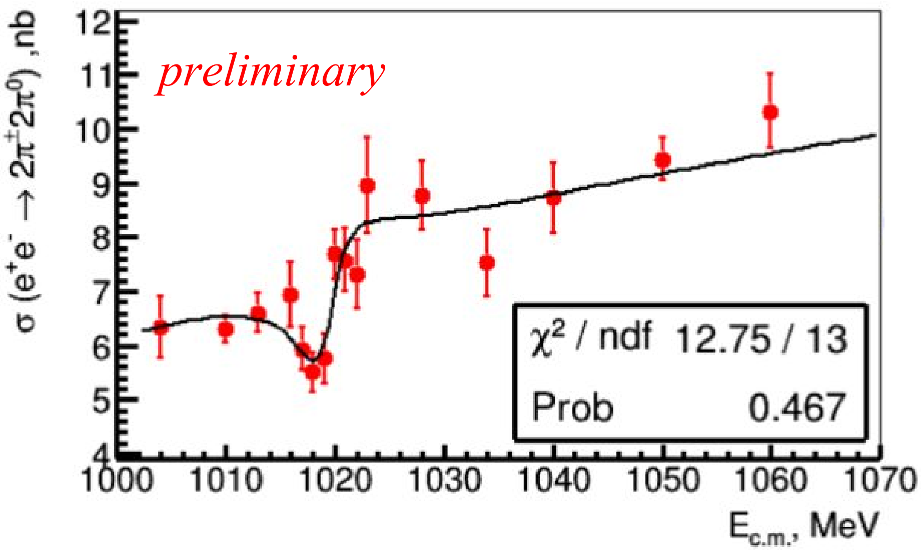


The comparison of χ^2_{5C} distributions for data (filled) and simulated (open) events at $E_{c.m.}$ = 1.01 GeV. The events with $\chi^2_{5C} < 30$ were used for signal calculation. As a result $\boldsymbol{\varepsilon_{reg}} \sim$ **15%.**



The approximation of $m_{\gamma\gamma(3\text{-}4)}$ distribution at $E_{c.m.}$ = 1.01 GeV. The background and signal shapes was extracted from simulation with additional smearing.

Cross section of $e^+e^- \to \pi^+\pi^- 2\pi^0$



The obtained cross section as a function of $E_{c.m.}$

$$\sigma(E_{c.m.}) = \sigma_0 \cdot f(E_{c.m.}) \cdot \left| 1 - Z \cdot \frac{m_\phi \Gamma_\phi}{m_\phi^2 - E_{c.m.}^2 - iE_{c.m.}\Gamma_\phi} \right|^2$$

$$f(E_{c.m.}) = e^{A(E_{c.m.} - m_\phi)}$$

$$\boldsymbol{\sigma_0(m_\varphi) = 7.54 \pm 0.15\ \mathrm{nb}}$$

$$\boldsymbol{\mathrm{Re}\, Z = 0.136 \pm 0.025}$$

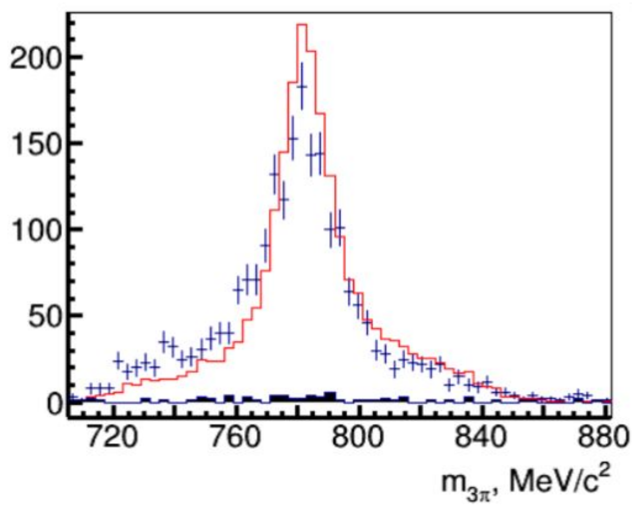
$$\boldsymbol{\mathrm{Im}\, Z = -\,0.084 \pm 0.023}$$

$$B(\varphi \to 4\pi) = \frac{\sigma_0(m_\varphi)|Z|^2}{\sigma_\varphi}$$

$$\sigma_\varphi = 12\pi B(\varphi \to ee)/m_\varphi^2$$

$$\boldsymbol{B(\varphi \to 2\pi^\pm 2\pi^0) = (5.3 \pm 1.6 \pm 0.8) \cdot 10^{-5}}$$

$$B(\varphi \to \omega\pi) = (4.7 \pm 0.5) \cdot 10^{-5} \quad \text{(PDG)}$$



The comparison of $m_{3\pi}$ distributions for data (points) and simulated (histogram) events.

