

## CMD-3 and SND Results at VEPP-2000

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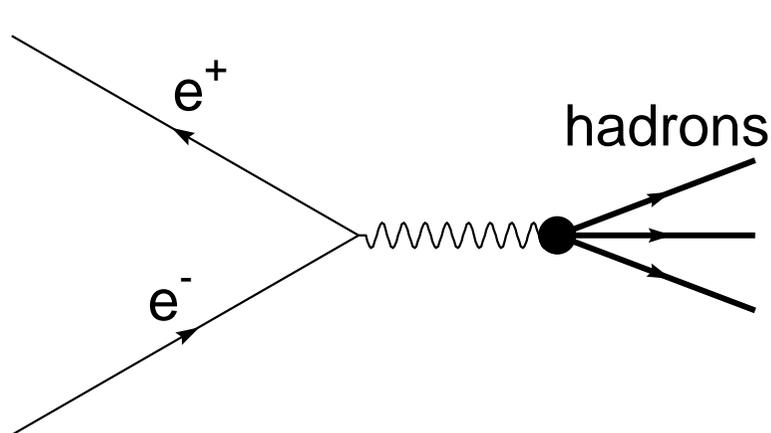
### Outline

1. General
2. VEPP-2000
3. Results from CMD-3 and SND
4. Conclusions

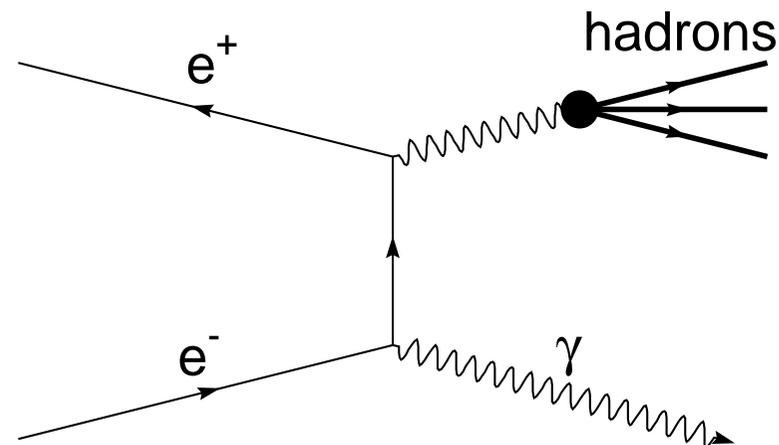
## What Can We Learn from Low Energy $e^+e^-$ Cross Sections?

1. Detailed study of exclusive processes  $e^+e^- \rightarrow (2 - 7)h, h = \pi, K, \eta, p, \dots$ 
  - Test of models and input to theory (ChPT, Vector Dominance, QCD, ...)
  - Properties of vector mesons ( $\rho', \omega', \phi', \dots$ )
  - Search for exotic states (tetraquarks, hybrids, glueballs)
  - Test of CVC relations between  $e^+e^-$  and  $\tau$ -lepton
  - Interactions of light ( $u, d, s$ ) quarks
2. High precision determination of  $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$  at low energies and fundamental quantities
  - $(g_\mu - 2)/2$
  - $\alpha(M_Z^2)$
  - QCD sum rules ( $\alpha_s$ , quark and gluon condensates)

## Scan and ISR



Scan

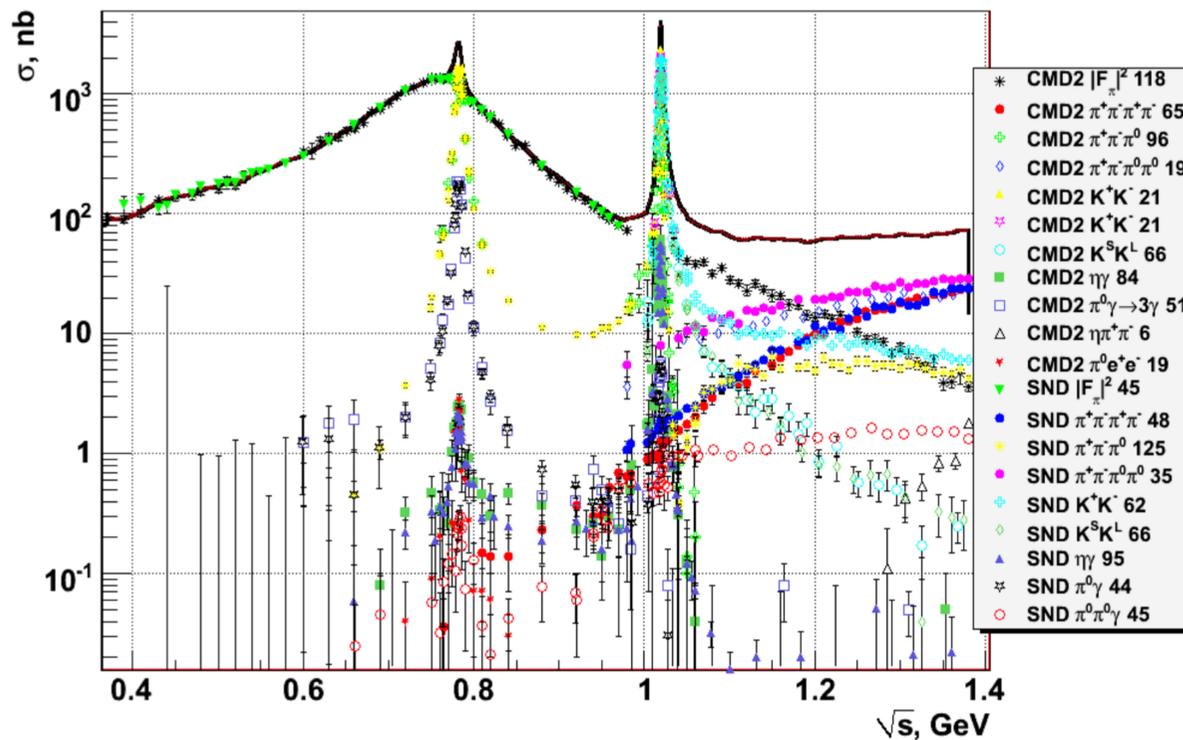


ISR

Scan can provide larger data samples, covers all final states,  
VEPP-2000 and VEPP-4M can perform scans with a small  $\sqrt{s}$  step

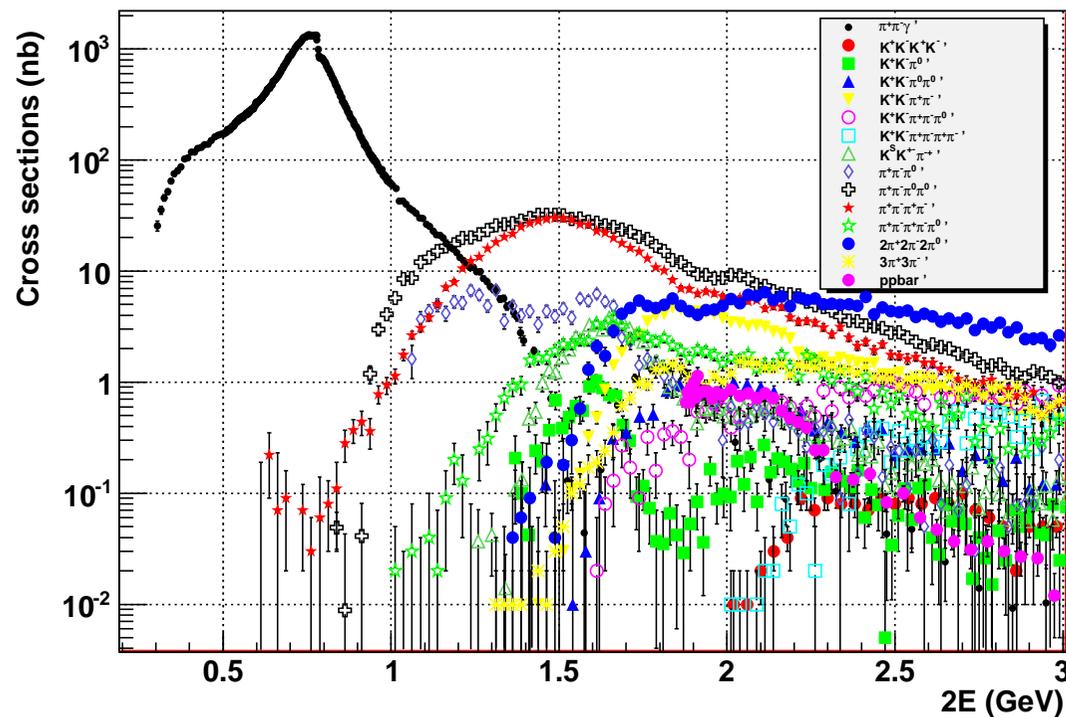
ISR benefits from the same systematics and flat acceptance,  
may suffer from more complicated radiative effects, all neutrals hardly possible

## Current Status of Exclusive Measurements – I



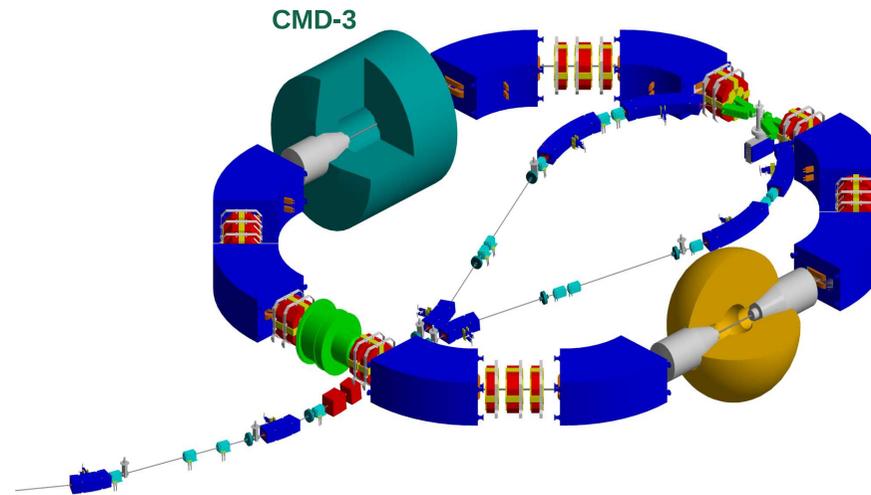
Impressive achievements of CMD-2, SND (scan at  $\sqrt{s} < 1.4$  GeV)  
and KLOE (ISR at  $\sqrt{s} < 1.0$  GeV)

## Current Status of Exclusive Measurements – II



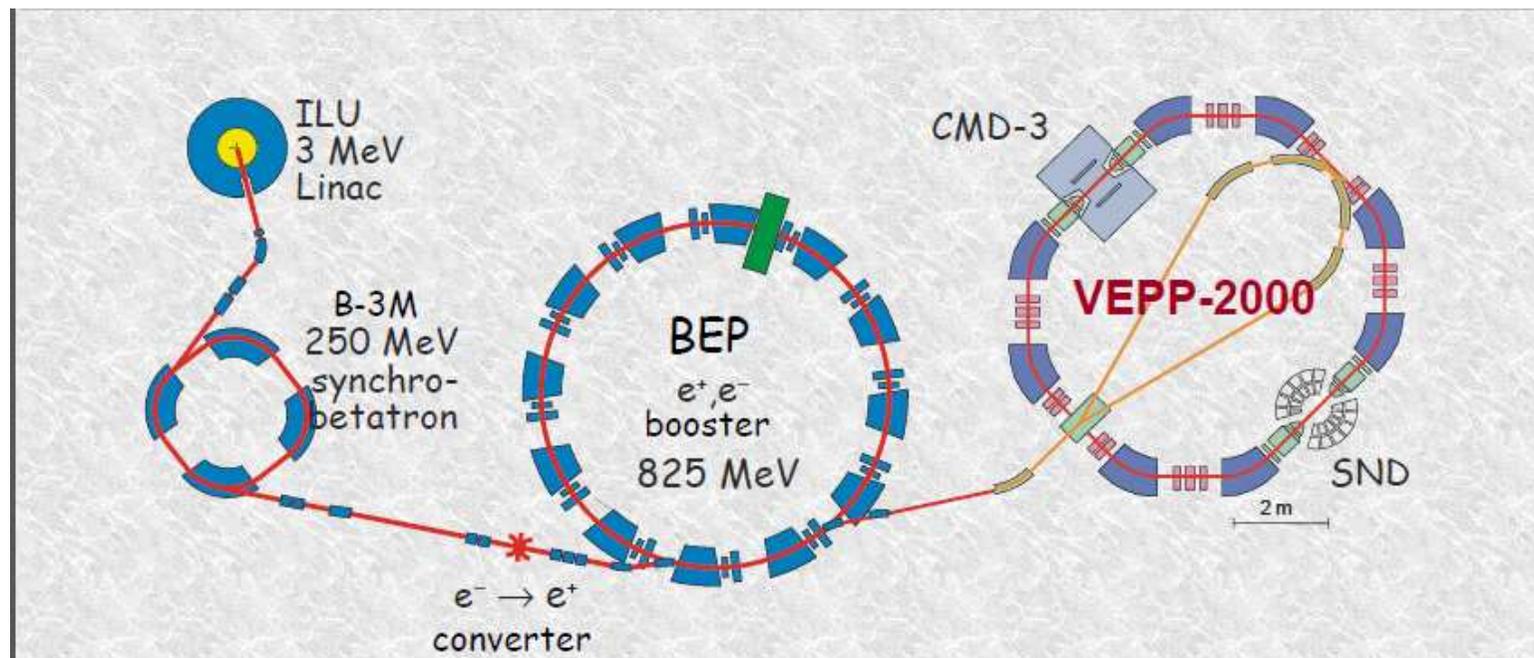
BaBar used ISR to study the energy range  $\sqrt{s} < 3.0$  GeV,  
 Belle and BESIII may contribute as well to ISR measurements

