

Hadronic Contribution to $g-2$: Update from the VEPP-2000

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(on behalf of CMD-3 and SND Collaborations)

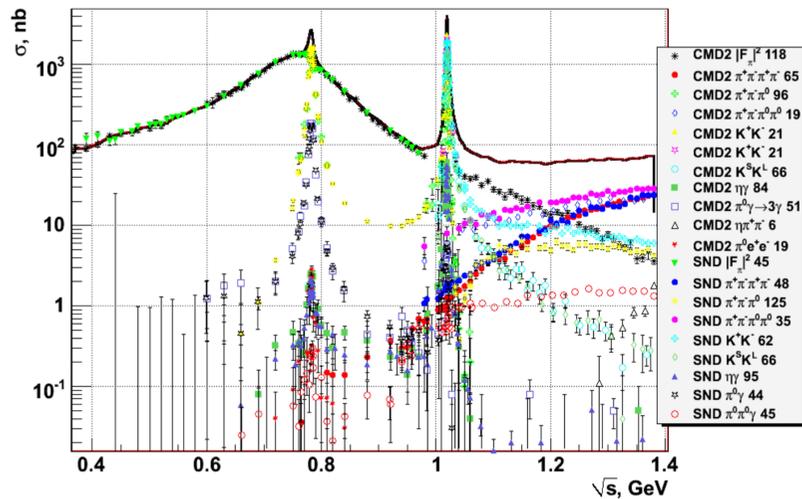
Outline

1. Results from CMD-3 and SND at VEPP-2000
2. $\gamma^{(*)}\gamma^{(*)} \rightarrow \text{hadrons}$ at VEPP-2000
3. Future and prospects

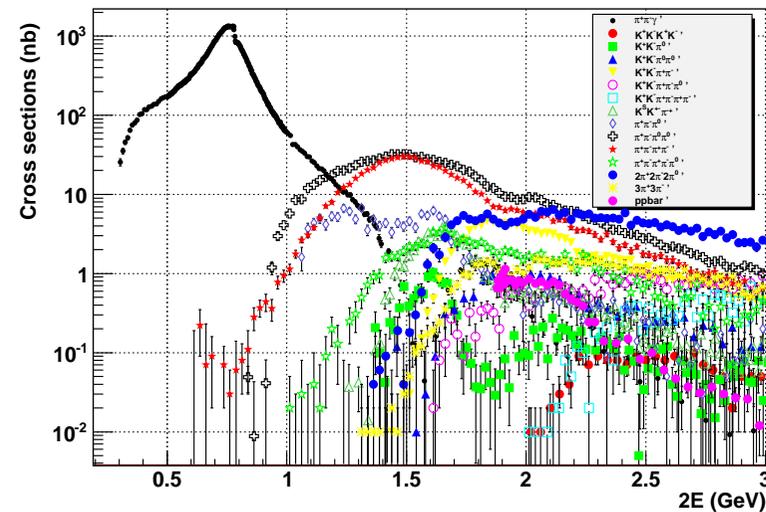
What Can We Learn from Low Energy e^+e^- Cross Sections?

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 τ -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 (α_s , quark and gluon condensates)

Current Status of Exclusive Measurements



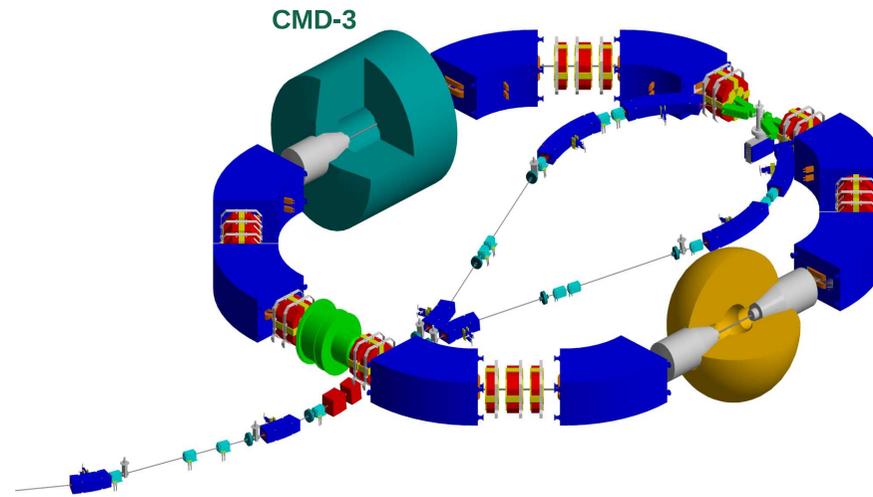
Scan at CMD-2/SND below 1.4 GeV



ISR at BaBar up to 3 GeV

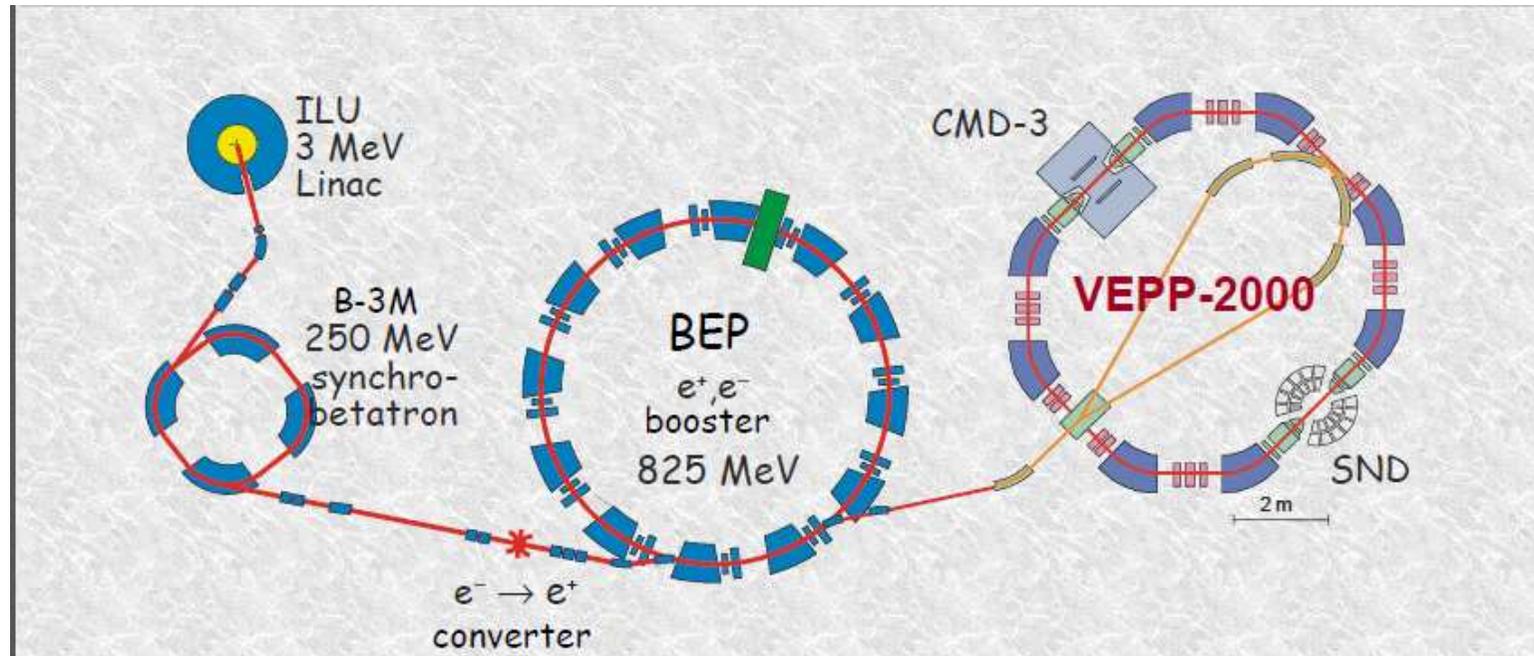
Scan measurements should be done up to 2 GeV (VEPP-2000!),
 Current ISR players are BaBar, KLOE-2 and BESIII with BelleII in future