Besides dominant amplitude $e^+e^- \to \omega\pi^0 \to 2\pi^\pm 2\pi^0$ there is $e^+e^- \to a1\pi \to 2\pi^\pm 2\pi^0$. The relative amplitude and phase of these mechanisms can be precisely obtained with KLOE-2 via the PWA

Study of $e^+e^- \to 2\pi^+2\pi^-$ process

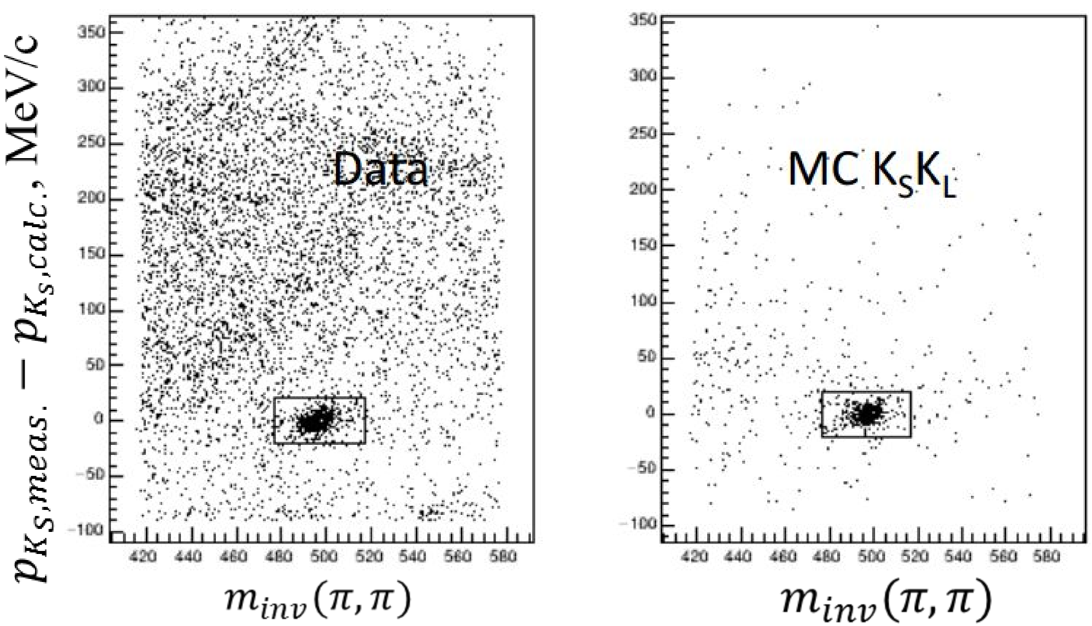
- Energy range $\sqrt{s} \in (0.92\ \mathrm{GeV}; 1.06\ \mathrm{GeV})$
- 22 energy points with $L_{int} = 9.8\ pb^{-1}$

Events selection

- 3 or 4 «good tracks» in the event, passing from the beams interaction region and having dE/dx typical for pions
- Backgrounds:

1) $e^+e^- \to \phi$
   - $\pi^+\pi^-\pi^0$ (suppressed by $m_{recoil}(\pi_i,\pi_j) > 2m_\pi$)
   - K^+K^- (suppressed by cuts on dE/dx)
   - K_SK_L (suppressed by cuts on $p_{K_S,measured}$ and $m_{inv}(\pi,\pi)$)