## VEPP-2000 – I



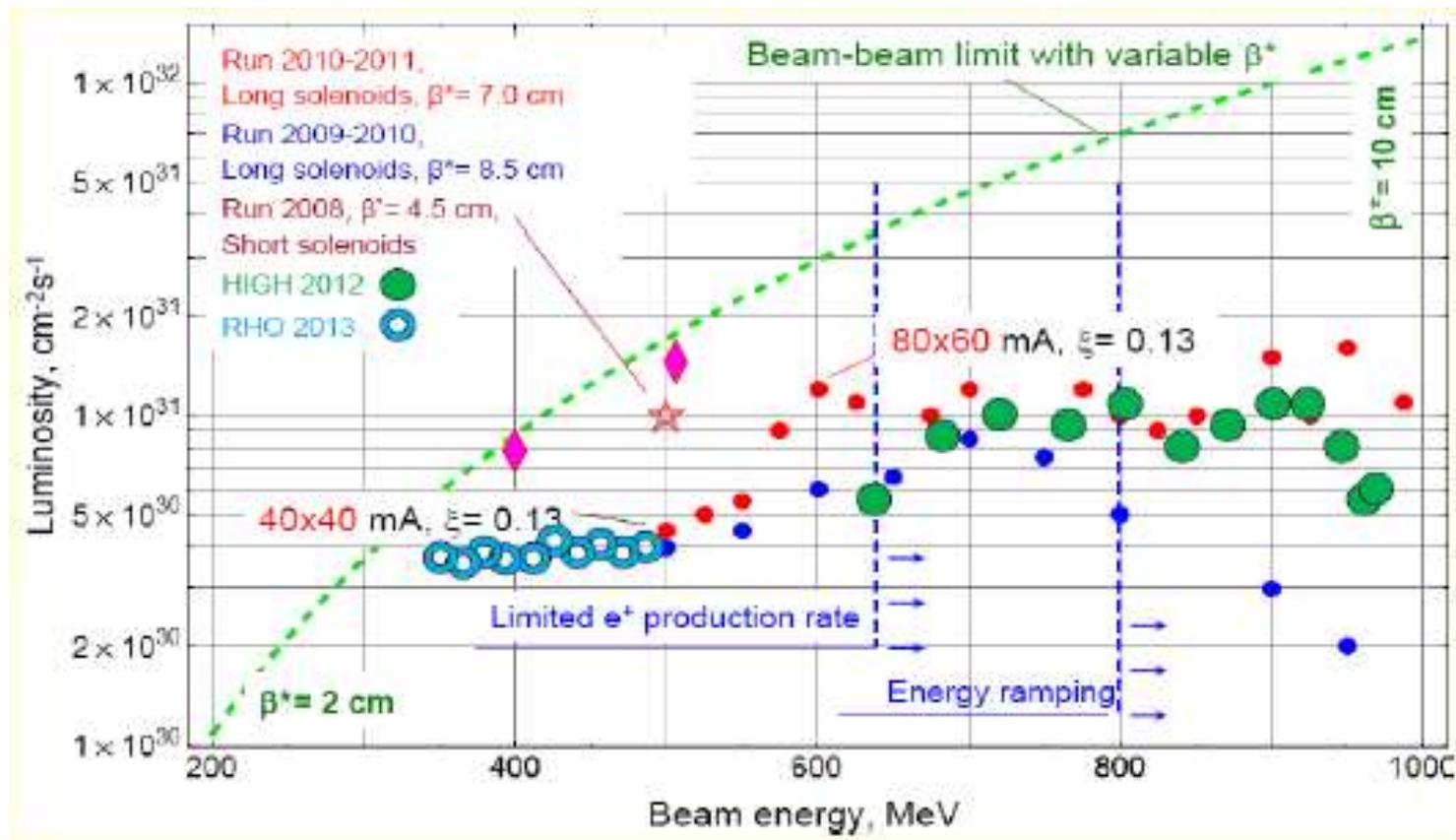
Collider	Operation	$\sqrt{s}$ , MeV	$\mathcal{L}$ , $10^{30} \text{cm}^{-2} \text{s}^{-1}$
VEPP-2M	1975-2000	[360,1400]	3
VEPP-2000	2010-	$[2m_\pi, 2000]$	100

## VEPP-2000 – II

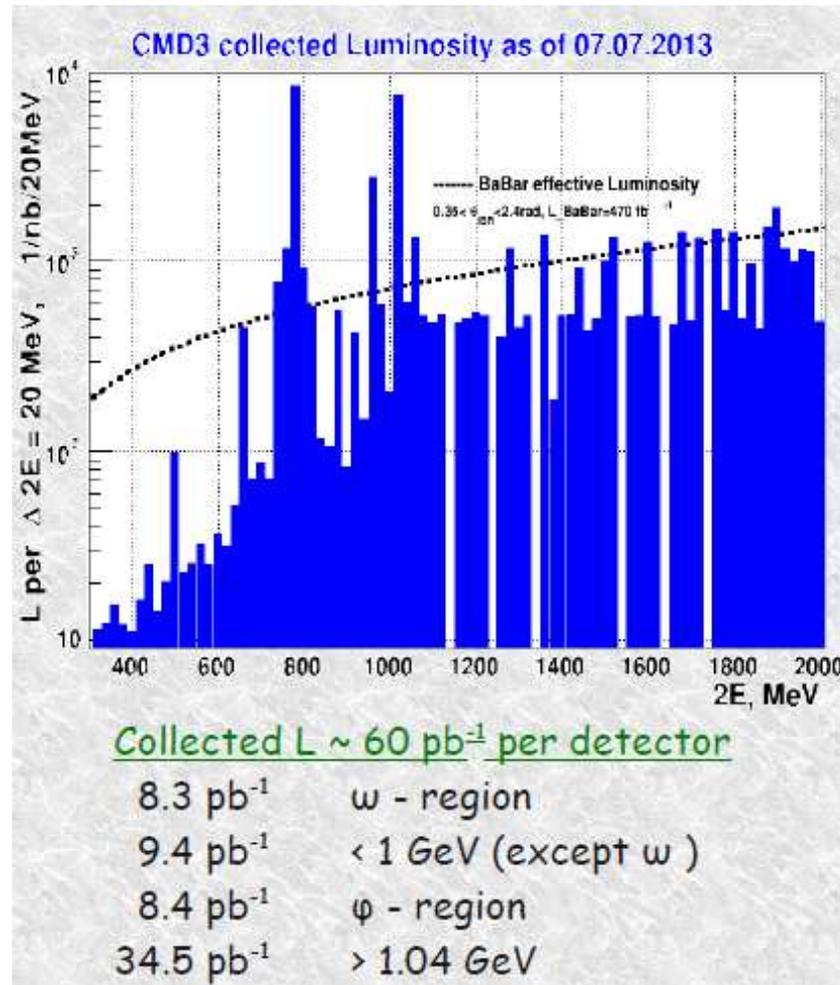


New optics with round beams  $\Rightarrow$  higher luminosity,  
precise beam energy measurement using LCBS