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

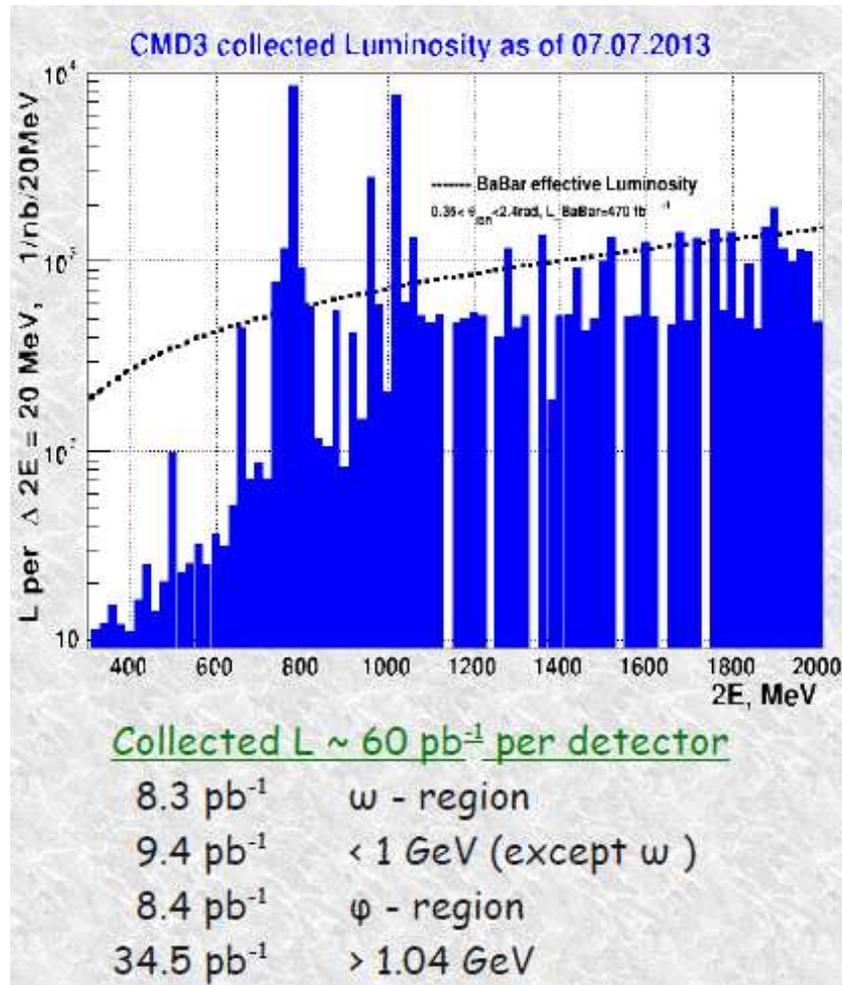
VEPP-2000 – II



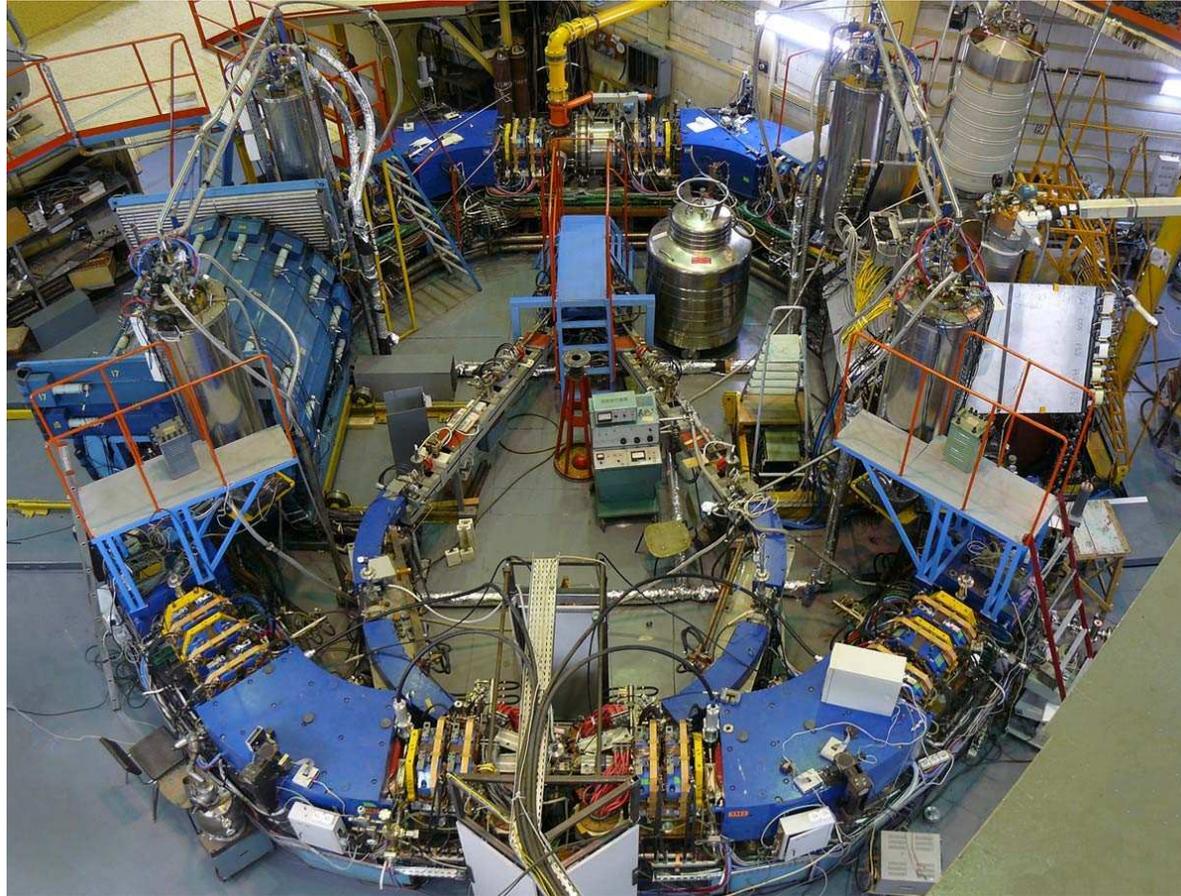
New optics with round beams \Rightarrow higher luminosity,
precise beam energy measurement using LCBS

In 2013-2015 the complex was upgraded to increase the booster
energy to 1 GeV and commission the new injection complex

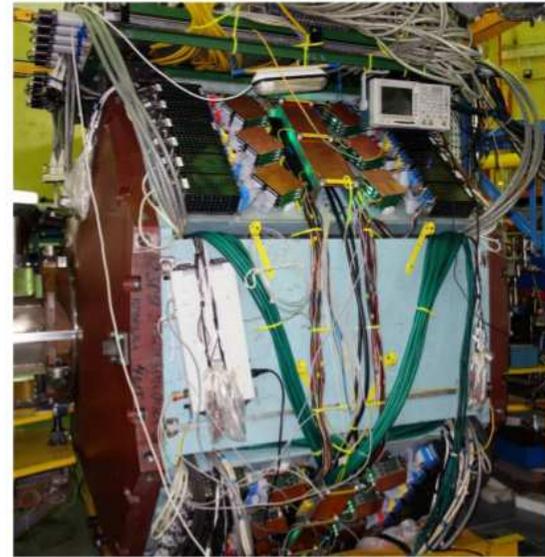
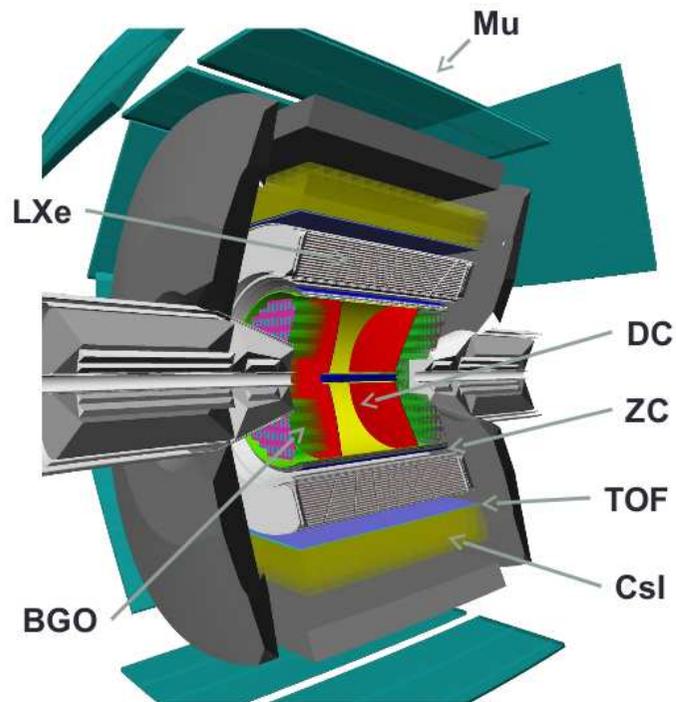
Data Taking at VEPP-2000