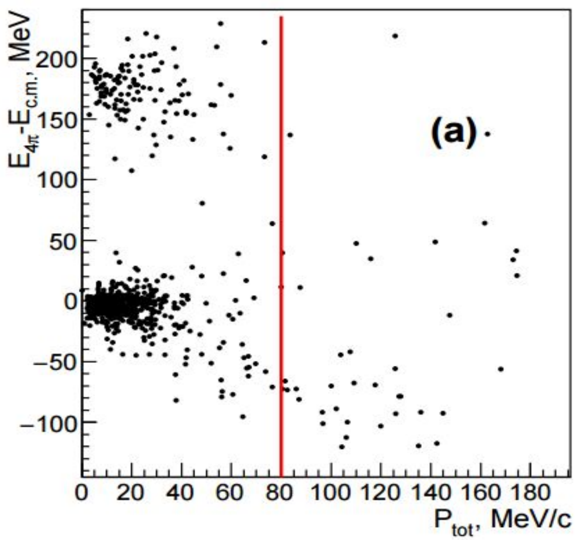
2) $e^+e^- \to 2e^+2e^-$



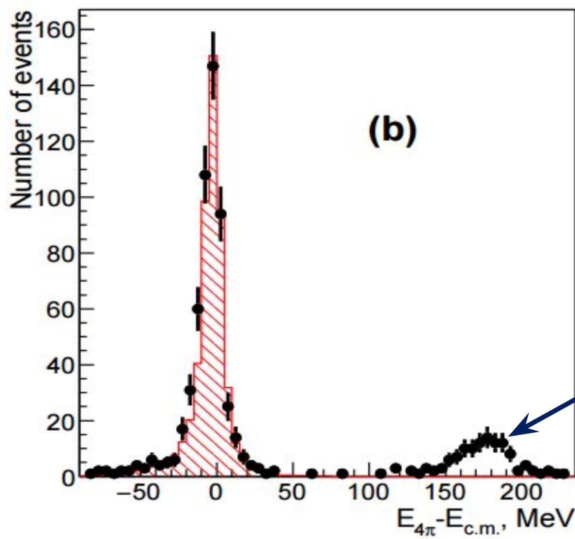
Selected events and signal/background separation