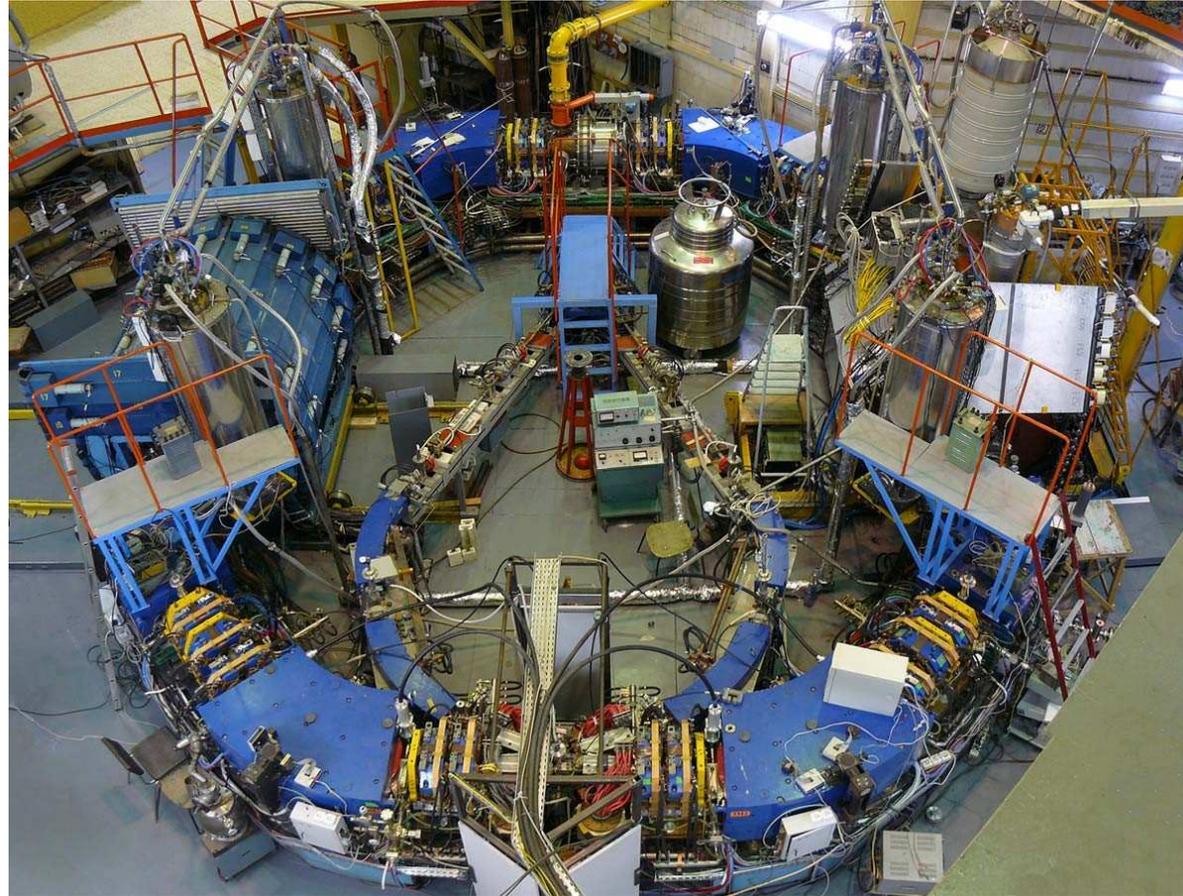
## VEPP-2000 – III



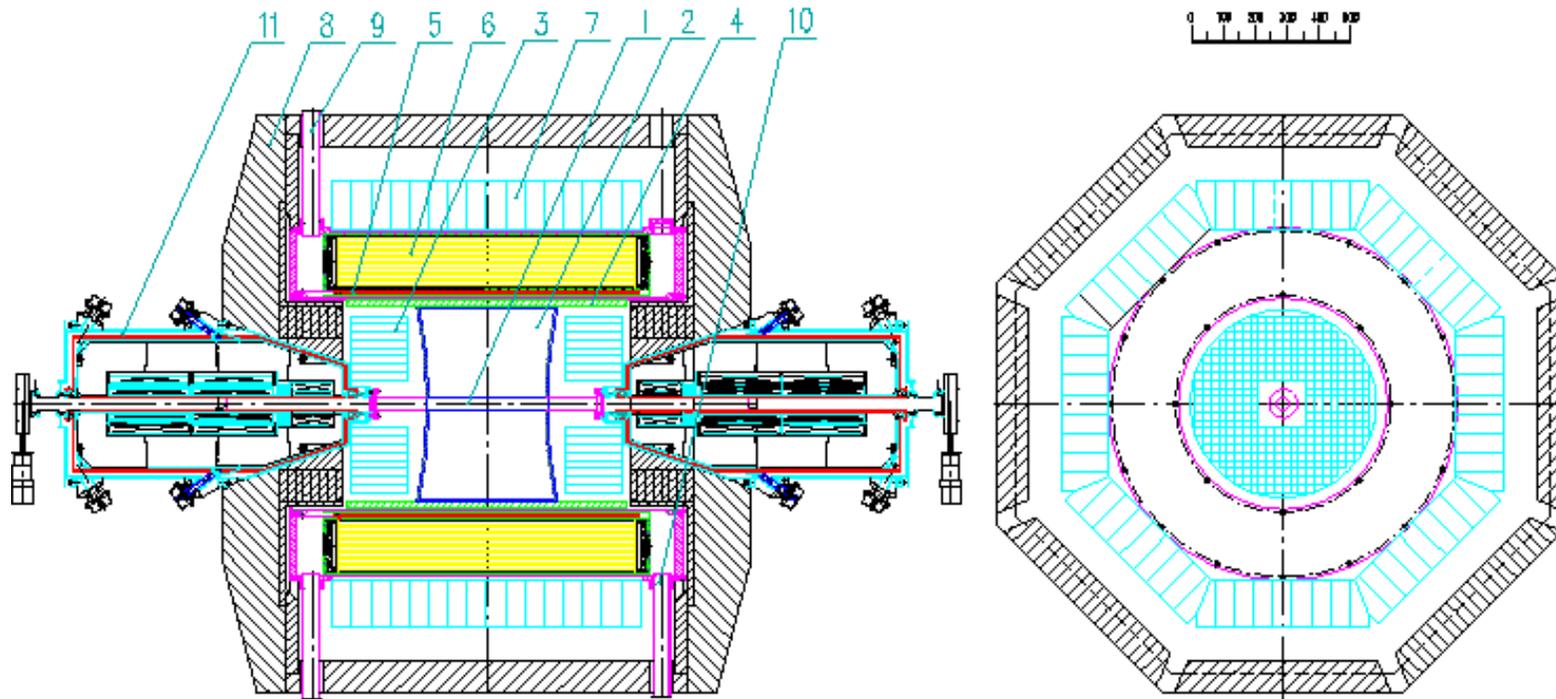
Data Taking at VEPP-2000



## VEPP-2000 and Detectors

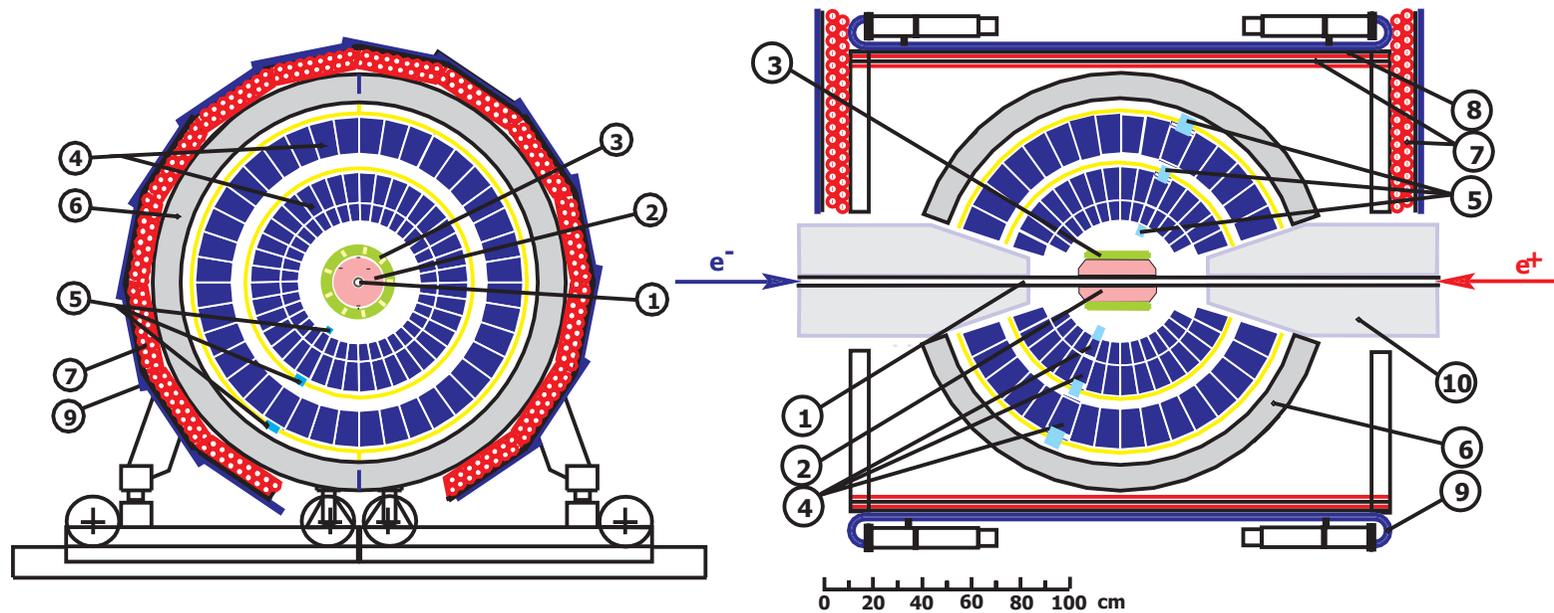


## CMD-3



General-purpose magnetic (1.3T) detector with 3 e/m calorimeters (LXe, CsI, BGO)

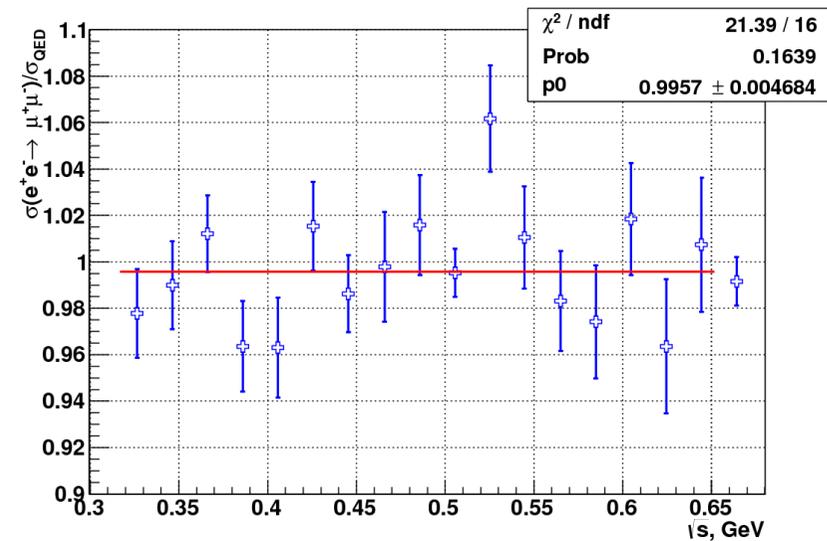
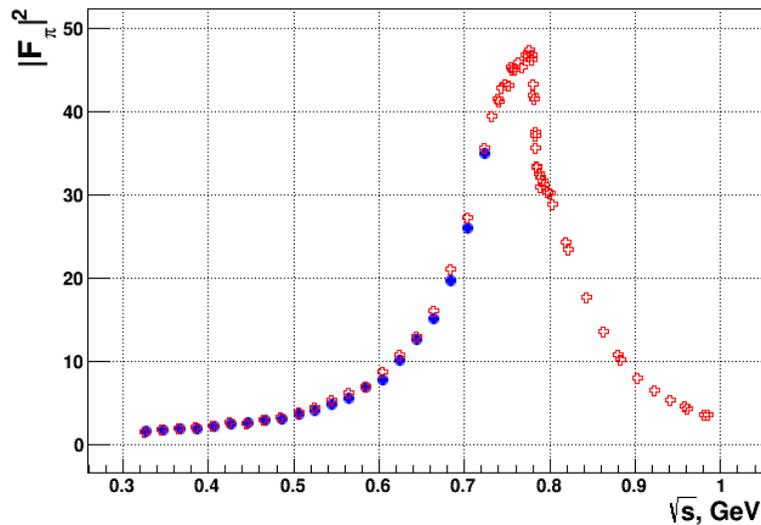
SND



High-resolution NaI calorimeter with excellent tracking and PID

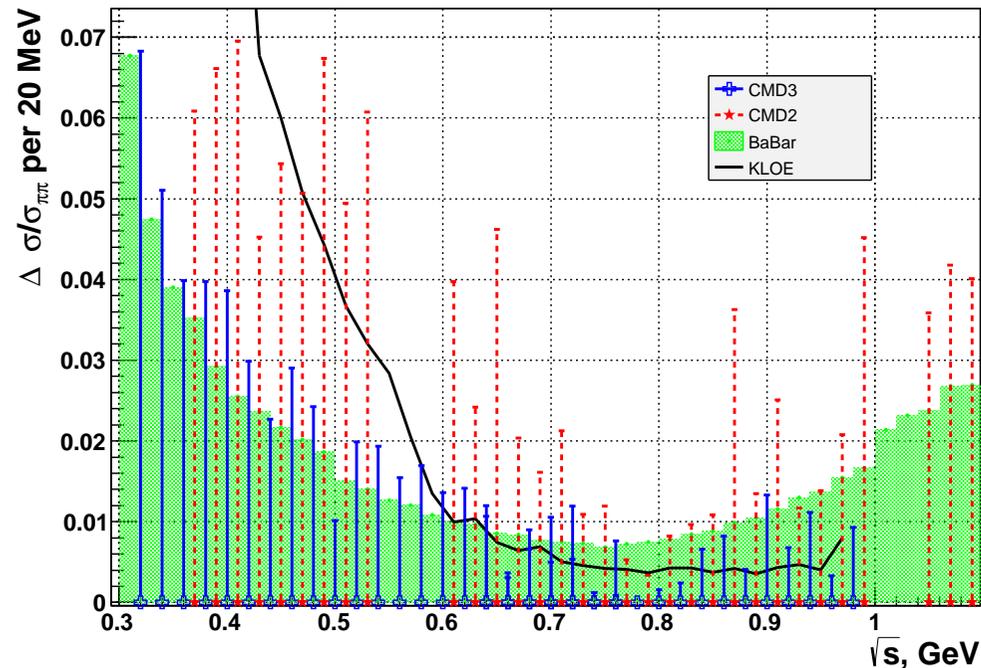
## Performance of VEPP-2000 and Detectors

- The maximum luminosity is  $2 \cdot 10^{31} \text{ cm}^{-1}\text{s}^{-1}$  at 1.7-1.8 GeV, falling much slower with decreasing energy than before the round beams
- The integrated luminosity is about  $60 \text{ pb}^{-1}$  per detector, a factor of 6 higher than before from  $\phi$  to 2 GeV, the number of multihadronic events per  $1 \text{ pb}^{-1} \sim 50k$
- In 2013 we reached  $2 \times 160 \text{ MeV}$ , the smallest  $\sqrt{s}$  ever
- At high energies lumi is limited by a deficit of positrons and maximum energy of the booster (825 MeV now)
- A long shutdown until 2015 to increase the booster energy to 1 GeV and commission the new injection complex to reach  $10^{32} \text{ cm}^{-1}\text{s}^{-1}$
- Both detectors perform reasonably well with reconstruction of both tracks and photons and redundancy ( $\eta \rightarrow 2\gamma, \pi^+\pi^-\pi^0, 3\pi^0, \pi^+\pi^-\gamma, \omega \rightarrow \pi^+\pi^-\pi^0, \pi^0\gamma$ )

$$e^+e^- \rightarrow \pi^+\pi^- \text{ at CMD-3 - I}$$


Identification at low energy - by DC with separation of  $\mu^+\mu^-$

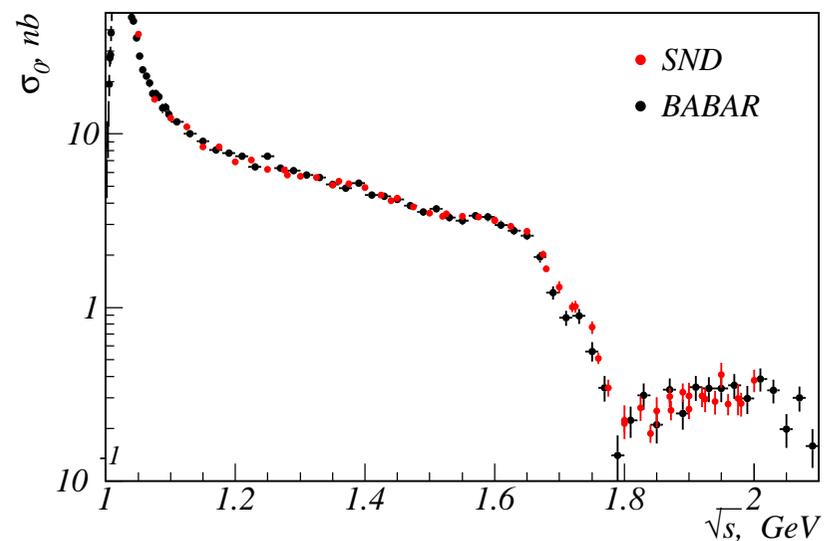
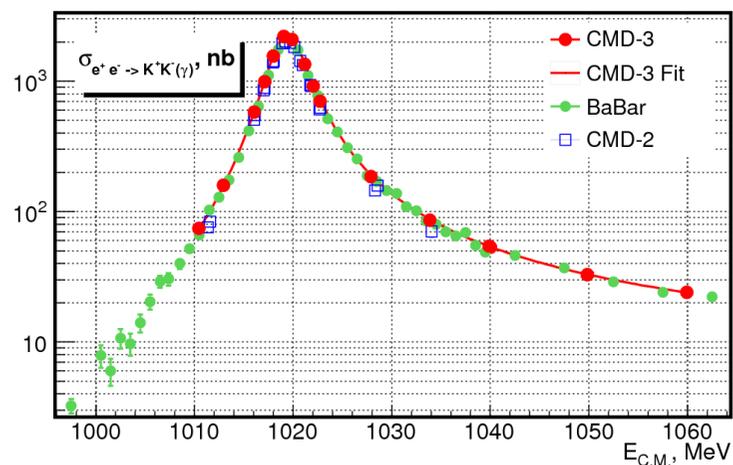
At high energy - by energy deposition in calorimeters

$$e^+e^- \rightarrow \pi^+\pi^- \text{ at CMD-3 - II}$$


Statistical precision better than that of BaBar

Systematic error: goal 0.35% at the  $\rho$  (BaBar achieved 0.5%)