VEPP-2000 and Detectors



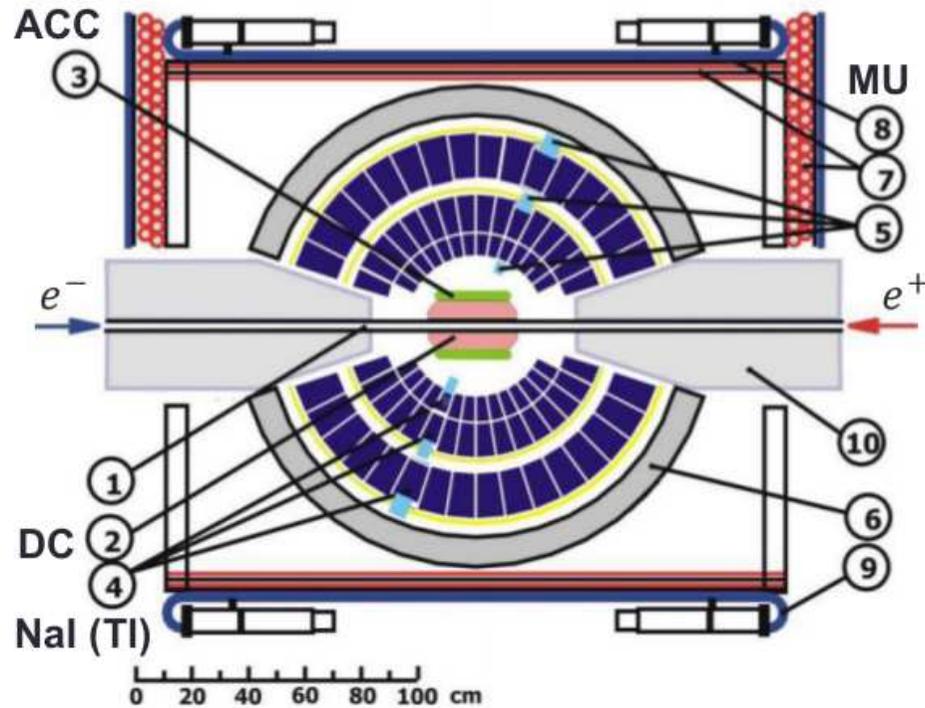
Detector CMD-3



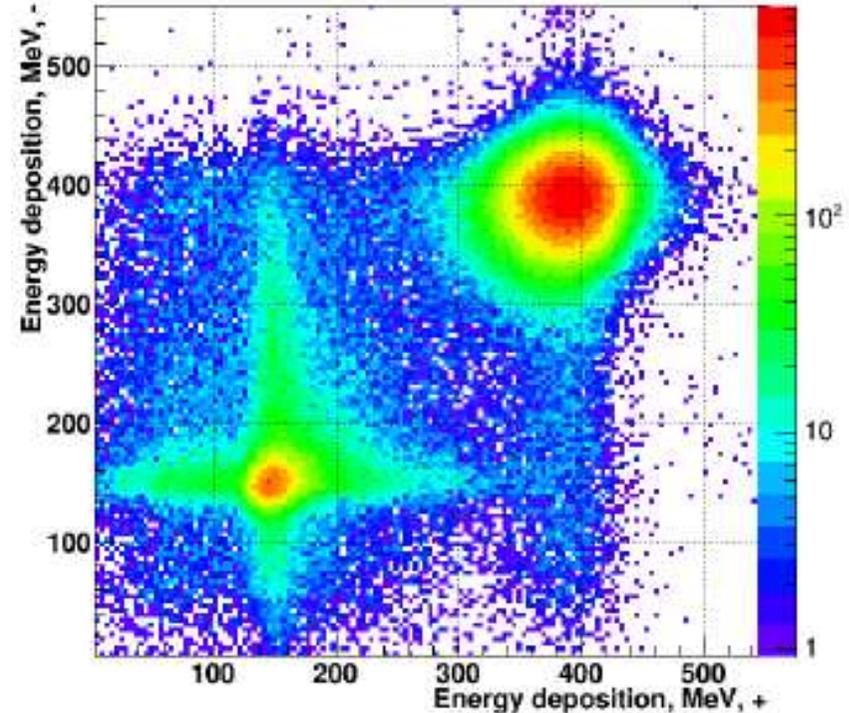
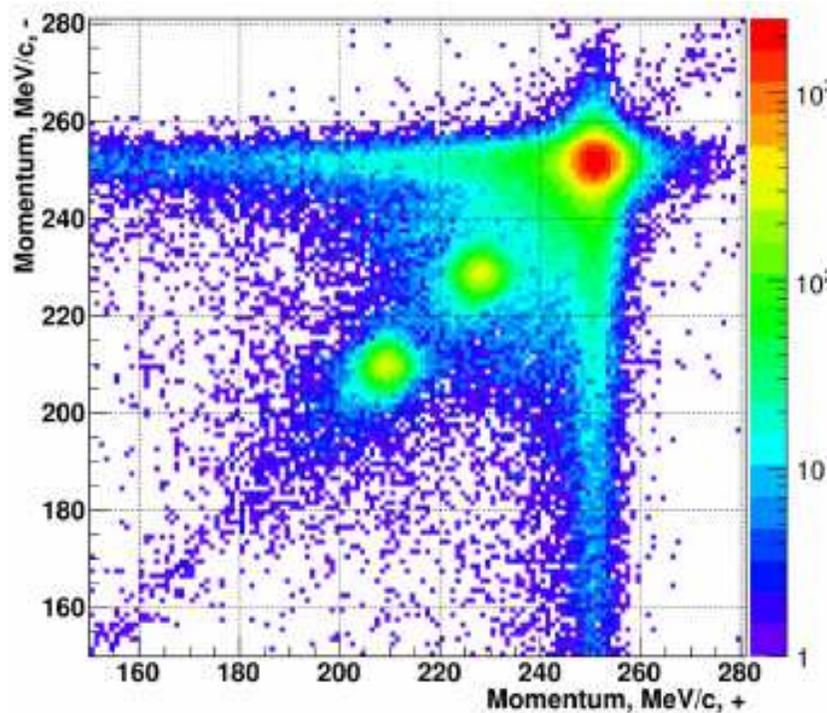
1.3 T magnetic field
Tracking: $\sigma_{R\phi} \sim 100 \mu$, $\sigma_z \sim 2 \text{ mm}$
Combined EM calorimeter (LXe, CsI, BGO), $\sigma_E \sim 3\% - 8\%$

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

Detector SND

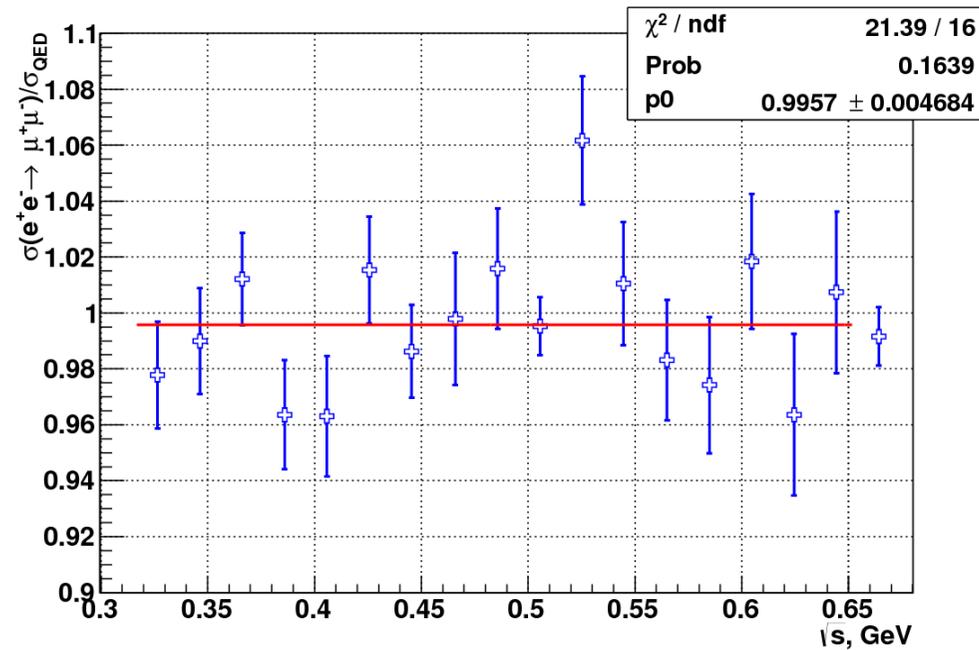


High-resolution NaI calorimeter with excellent tracking and PID

$e^+e^- \rightarrow \pi^+\pi^-$ at CMD-3 – I

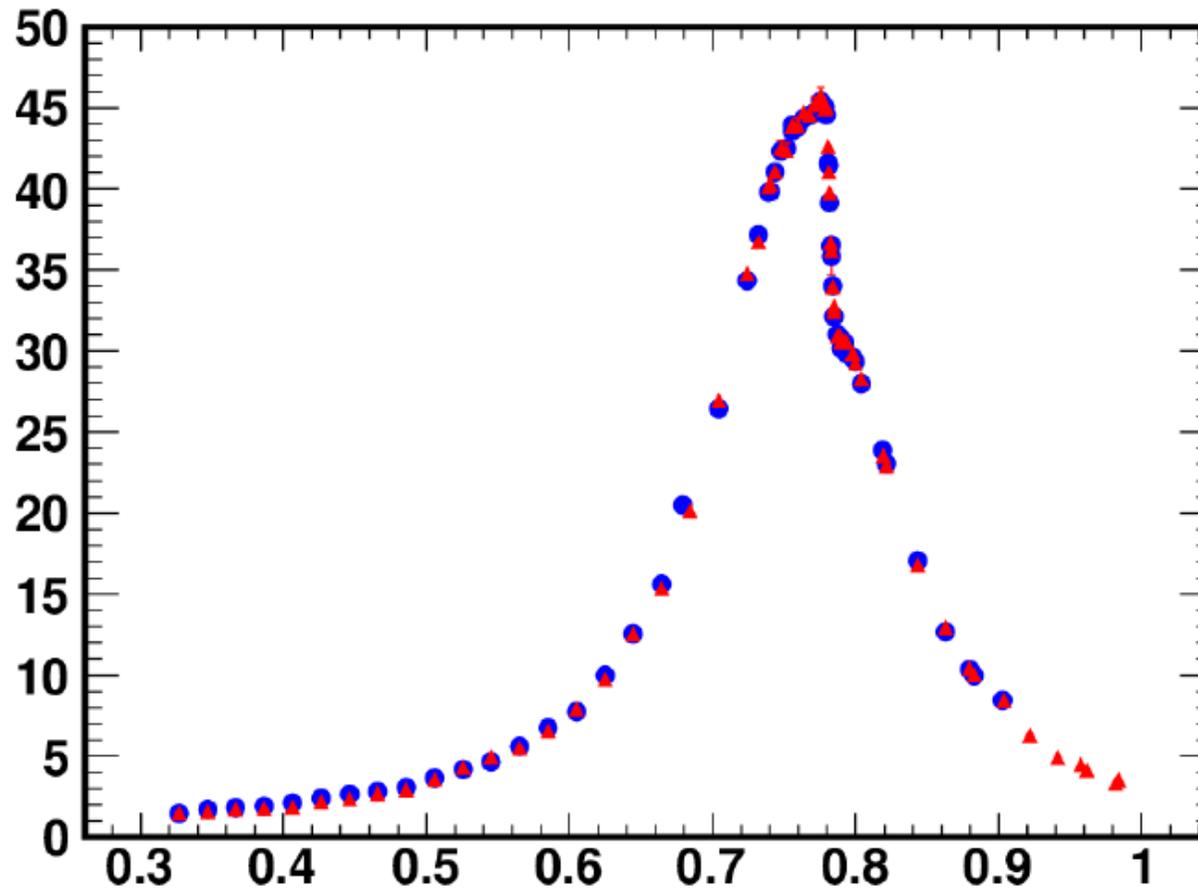
Identification below 900 MeV - by DC with separation of $\mu^+\mu^-$