$N_{tracks} = 4$: 3690 ± 61 signal events

$E_{beam} = 958$ MeV



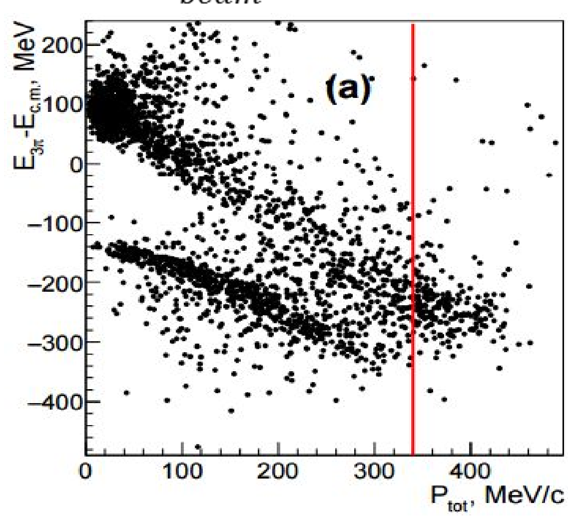
$E_{beam} = 958$ MeV



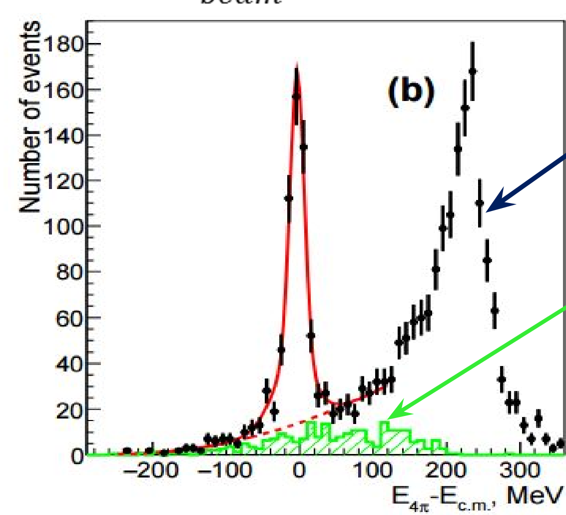
$e^+e^- \to 2e^+2e^-$

$N_{tracks} = 3$: 3108 ± 69 signal events

$E_{beam} = 958$ MeV



$E_{beam} = 958$ MeV



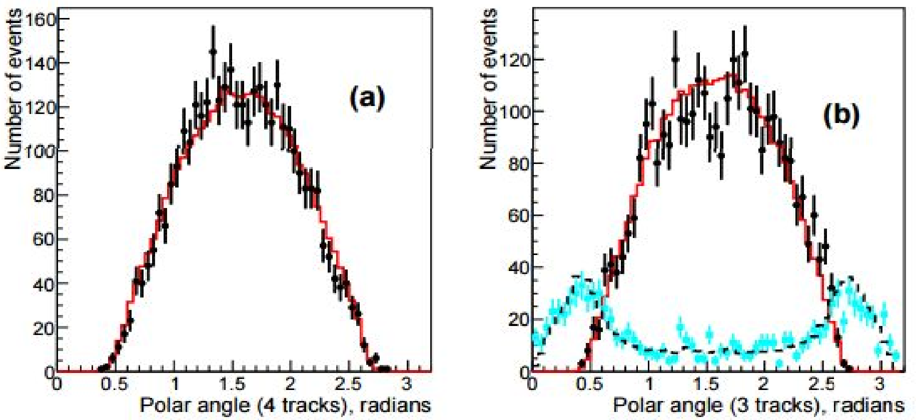
$e^+e^- \to 2e^+2e^-$

MC: $e^+e^- \to 3\pi$

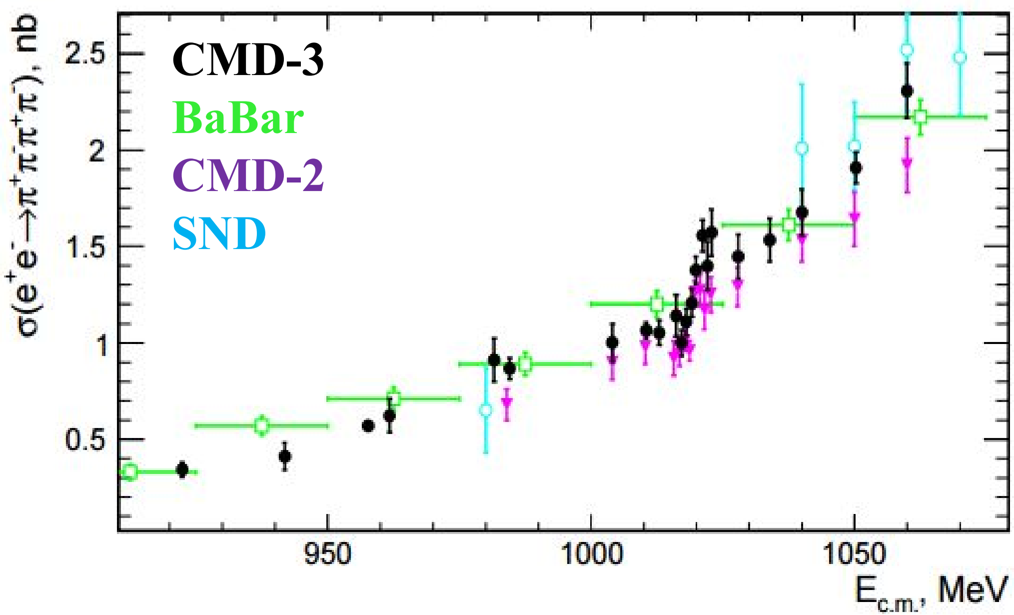
Detection efficiency

- $a_1(1260)^{\pm}\pi^{\mp}$ is known to dominate this process
- Very small difference in any distribution between $a_1(1260)^{\pm}\pi^{\mp}$ and $\rho f_0(600)$ or phase space

$N_{tracks} = 4$ $N_{tracks} = 3$



Cross section of $e^+e^- \to 2\pi^+2\pi^-$



Systematic uncertainties

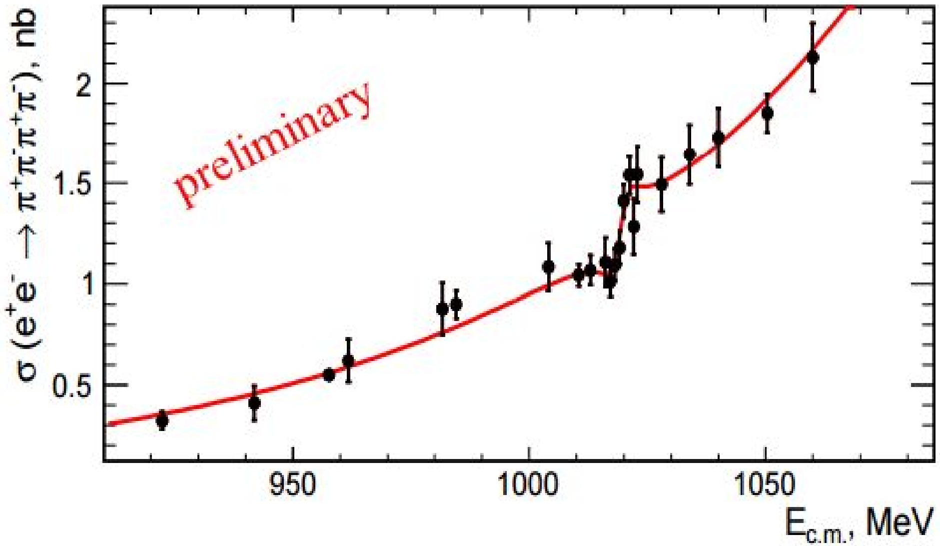
- Model dependence (~1%) is reduced by using N_{tracks} =3 events
- Luminosity uncertainty ~1%
- Uncertainty of ~3% in background subtraction in N_{tracks} =3 class
- Radiative correction uncertainty ~1%
- Overall systematic uncertainty ~3.6%