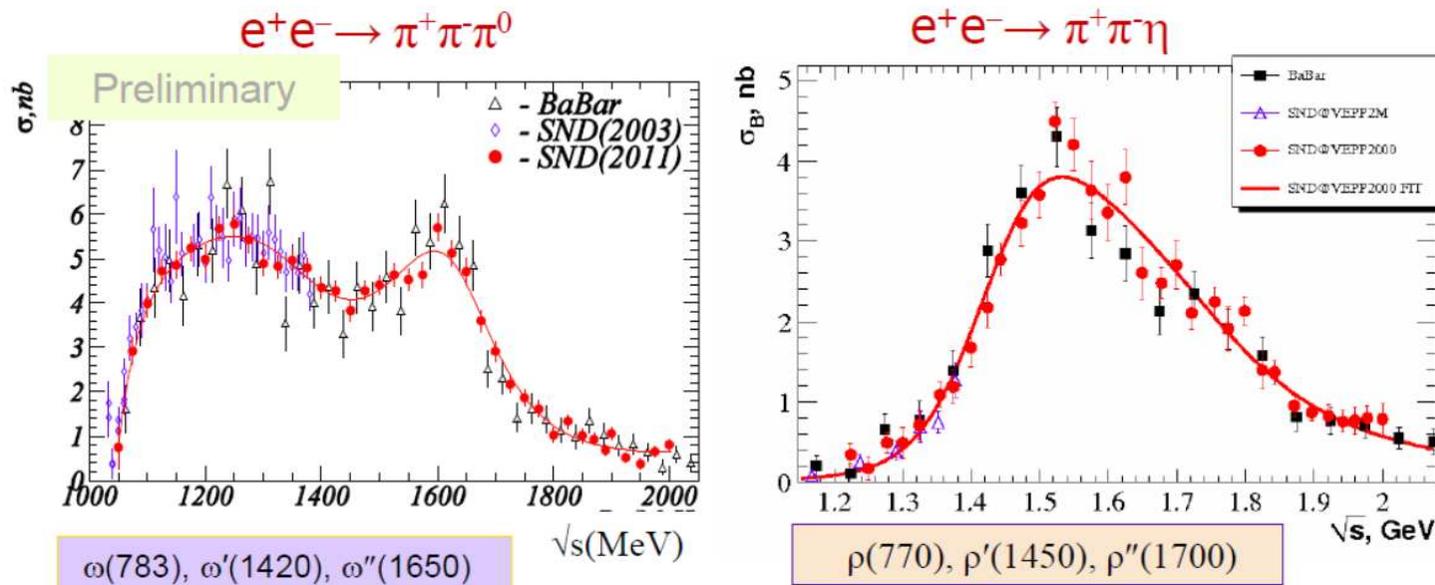
$$e^+e^- \rightarrow K^+K^-$$



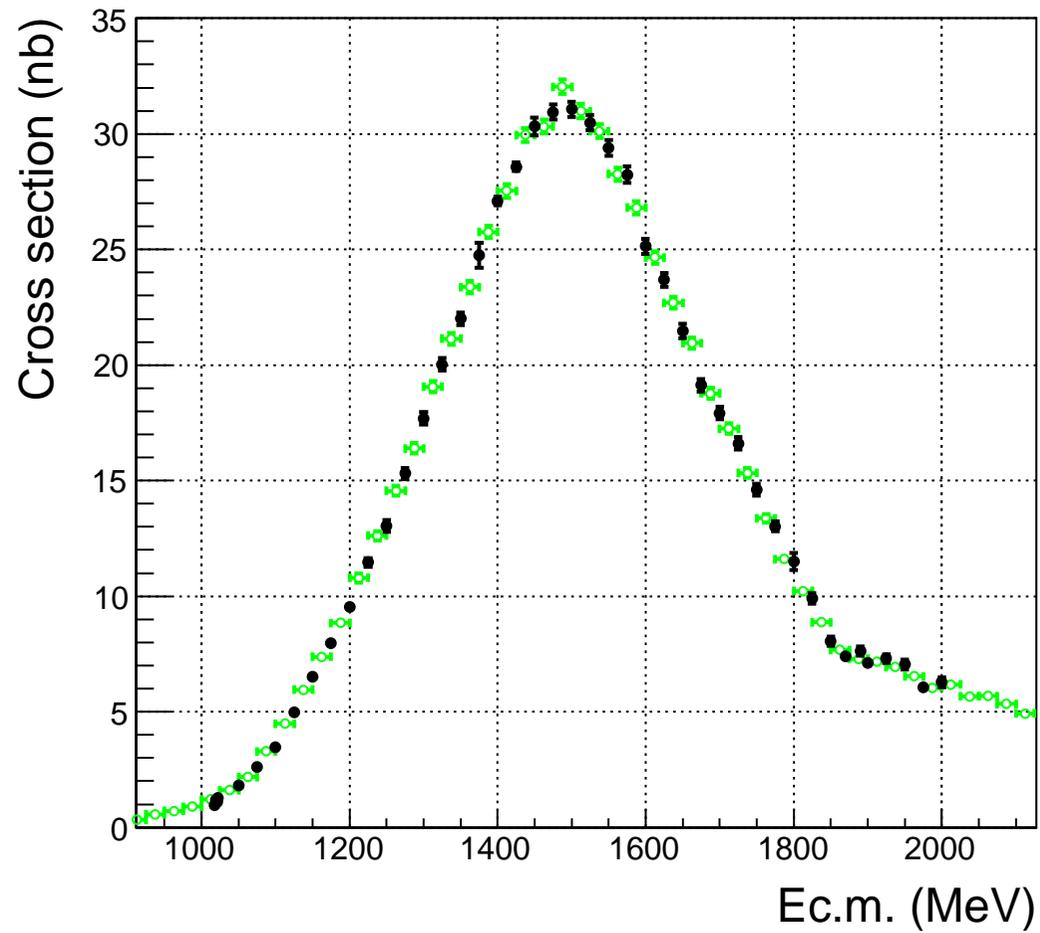
BaBar claims aggressive systematics of 0.72% at the  $\phi$ , increasing to 7% at 2 GeV

CMD-3 hopes to reach (1-2)% at the  $\phi$  and not much worse at higher energy

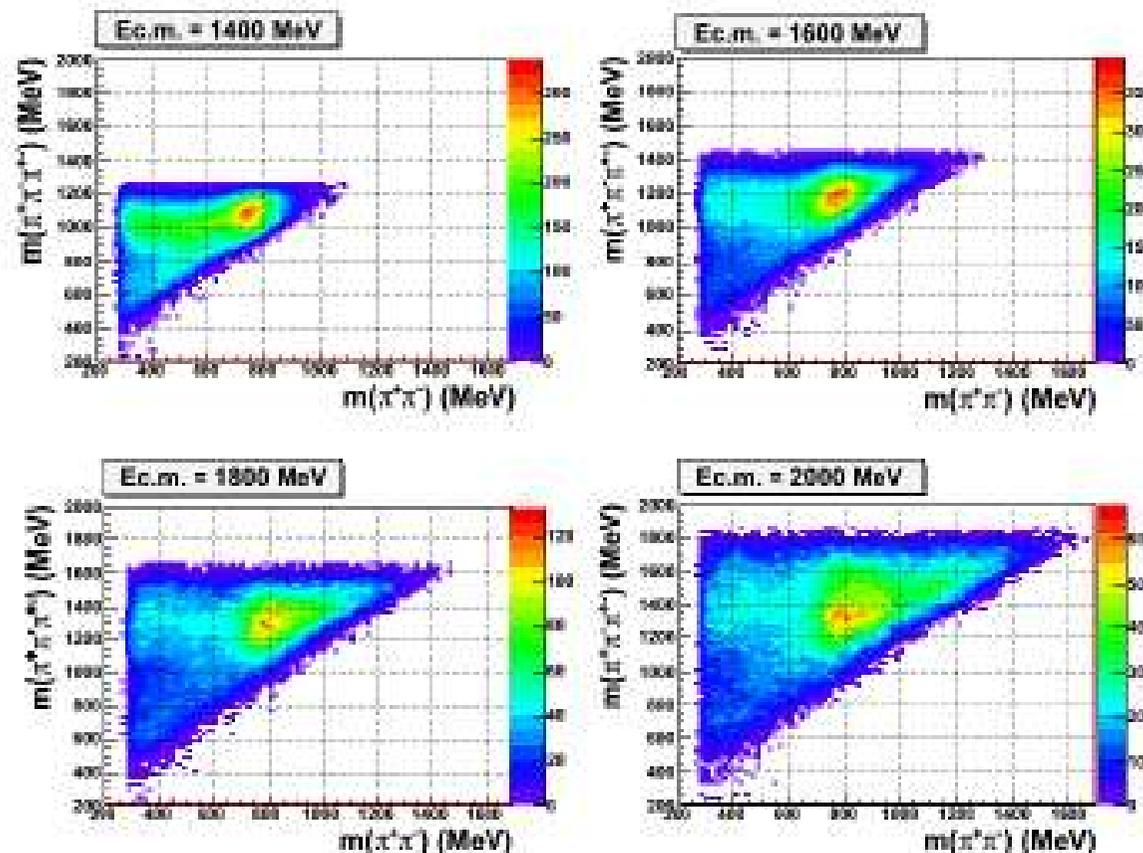
$e^+e^- \rightarrow \pi^+\pi^-\pi^0$  and  $e^+e^- \rightarrow \pi^+\pi^-\eta$  at SND



At each  $\sqrt{s}$  full information on invariant masses

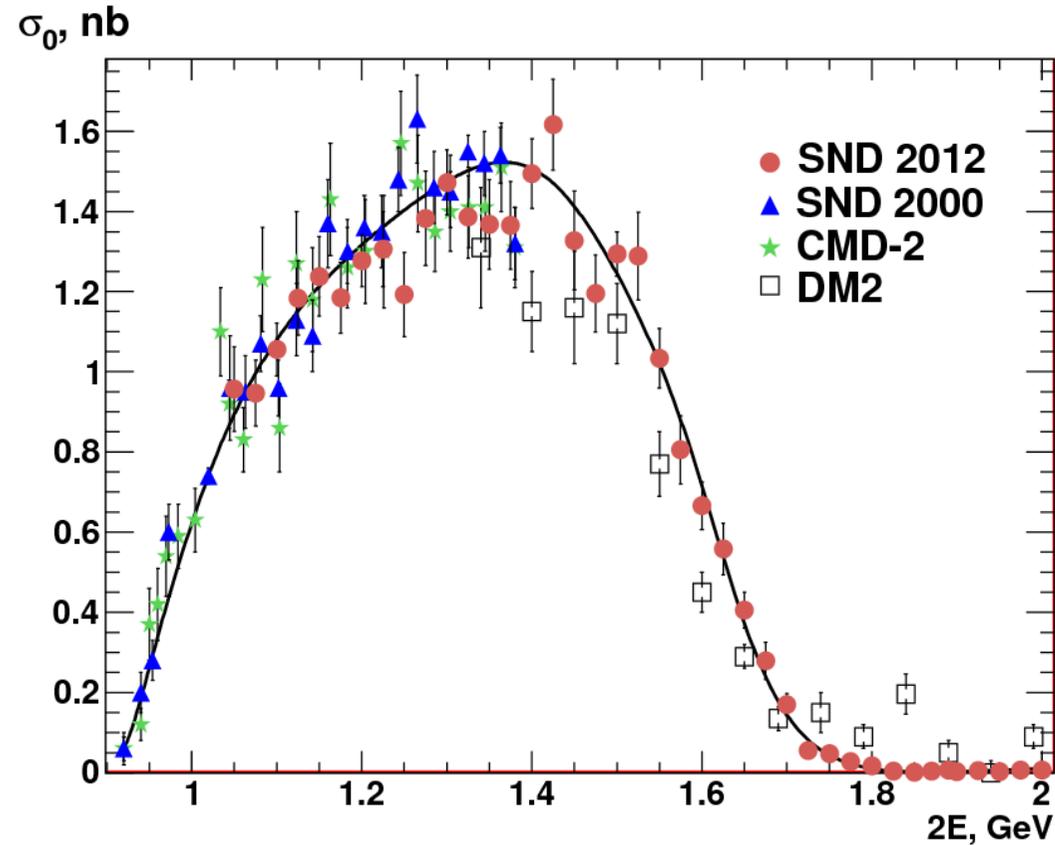
$$e^+e^- \rightarrow 2\pi^+2\pi^- \text{ at CMD-3}$$