At higher energy - by energy deposition in calorimeters

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


Muon separation, $N_{\pi\pi}$ and $N_{\mu\mu}$

Direct cross check of rad. corrections with $\pi^+\pi^-\gamma$

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


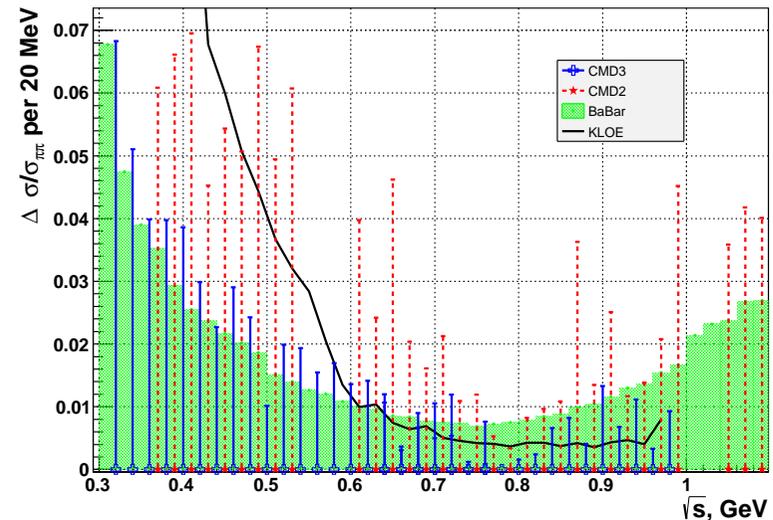
Systematic error: goal 0.35% at the ρ (BaBar achieved 0.5%)

I. Logashenko, ICHEP-2016

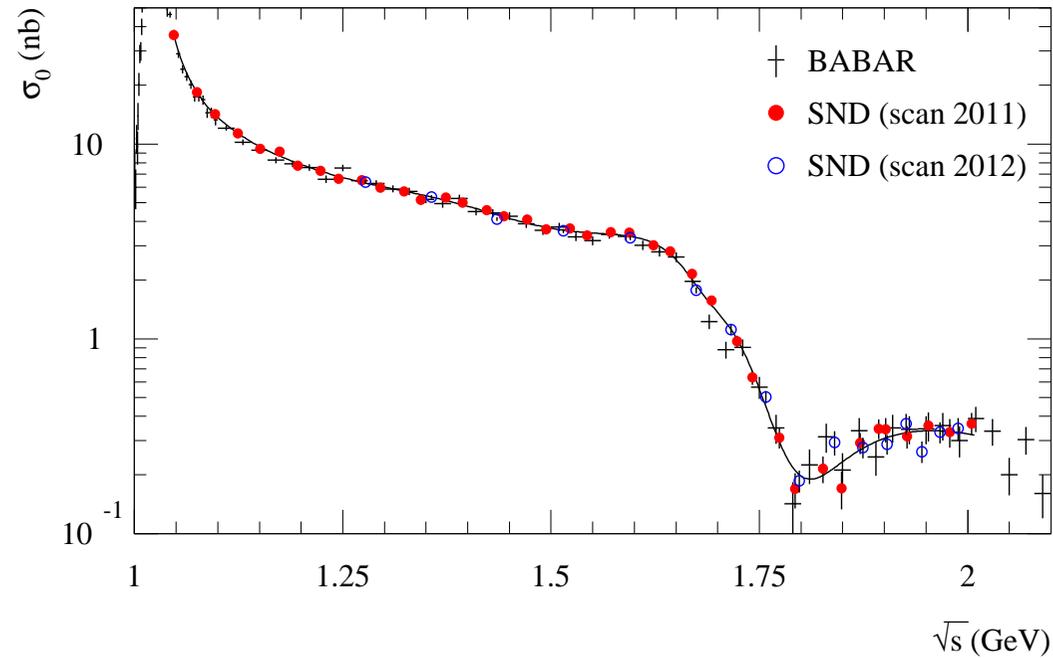
$$e^+e^- \rightarrow \pi^+\pi^- \text{ at CMD-3 - IV}$$

$e/\mu/\pi$ separation	0.5-1.5 (0.2)
Fiducial volume	0.3-0.5 (0.1)
Beam Energy	0.1 (0.1)
Rad. corrections	0.2 (0.1)
Det. efficiency	0.5-1.5 (0.1)

Main sources of systematics



Statistics not worse than at BaBar

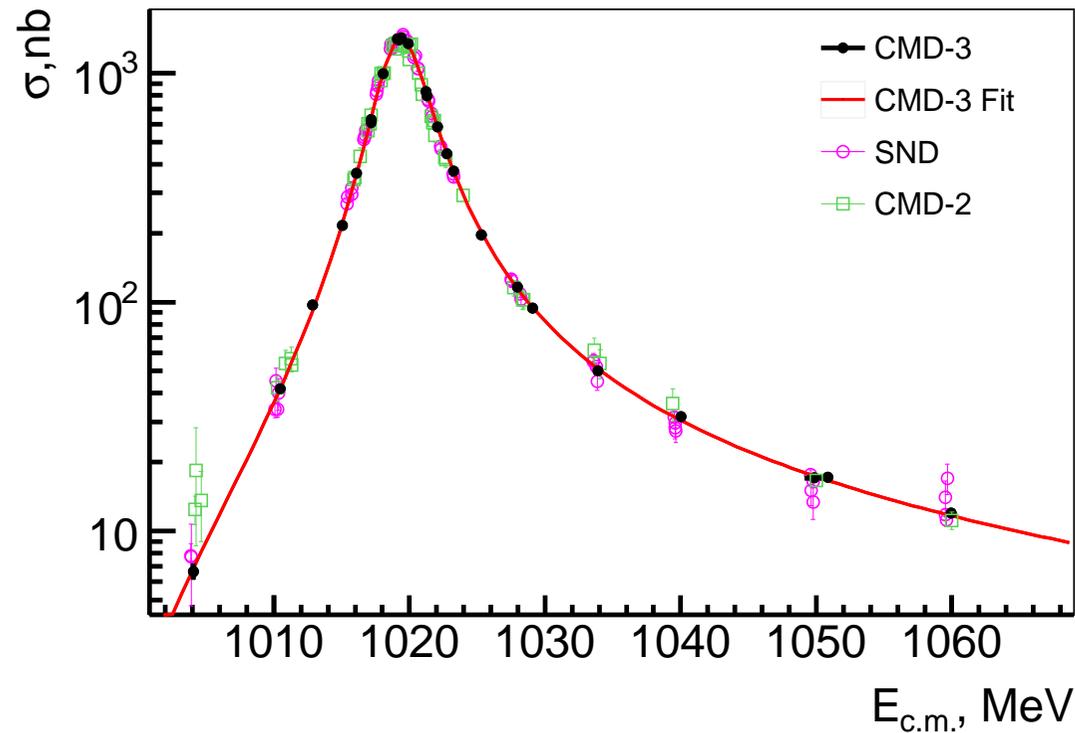
$e^+e^- \rightarrow K^+K^-$ at SND

SND agrees with BaBar and has better precision

Disagreement with SND at VEPP-2M and DM2 is confirmed

M.N. Achasov et al., arXiv:1608.08757

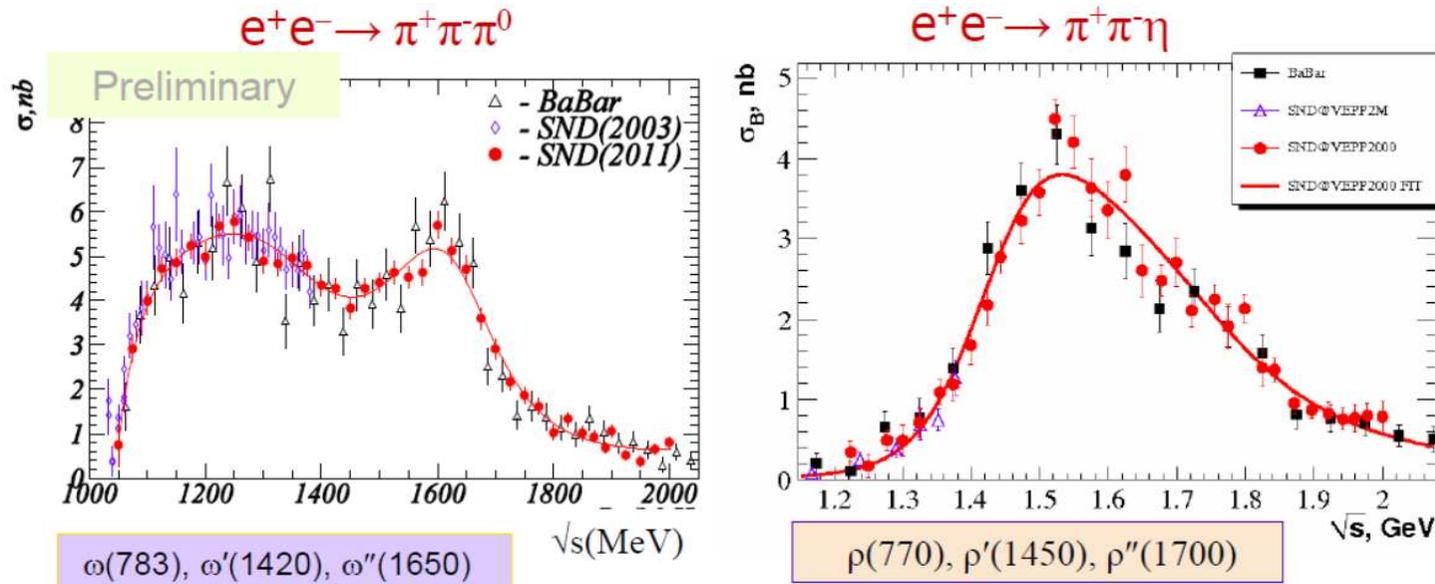
$$e^+e^- \rightarrow \phi \rightarrow K_S^0 K_L^0 \text{ at CMD-3}$$