$e^+e^- \to 2\pi^+2\pi^-$ cross section interpretation

- Interference of nonresonant amplitude with $\phi \to 2\pi^+2\pi^-$ is evident

$$\sigma(\mathrm{E_{c.m.}}) = \sigma_0 \cdot \mathrm{f(E_{c.m.})} \cdot \left|1 - \mathrm{Z} \cdot \frac{\mathrm{m_\phi \Gamma_\phi}}{\mathrm{m_\phi^2 - E_{c.m.}^2 - iE_{c.m.}\Gamma_\phi}}\right|^2$$

$$\mathrm{f(E_{c.m.})} = e^{A(\mathrm{E_{c.m.} - m_\phi})}$$



Fit results

$$\sigma_0 = 1.263 \pm 0.027 \text{ nb},$$
$$\mathrm{Re\ Z} = 0.146 \pm 0.030,$$
$$\mathrm{Im\ Z} = -0.002 \pm 0.024$$

$$\sigma_\phi = 12\pi\mathcal{B}(\phi \to e^+e^-)/m_\phi^2 = 4172 \pm 42 \text{ nb}$$

$$\mathcal{B}(\phi \to \pi^+\pi^-\pi^+\pi^-) = \sigma_0 \cdot |\mathrm{Z}|^2/\sigma_\phi = (6.5 \pm 2.7 \pm 1.6) \times 10^{-6}$$

- Previous CMD-2 measurement: $\mathcal{B}(\phi \to \pi^+\pi^-\pi^+\pi^-) = (4.0^{+2.8}_{-2.2}) \times 10^{-6}$
- This result doesn't contradict the estimation according to vacuum polarization (which assumes Im Z = 0):

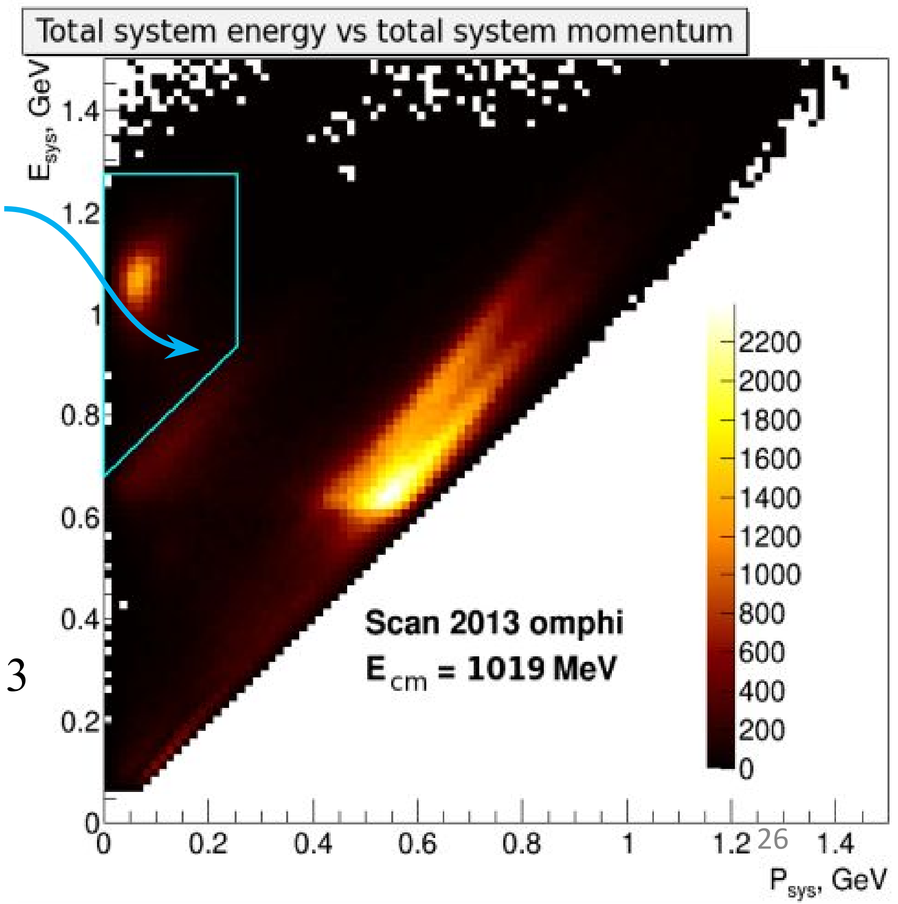
$$\mathcal{B}(\phi \to \gamma^* \to 4\pi) = 9 \cdot \mathcal{B}(\phi \to e^+e^-)^2/\alpha^2 \cdot \sigma_0/\sigma_\phi = 4.8 \times 10^{-6}$$