## Dynamics of $e^+e^- \rightarrow 2\pi^+2\pi^-$ at CMD-3



A  $\rho^0$  is always present,  $a_1^\pm(1260)\pi^\mp$  ( $a_2^\pm(1320)\pi^\mp$ ) significant, at higher  $\sqrt{s}$  other mechanisms like  $\rho^0 f_0$ ,  $\rho^0 f_2(1270)$  appear

$$e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^0\pi^0\gamma \text{ at SND}$$

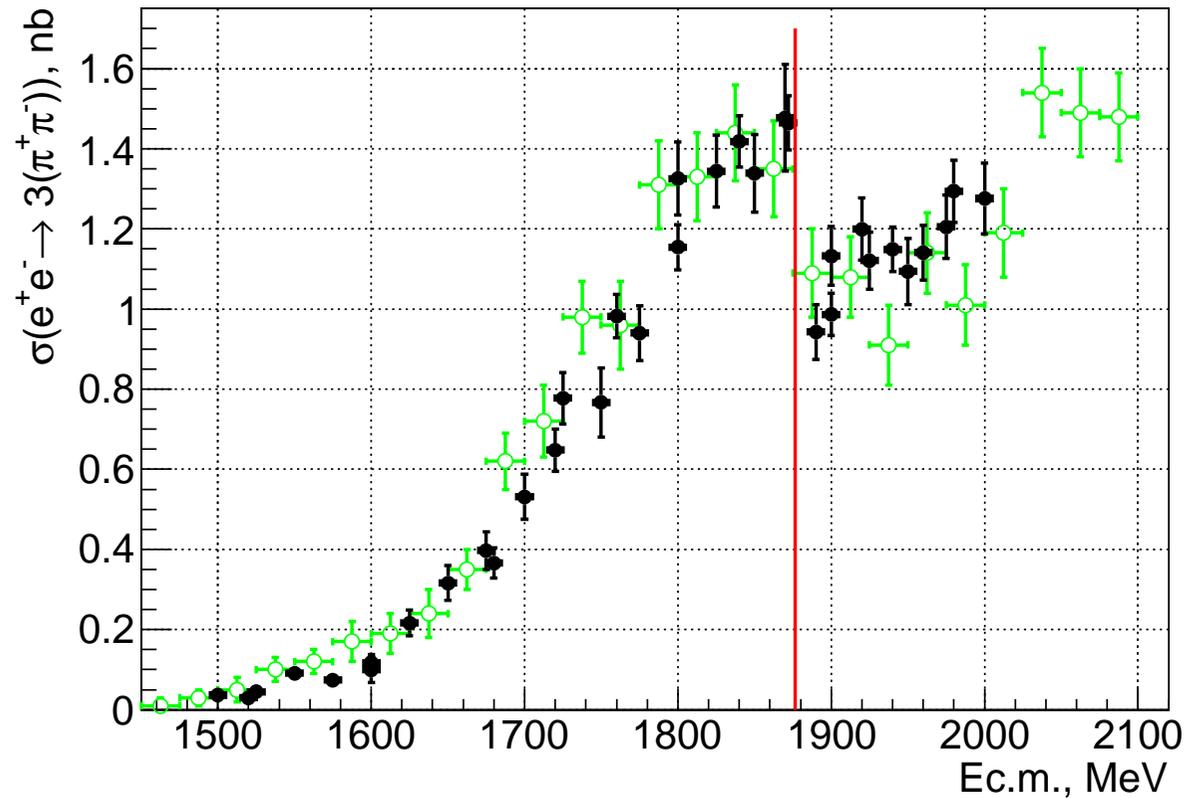


Phys. Rev. D 88 (2013) 054013

First observation above 1.4 GeV

$$e^+e^- \rightarrow 3\pi^+3\pi^- \text{ at CMD-3 - I}$$

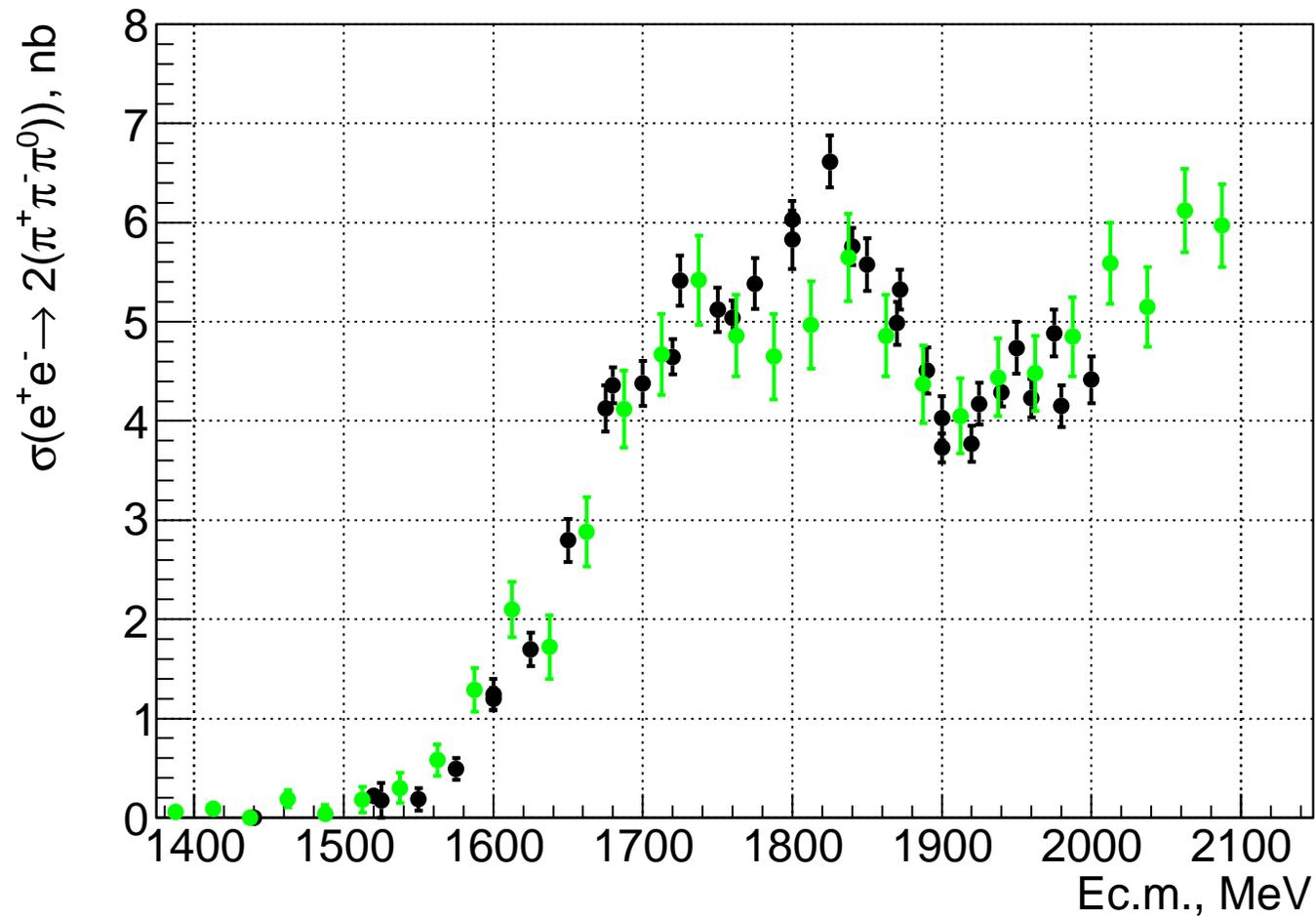
1.  $\int Ldt = 22 \text{ pb}^{-1}$  from 1.5 to 2.0 GeV, 25 MeV step
2. About 8k five- (5069) and six-track (2887) events selected
3. We study dynamics, pure phase space doesn't work, three models with  $J^{PC} = 1^{--}$ , each with one  $\rho^0$ /event:
  - $\rho(1450)(\pi^+\pi^-)_{\text{S-wave}} \rightarrow a_1(1260)^\pm \pi^\mp \pi^+\pi^- \rightarrow \rho^0 2(\pi^+\pi^-) \rightarrow 3(\pi^+\pi^-)$
  - $\rho(770)(2\pi^+2\pi^-)_{\text{S-wave}} \rightarrow 3(\pi^+\pi^-)$   
3 options for  $2\pi^+2\pi^-$ : phase space,  $f_0(1370)$ ,  $f_0(1500)$
  - $\rho(770)f_2(1270) \rightarrow 3(\pi^+\pi^-)$
  - The best description is with one  $\rho(770)$  and 4 pions in S-wave
4. Full analysis of dynamics - common for  $3\pi^+3\pi^-$ ,  $2\pi^+2\pi^-2\pi^0$ ,  $\pi^+\pi^-4\pi^0$
5. The systematic uncertainty is 6%, to be improved to 3%

$$e^+e^- \rightarrow 3\pi^+3\pi^- \text{ at CMD-3- II}$$


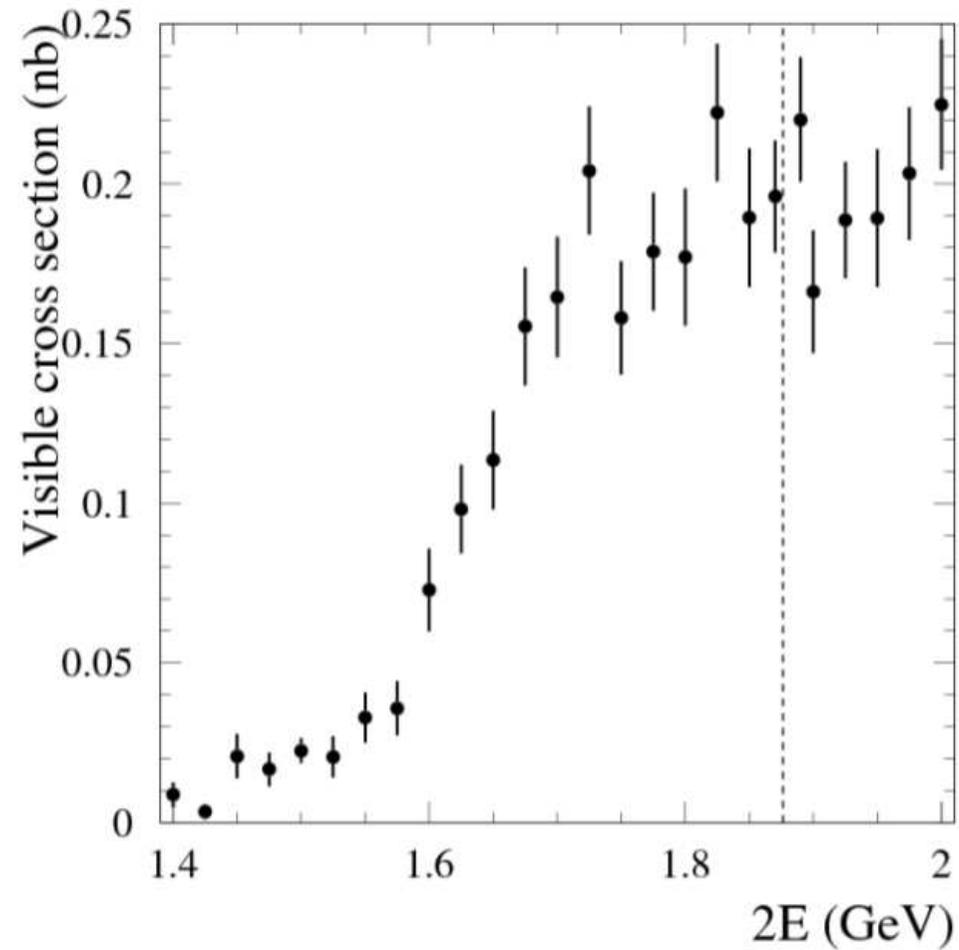
The dip structure near  $N\bar{N}$  threshold is confirmed