The most precise measurement of the cross section
based on 6.5×10^5 events, 1.8% systematic uncertainty

E.A. Kozyrev et al., Phys. Lett. B760 (2016) 314

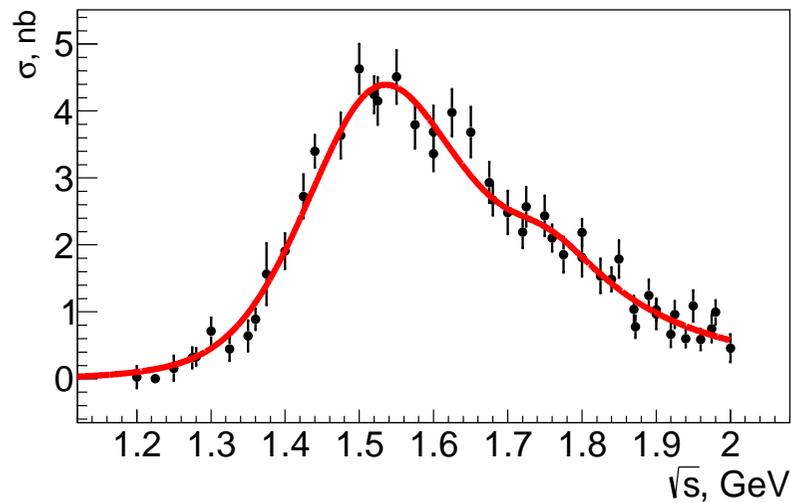
$e^+e^- \rightarrow \pi^+\pi^-\pi^0$ and $e^+e^- \rightarrow \pi^+\pi^-\eta$ at SND



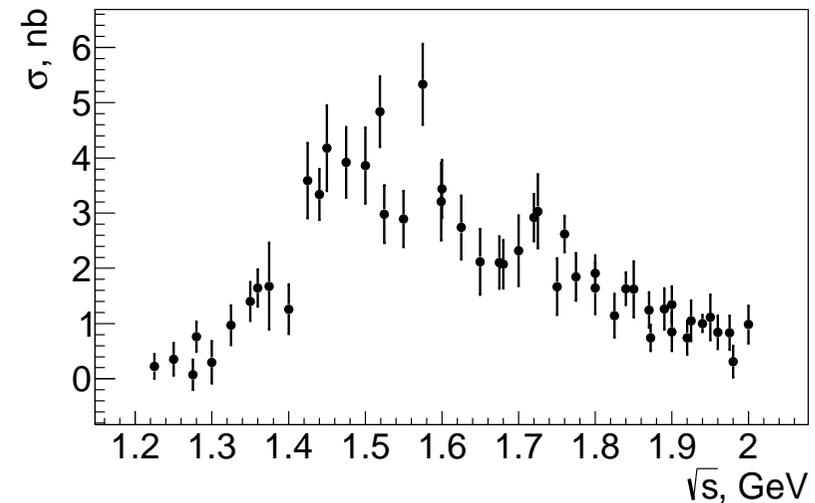
At each \sqrt{s} full information on invariant masses

$\pi^+\pi^-\pi^0$: V. Aulchenko et al., JETP 121 (2015) 34,

$\pi^+\pi^-\eta$: V. Aulchenko et al., Phys. Rev. D 91 (2015) 052013

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


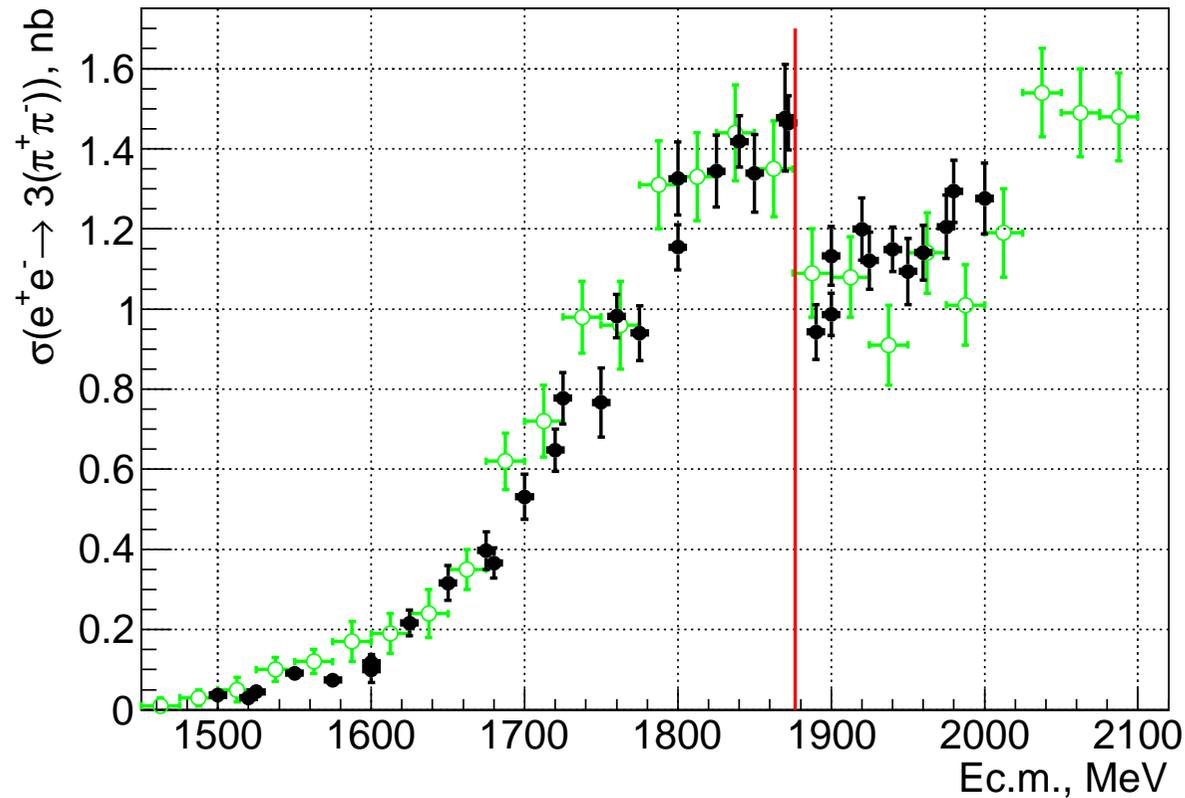
$\eta \rightarrow 2\gamma$, 6800 events, 8% syst.



$\eta \rightarrow \pi^+\pi^-\pi^0$, 1250 events, 10% syst.

CMD-3 - Preliminary

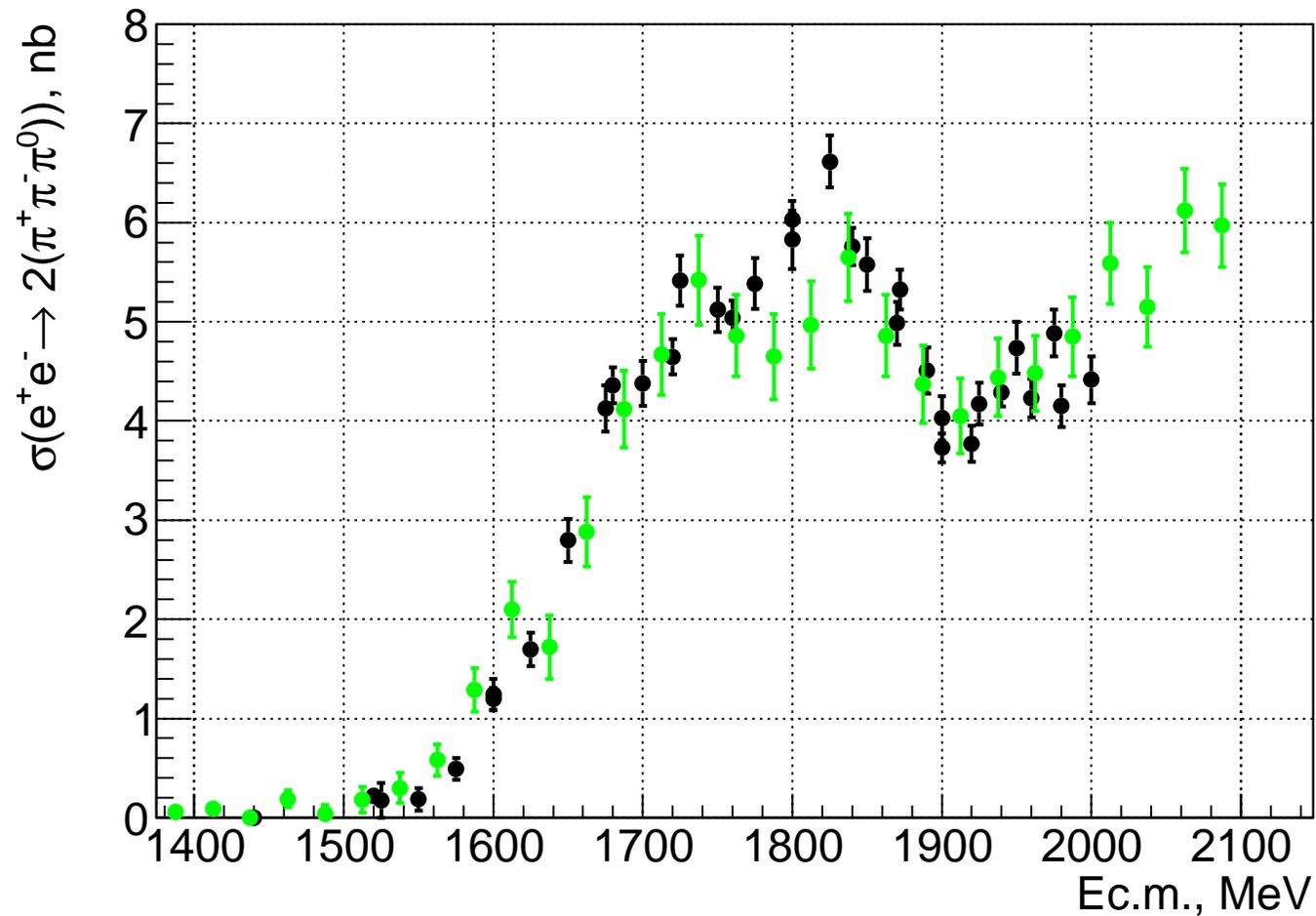
Will we unambiguously observe the $\rho(1700)$?