Study of $e^+e^- \to \eta\gamma$ process

- Energy range $\sqrt{s} \in (1.0\ \text{GeV}; 1.03\ \text{GeV})$
- 12 energy points with $L_{int} = 5.5\ pb^{-1}$
- Process is studied in $\eta \to 2\gamma$ mode

Events selection

- No charged tracks
- At least 3 photons with $\theta_\gamma \in (0.42; \pi - 0.42)$
- Some kinematic requirements on the total energy and momentum of the system of 3 photons
- Backgrounds: $e^+e^- \to \pi^0\gamma$, 3γ (QED)

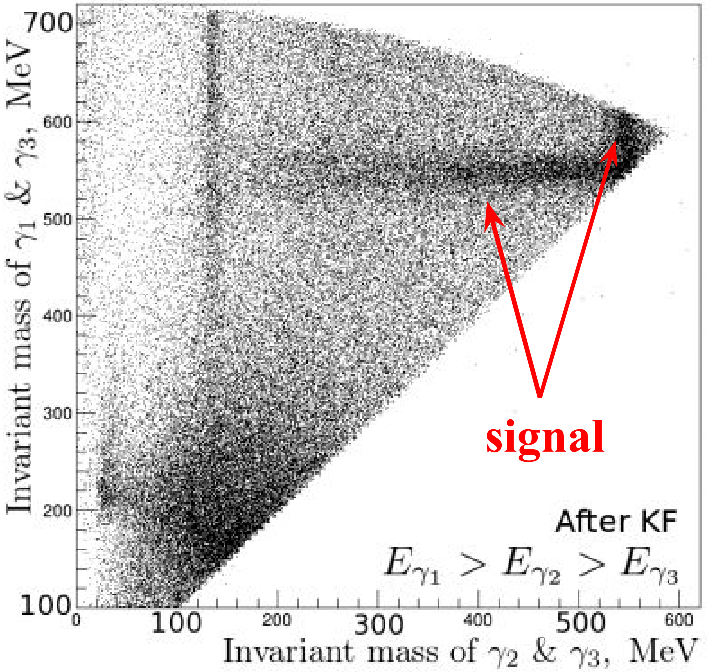


Kinematic fit

- Energy-momentum conservation required
- Common vertex as a variated parameter for 3 photons is assumed

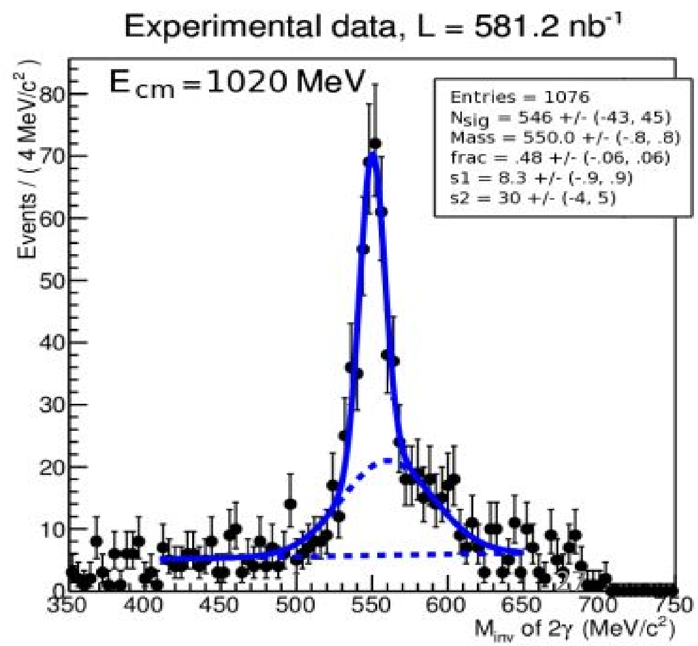
Selected events

- 3 selected photons are arranged on their energy: $E_{\gamma 1} > E_{\gamma 2} > E_{\gamma 3}$
- In the majority of cases, in the $\phi(1020)$ energy region, the monochromatic photon in $\eta\gamma \to 3\gamma$ has a medium energy $E_{\gamma 2}$