Phys. Lett. B 723 (2013) 82

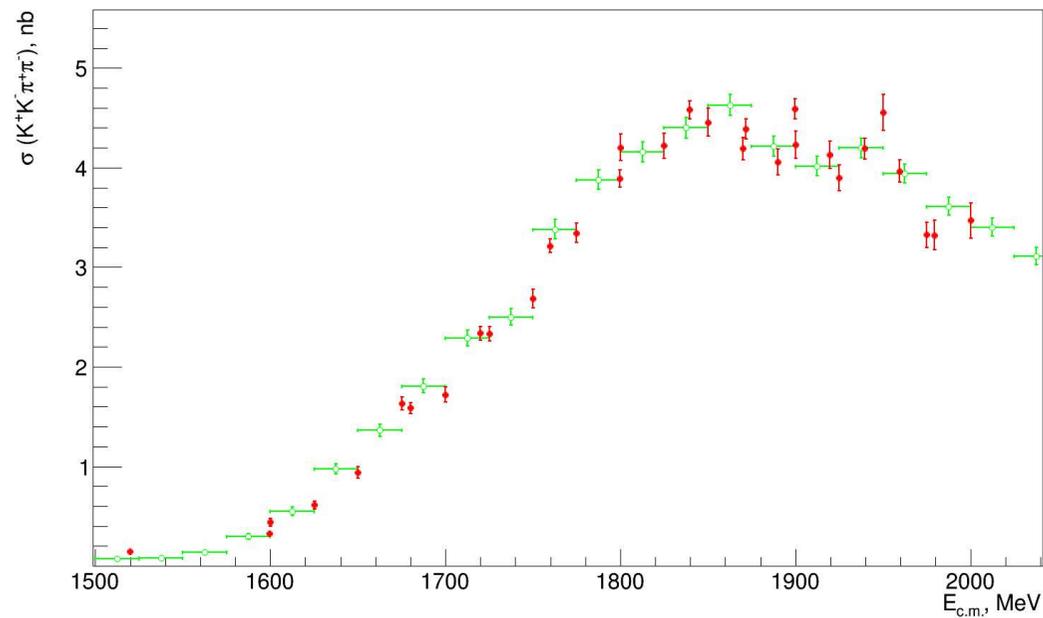
$$e^+e^- \rightarrow 2\pi^+2\pi^-2\pi^0 \text{ at CMD-3}$$



The dip structure near  $N\bar{N}$  threshold also seen

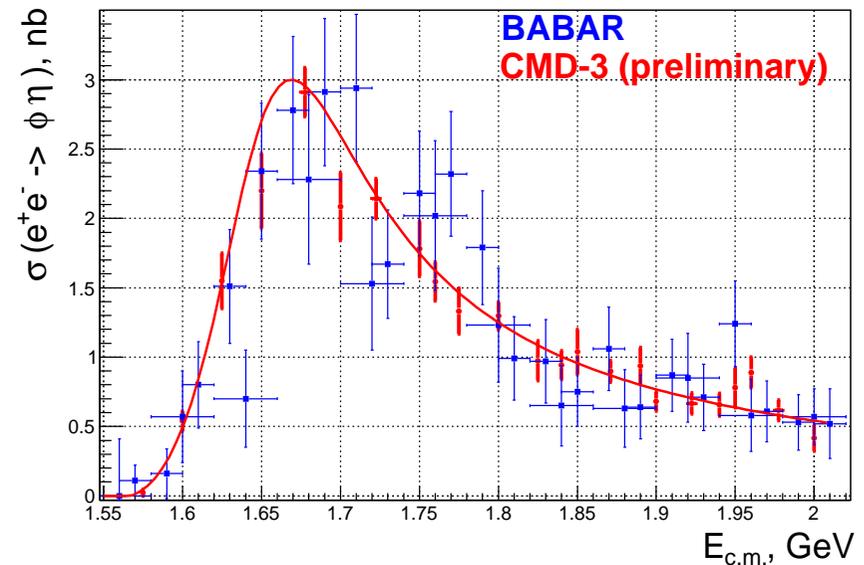
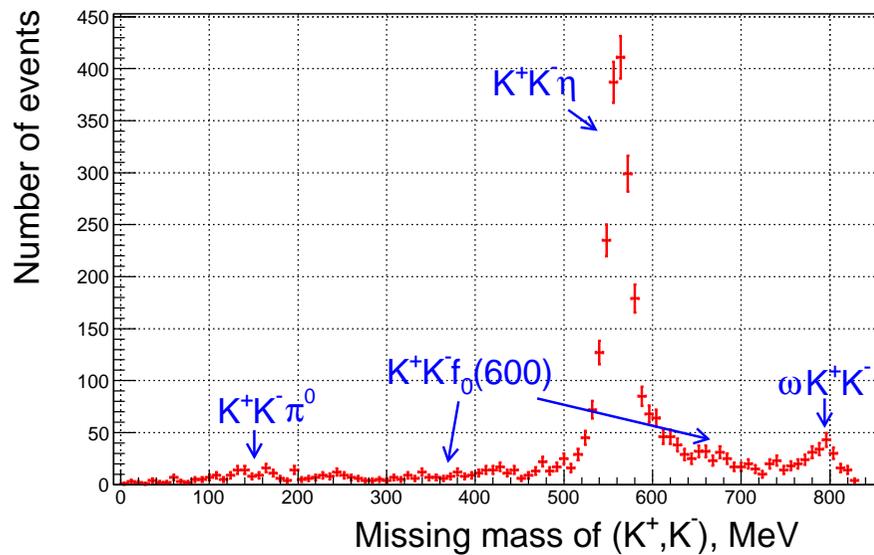
$$e^+e^- \rightarrow \pi^+\pi^-4\pi^0 \text{ at SND}$$


First ever measurement of the process

$$e^+e^- \rightarrow K^+K^-\pi^+\pi^- \text{ at CMD-3}$$


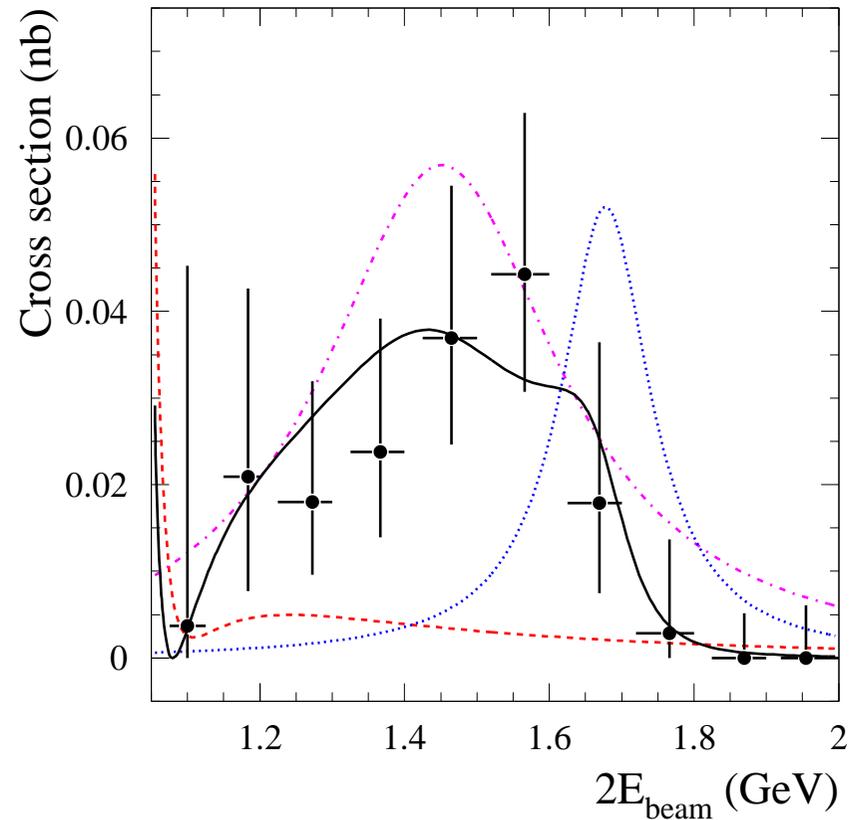
We expect the  $\phi(1680)$  after disentangling various mechanisms

$$e^+e^- \rightarrow \eta K^+ K^- \text{ at CMD-3}$$



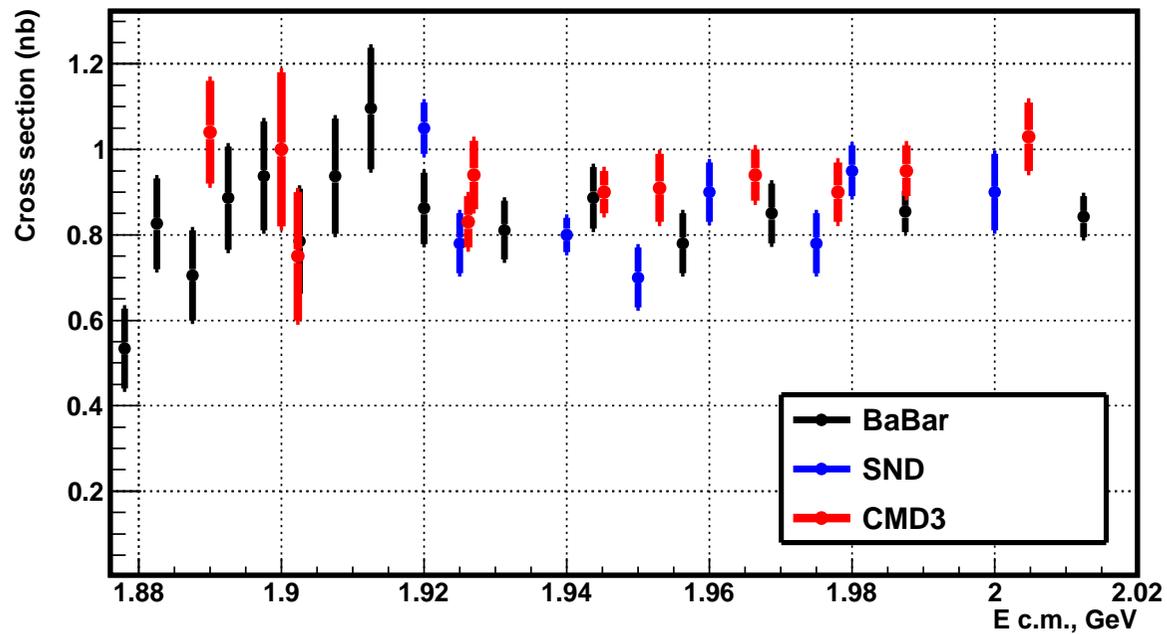
Dynamics is dominated by  $\phi\eta$   
 The  $\phi(1680)$  meson is clearly seen