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


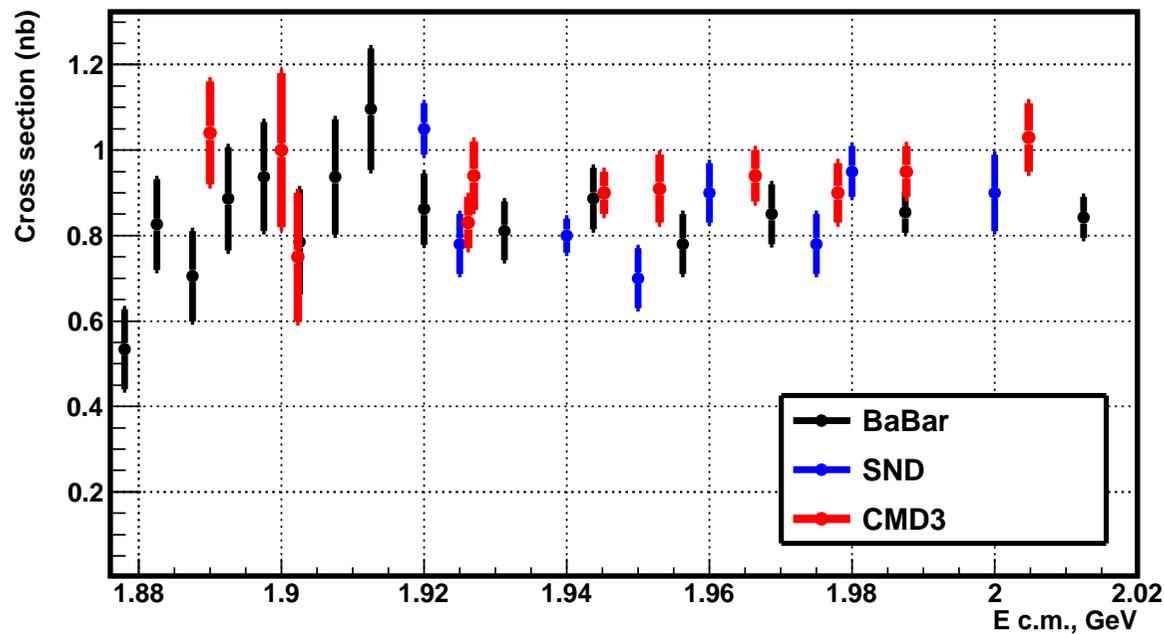
The dip structure near $N\bar{N}$ threshold is confirmed

R.R. Akhmetshin et al., Phys. Lett. B 723 (2013) 82

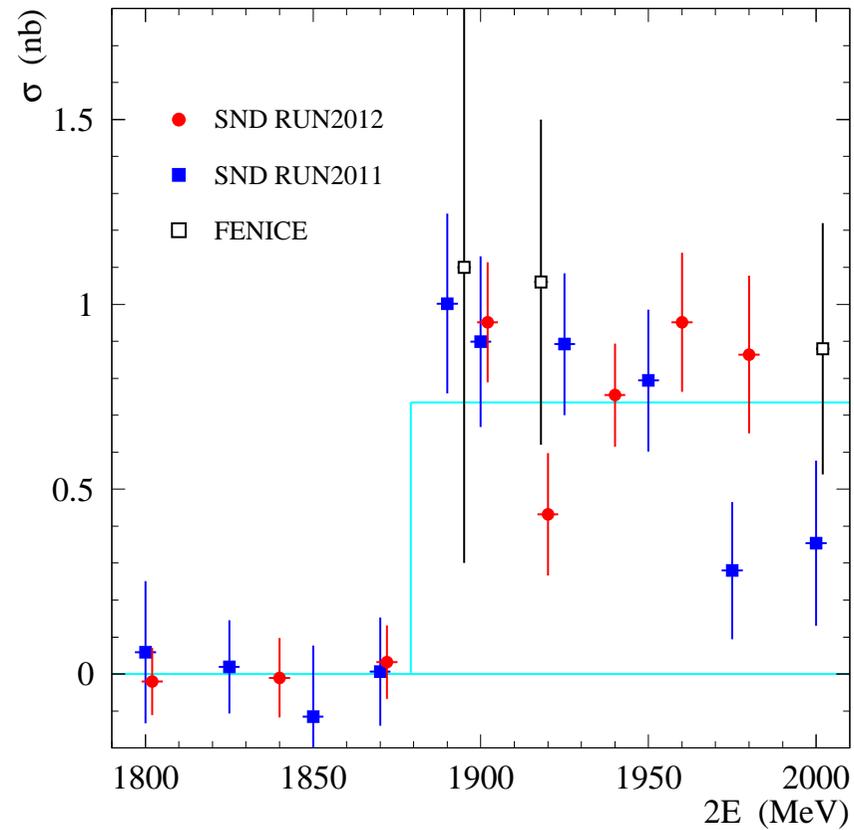
$$e^+e^- \rightarrow 2\pi^+2\pi^-2\pi^0 \text{ at CMD-3}$$



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

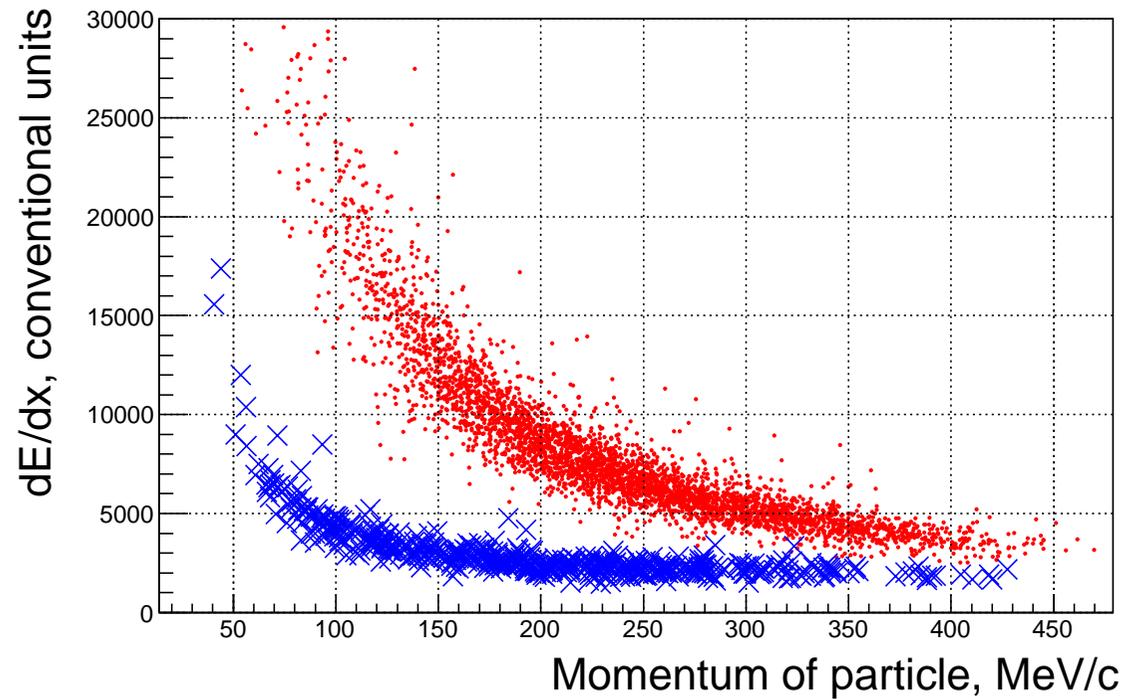
$p\bar{p}$ Production at VEPP-2000

In addition to cross sections, first attempts of measuring f/f made
R.R. Akhmetshin et al., Phys. Lett. B759 (2016) 634