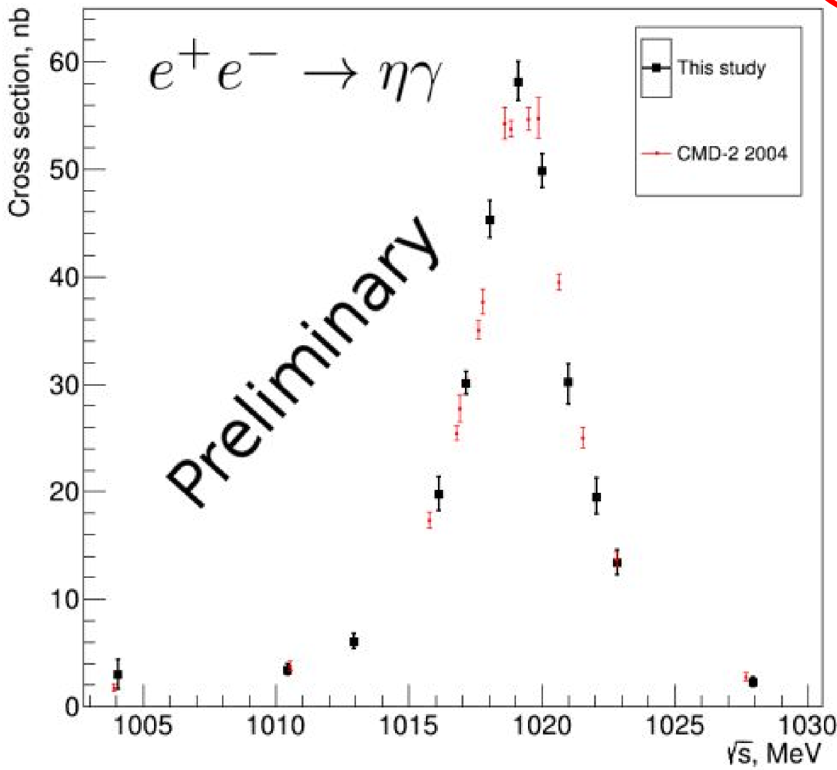
Signal/background separation

- Signal/background separation is performed using $M_{inv}(\gamma_1, \gamma_3)$ distribution
- The form of signal (resonance in $M_{inv}(\gamma, \gamma)$ distribution) if fixed from MC
- The background shape is determined using the simultaneous fit of the data and MC for background

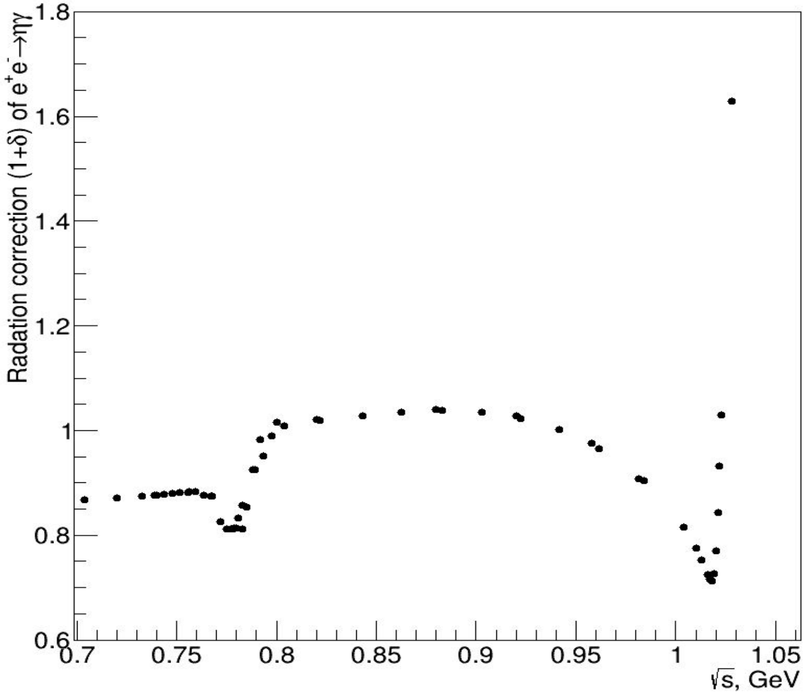


Cross section of $e^+e^- \to \eta\gamma$

$$\sigma_{Born}\left(e^+e^- \to P\gamma\right) = \frac{N}{L \cdot \varepsilon_{NT} \cdot \varepsilon_{det} \cdot (1+\delta_{rad})}\left(\frac{\varepsilon_\gamma^{sim}}{\varepsilon_\gamma^{exp}}\right)^3$$