$$e^+e^- \rightarrow \eta\gamma \text{ at SND}$$



The first measurement above 1.4 GeV, Phys. Rev. D90 (2014) 032002

Dominated by the  $\rho(1450)$  and  $\phi(1680)$  mesons

$p\bar{p}$  Production at VEPP-2000

In addition to cross sections, first attempts of measuring  $f/f$  made

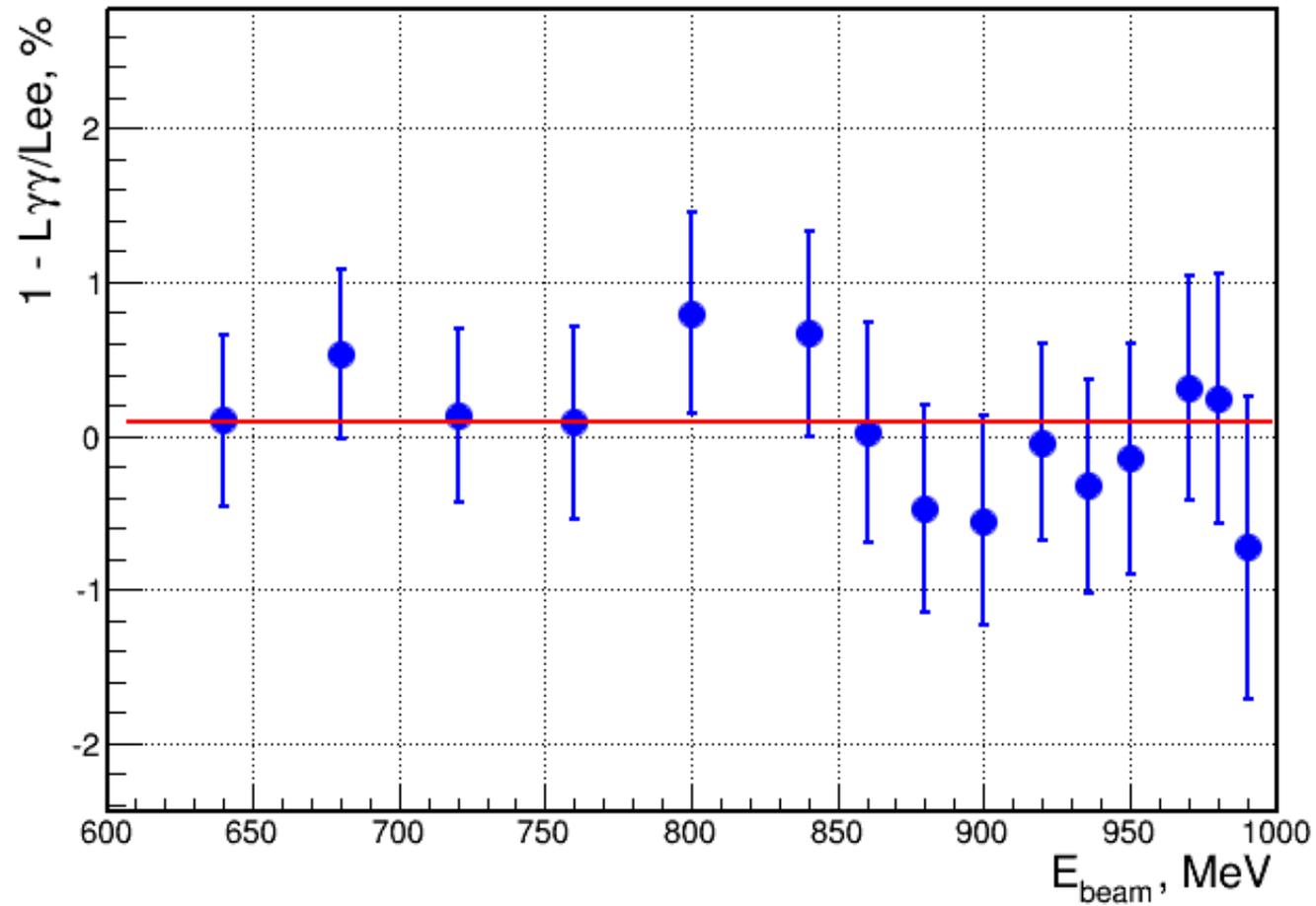


## Conclusions

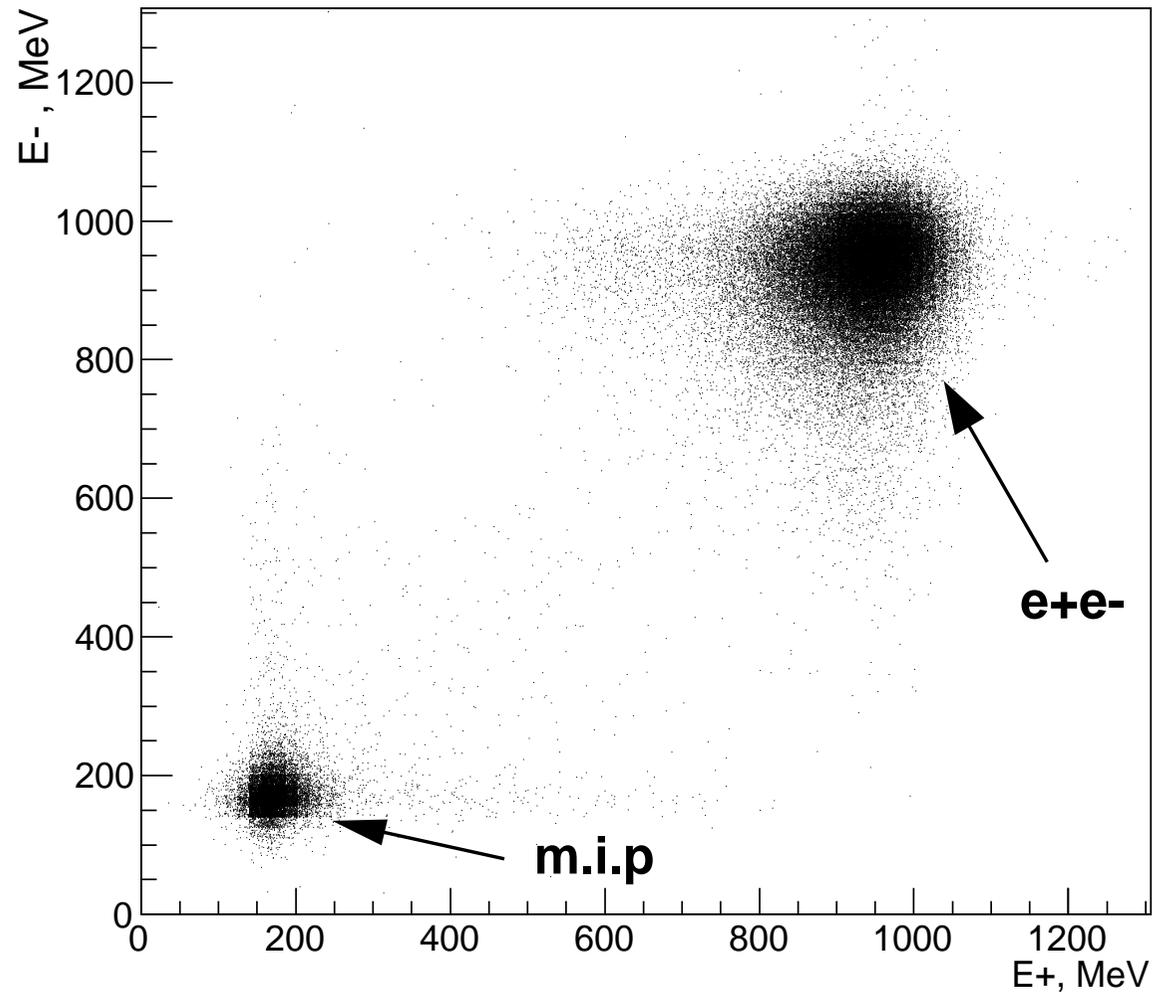
- VEPP-2000 is running smoothly with CMD-3 and SND, their accuracy is comparable or better than ISR measurements
- The goals are 0.35%(0.5%) for  $\pi^+\pi^-$  and 3% for multibody modes
- Below 2 GeV progress (a factor of 2-3) expected in exclusive  $\sigma$ 's due to scans in Novosibirsk and ISR from KLOE2, BaBar, Belle, BES3 and Belle2
- Various high-statistics experiments will substantially improve the accuracy of vacuum polarization calculations for  $(g_\mu - 2)/2$
- Higher statistics ( $\sim 1\text{fb}^{-1}$ ) will allow a study of dynamics, thus mesons with various quantum numbers complementary to unprecedented COMPASS data samples

Back-up

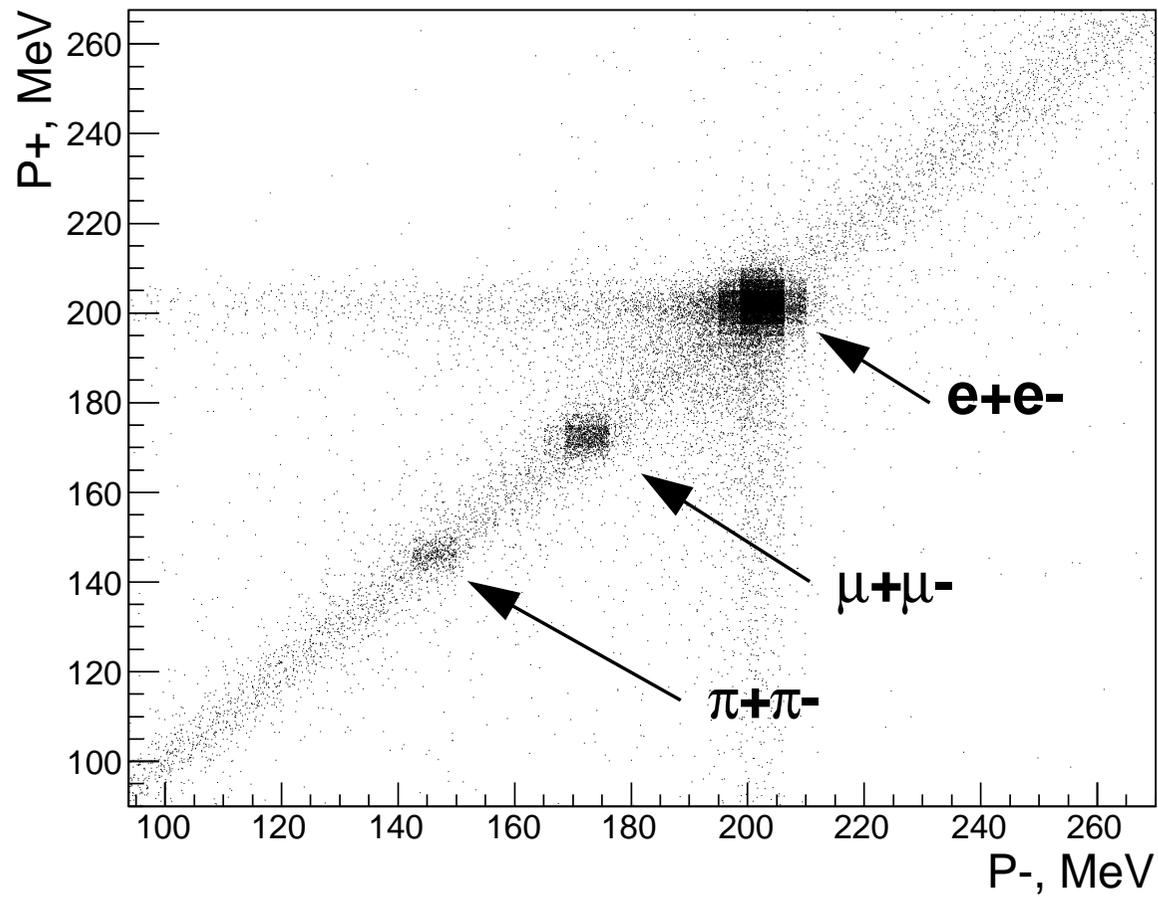
## Luminosity Measurement at CMD-3

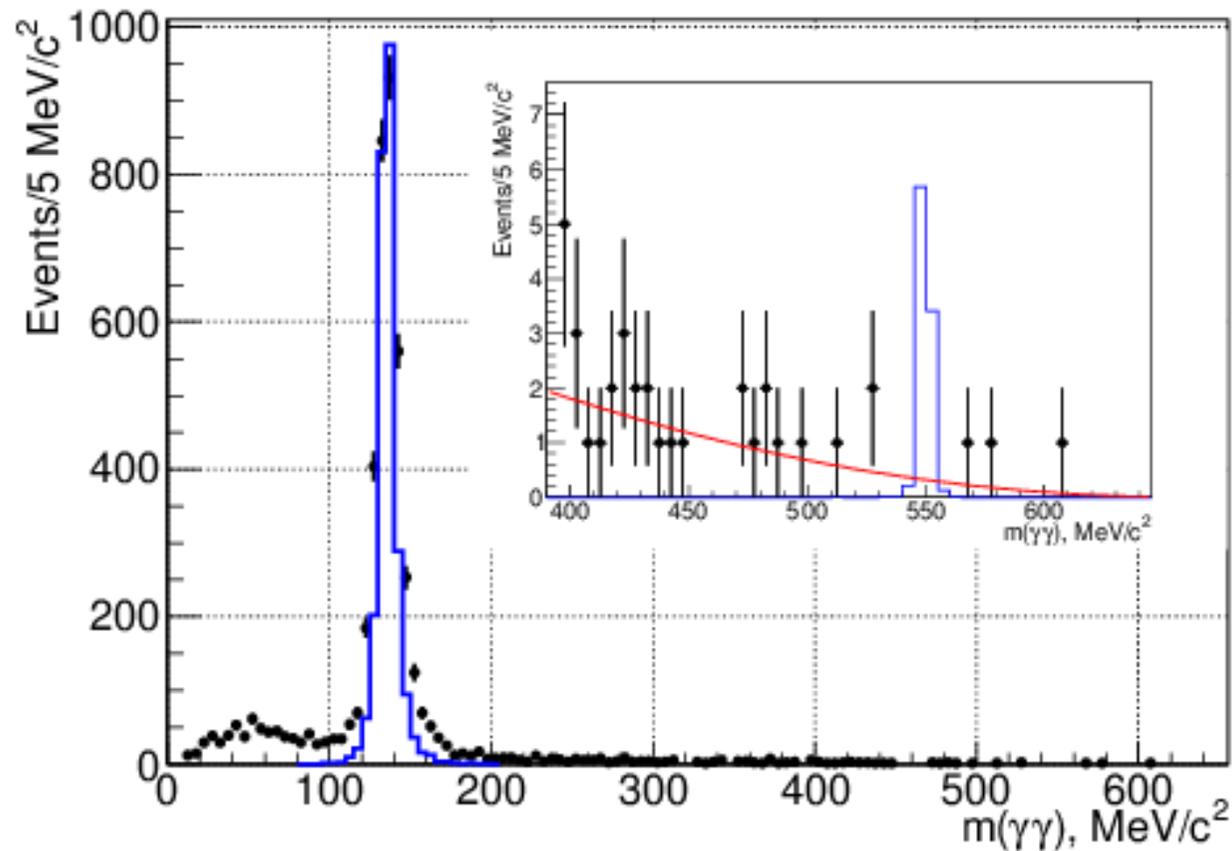


## Particle Identification at CMD-3 – I



## Particle Identification at CMD-3 – II

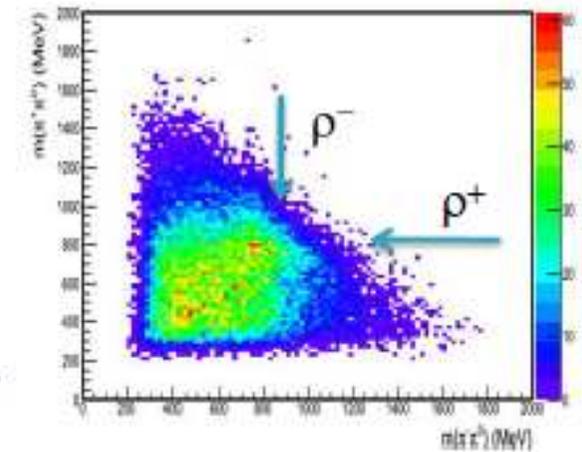
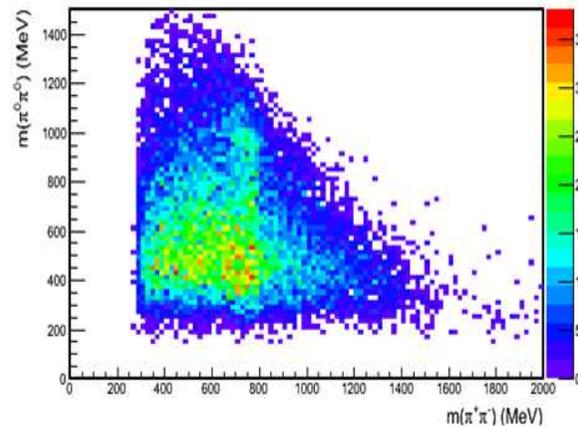
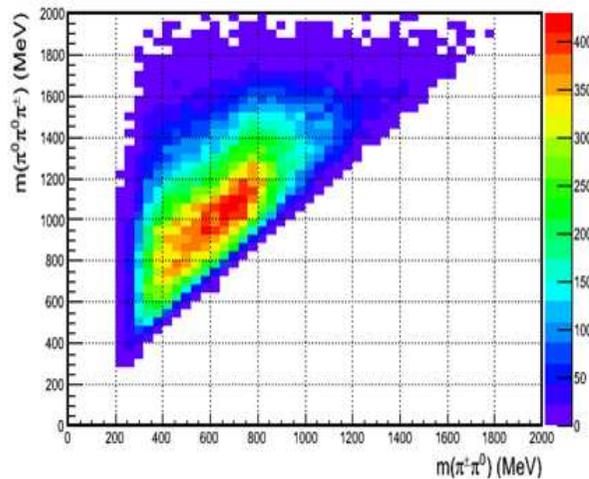