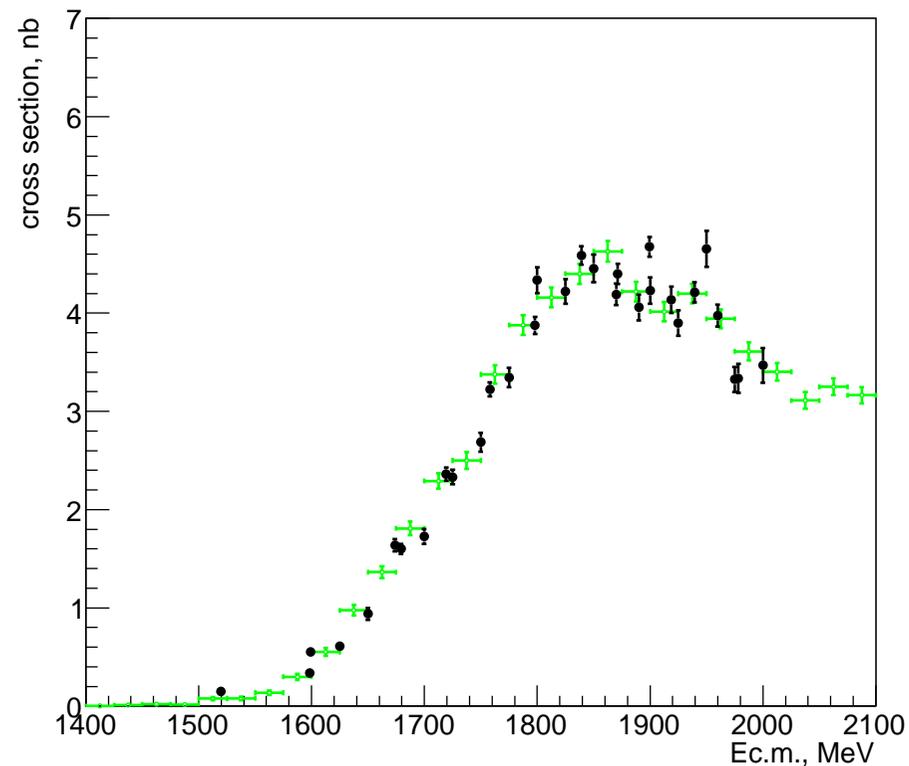
$e^+e^- \rightarrow n\bar{n}$ at SND

The first and more precise measurement after FENICE
M.N. Achasov et al., Phys. Rev. D 90 (2014) 112007

Multibody Final States with Charged Kaons



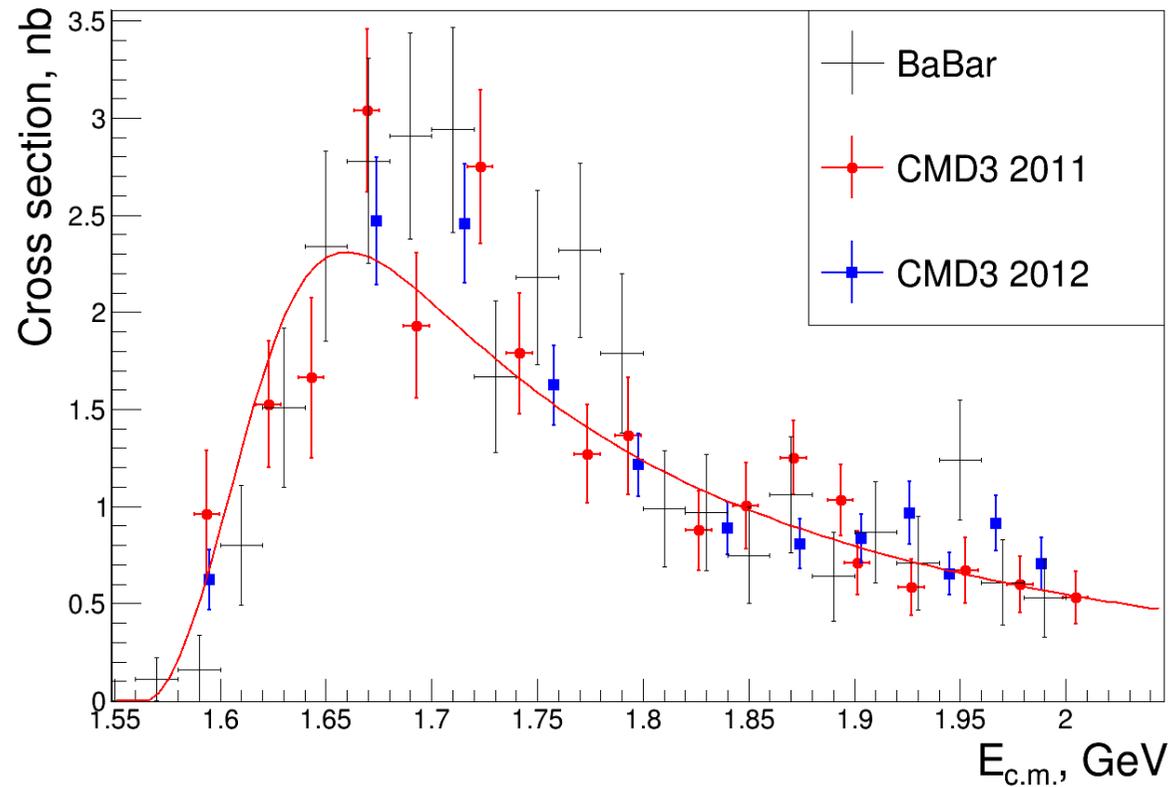
Ionization losses in DC (dE/dx) provide good K/π separation

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


From more than 10000 events many different mechanisms seen:
 $K_1(1270)\bar{K} \rightarrow K\bar{K}\rho$, $K^*(892)\bar{K}\pi$, $K_1(1400)\bar{K} \rightarrow K^*(892)\bar{K}\pi$, $\phi\pi^+\pi^-$

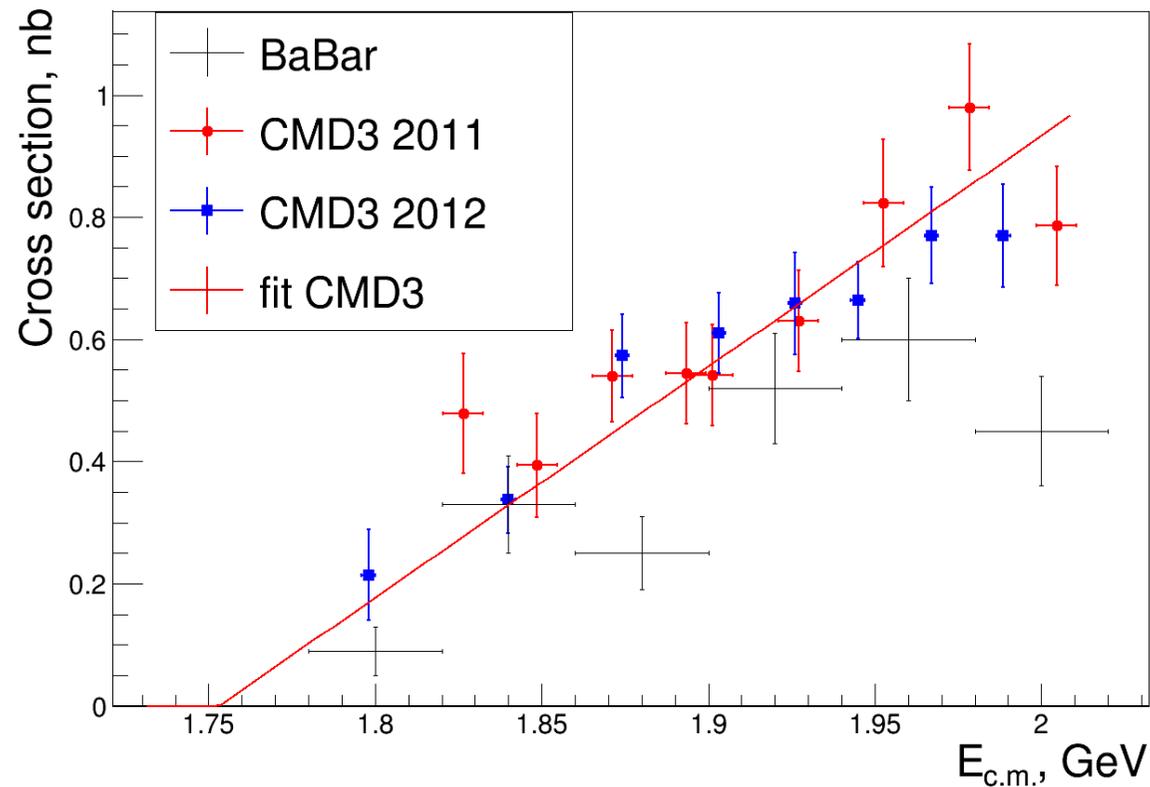
R.R. Akhmetshin et al., Phys. Lett. B 756 (2016) 153