Photon detection efficiency $\varepsilon(E_\gamma, \theta_\gamma)$ is now being studied in the experiment using $\phi \to \pi^+\pi^-\pi^0$ process



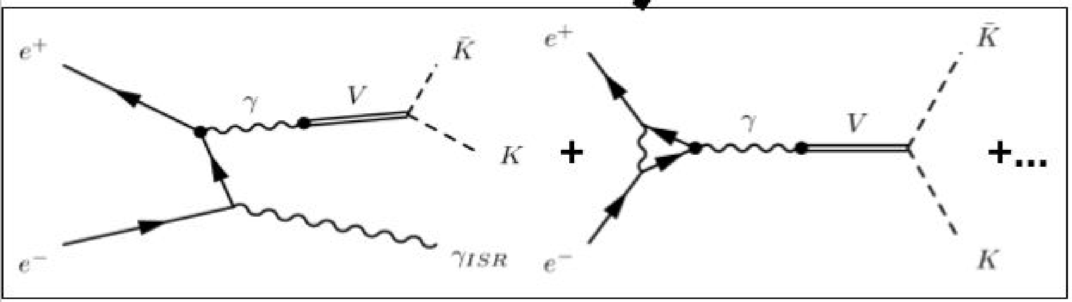
Conclusion

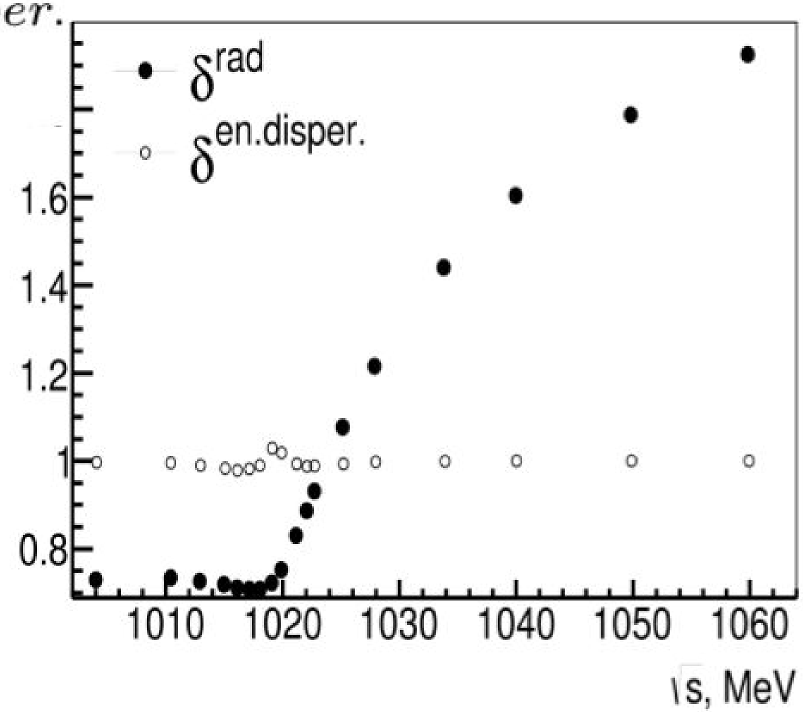
- The ϕ-meson region is mostly interesting for CMD-3 from the point of view of studying of detector responses
- Although the integrated luminosity of CMD-3 in this region cannot compete with that of KLOE-2, CMD-3, owing to the possibility of energy scan in wide range and precise beam energy measurement, can provide interesting results for the tasks in which systematic error is decisive
- The current results of the study of the processes $e^+e^- \to K\bar{K}, 4\pi, \eta\gamma$ in ϕ-meson region were presented. The preliminary results do not confirm the existence of $g_{\phi K^+K^-}/g_{\phi K_S K_L}$ puzzle. The branching $B(\phi \to 2\pi^+ 2\pi^-)$ was measured, the result agrees with previous CMD-2 measurement. The possibility of the extraction of relative amplitude and phase of $a_1(1260)\pi$ mechanism in $e^+e^- \to \pi^+\pi^- 2\pi^0$ process via the PWA analysis was discussed

backup slides

$$\sigma^{born} = \frac{N^{exp}}{\epsilon_{reg}\epsilon_{trig}L(1+\delta_{rad})}\delta^{en.disper.}$$

$ee \rightarrow ee\,,\, ee \rightarrow \gamma\gamma$





systematic uncertainty ~2% in both channel

source	systematic error, %
signal idenfication	1.5
efficiency of registration	0.7
radiative correction	0.5
energy dispersion correction	0.3
trigger efficiency	0.1
luminosity	1.5
total	2.4