Search for  $e^+e^- \rightarrow \eta' \rightarrow \eta\pi^+\pi^-$  at CMD-3

arXiv:1409.1664:

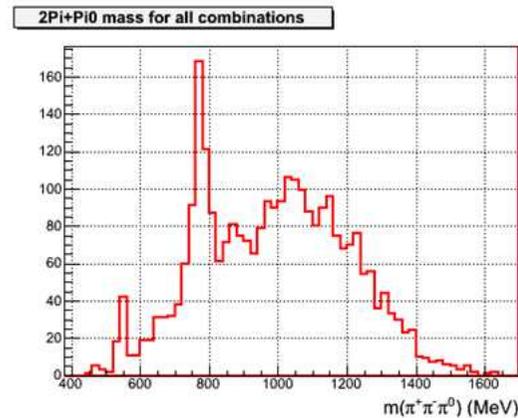
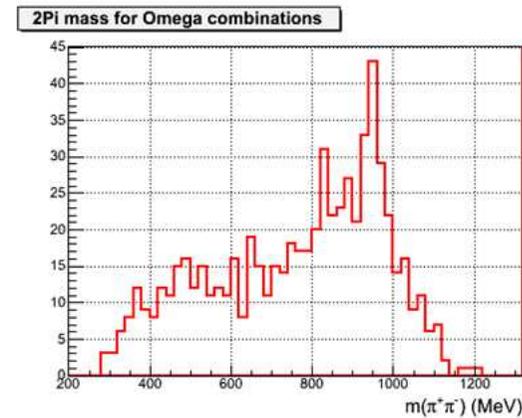
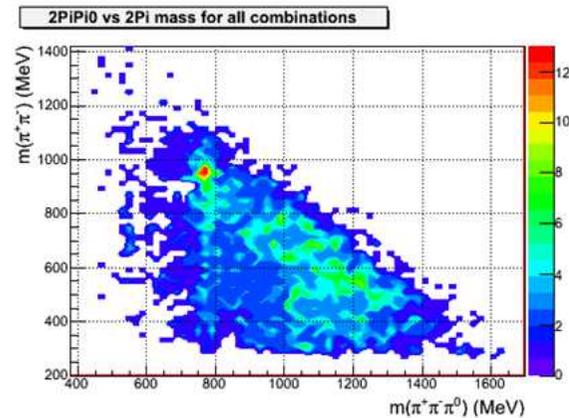
$$\mathcal{B}(\eta' \rightarrow e^+e^-) < 1.2 \times 10^{-8}$$

## Dynamics of $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ at CMD-3

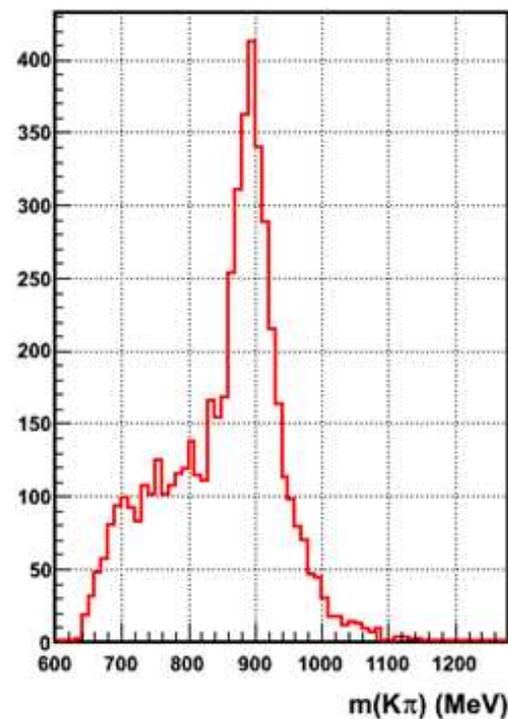
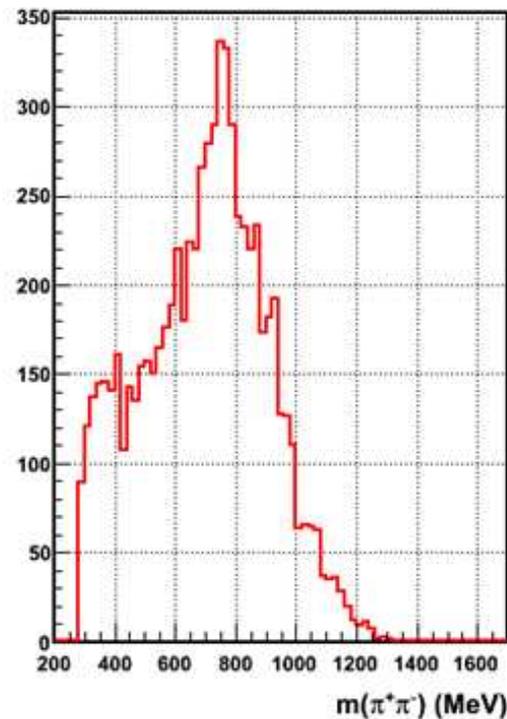


$a_1^\pm(1260)\pi^\mp$ ,  $\rho^0 f_0$  and  $\rho^+\rho^-$  intermediate states seen,  
 other mechanisms possible:  $a_2^\pm(1320)\pi^\mp$ ,  $\pi^\pm(1300)\pi^\mp$ , ...

$$e^+e^- \rightarrow 2\pi^+2\pi^-\pi^0 \text{ at CMD-3}$$

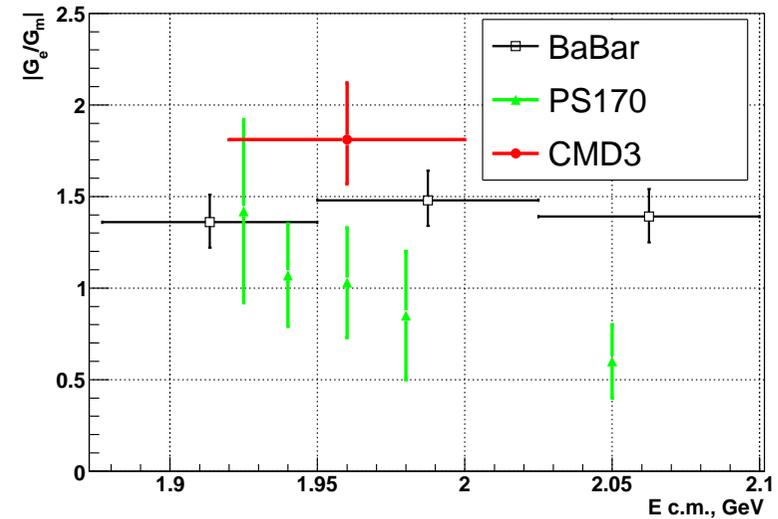
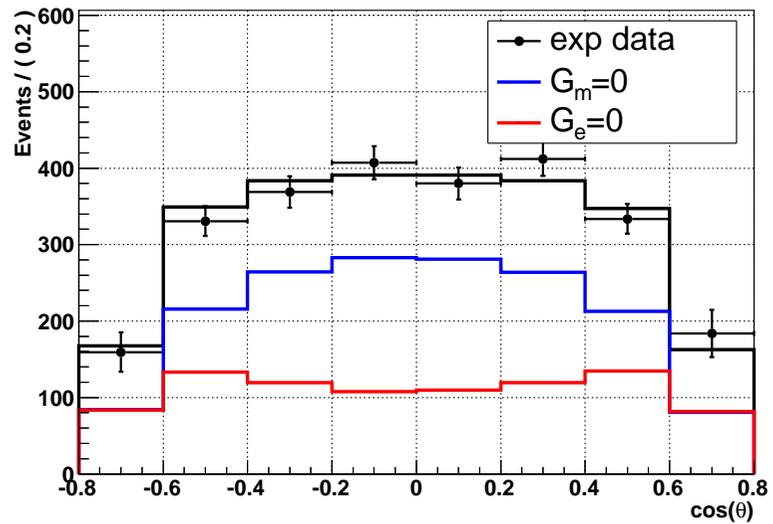


Various mechanisms seen:  $\omega\pi^+\pi^-$ ,  $\eta\pi^+\pi^-$ ,  $\omega f_0(980)$

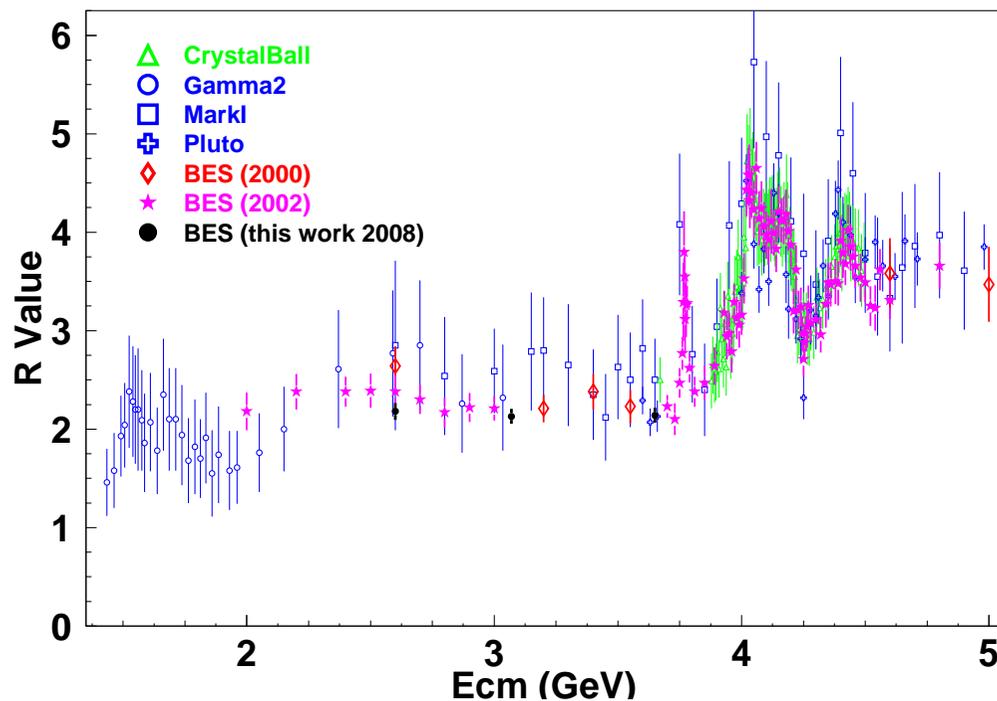
$$e^+e^- \rightarrow K^+K^-\pi^+\pi^- \text{ at CMD-3 - I}$$


Many different mechanisms seen:  $K_1(1270)\bar{K} \rightarrow K\bar{K}\rho$ ,  $K^*(892)\bar{K}\pi$ ,  
 $K_1(1400)\bar{K} \rightarrow K^*(892)\bar{K}\pi$ ,  $\phi\pi^+\pi^-$

## Proton Form Factors



## $R$ Measurement Below 5 GeV



Dominated by BES: stat. errors (3-5)%, syst. errors (5-8)%

J.Z. Bai et al., Phys.Rev.Lett. 84 (2000) 594, Phys.Rev.Lett. 88 (2002) 101802;

M. Ablikim et al., Phys.Rev.Lett. 97 (2006) 262001, Phys.Lett. B677 (2009) 239