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



1371 events, 6% systematic uncertainty, $\phi\eta$ only

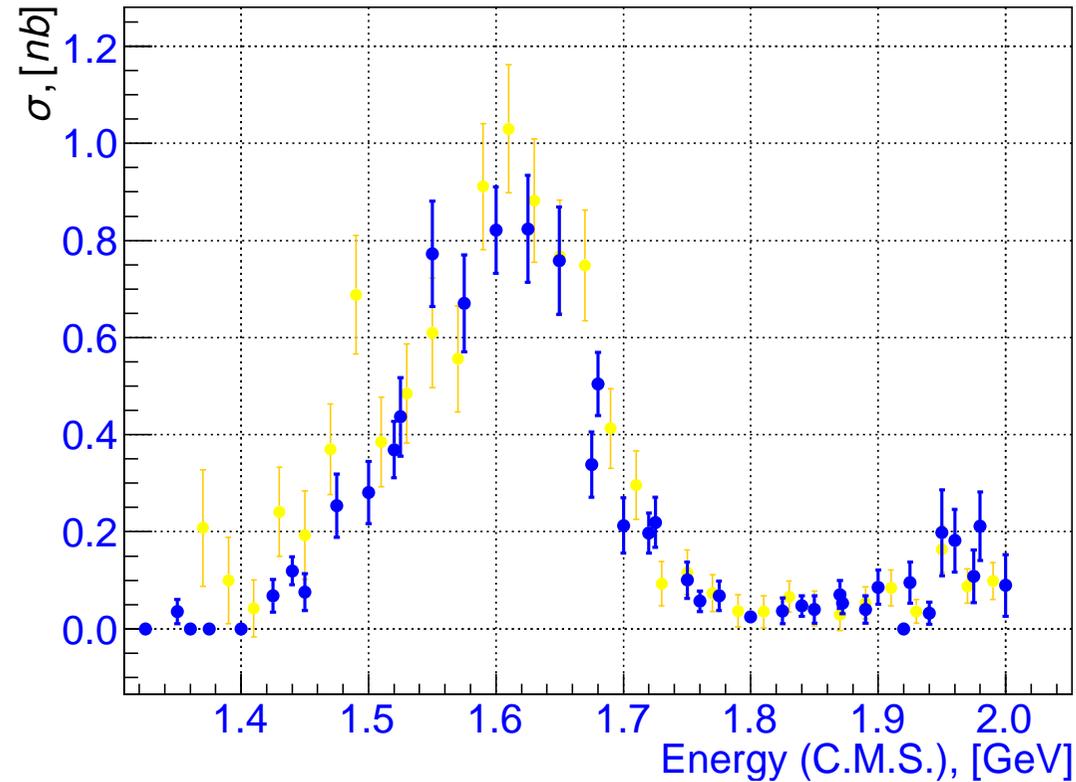
The cross section is consistent with and more precise than BaBar

$e^+e^- \rightarrow K^+K^-\omega$ at CMD-3

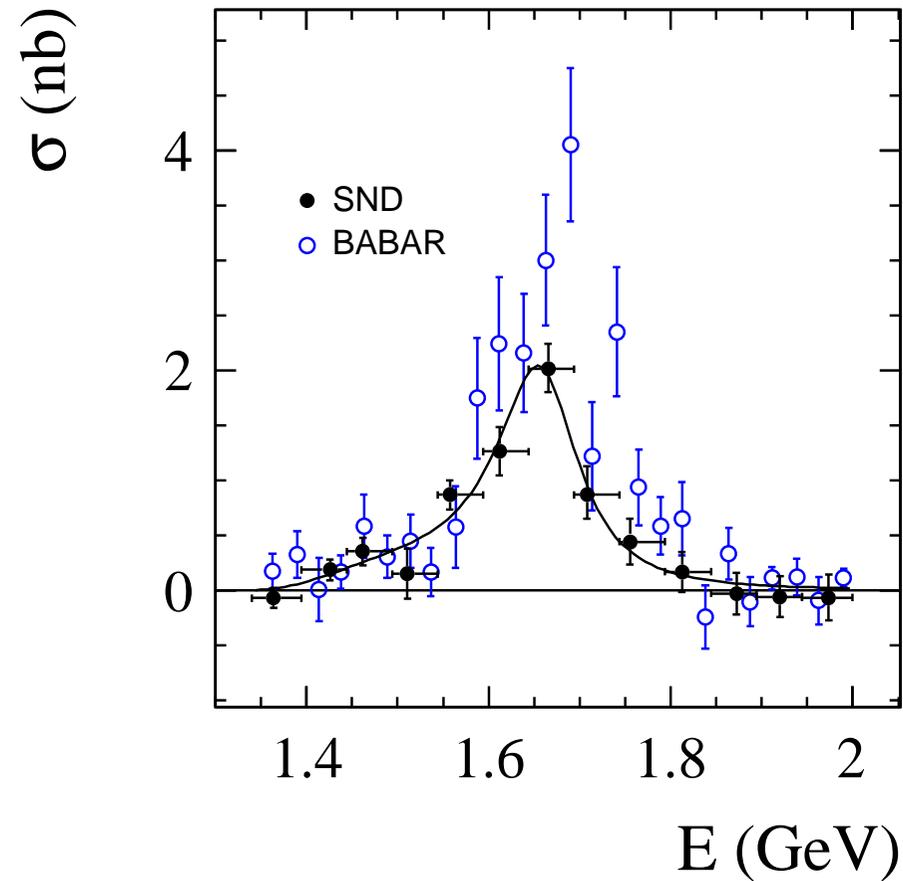
1016 events, 6% systematics

The cross section is consistent with and more precise than BaBar

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

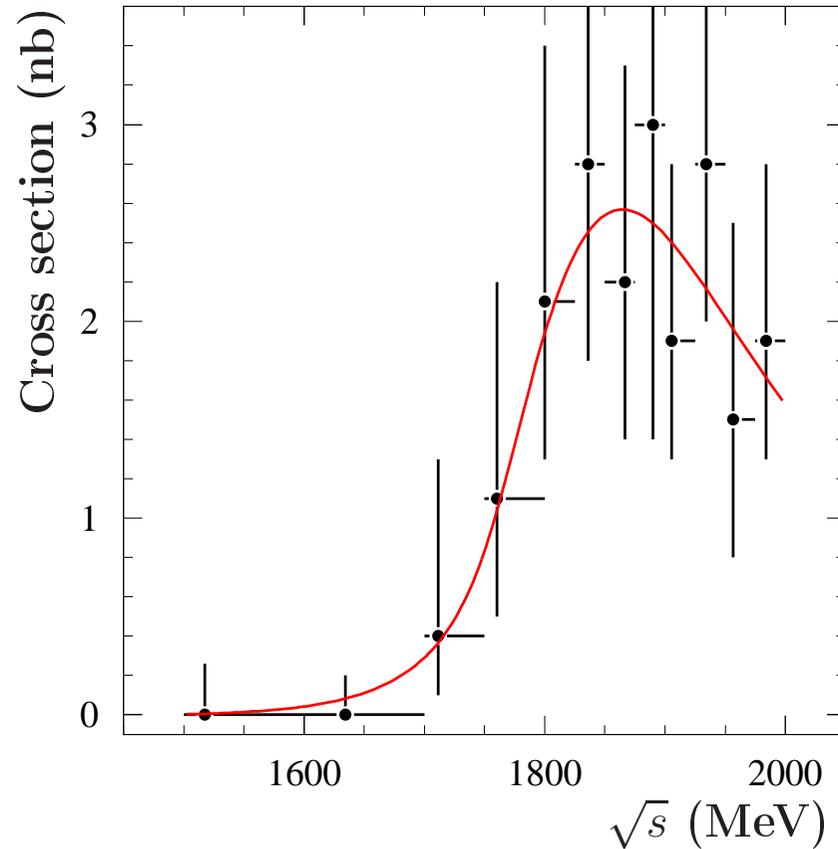


From 600 events the $\phi\pi^0$ and $K^{*\pm}(892)K^\mp$ mechanisms seen
The cross section is consistent with and more precise than BaBar

$e^+e^- \rightarrow \omega\eta$ at SND

850 $\pi^+\pi^-\pi^0\eta$ events, significant disagreement with BaBar above 1.6 GeV

M.N. Achasov et al., arXiv:1607.00371

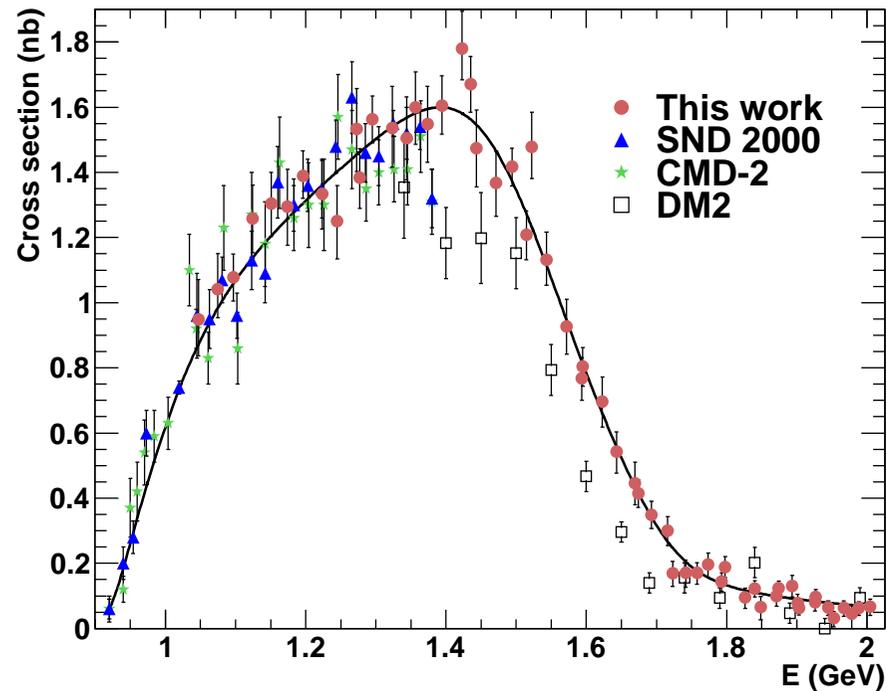
$$e^+e^- \rightarrow \omega\eta\pi^0 \text{ at SND}$$


First ever observation with 62 $\pi^0\pi^0\gamma\eta$ events

The $\omega a_0(980)$ mechanism dominates

M.N. Achasov et al., Phys. Rev. D94 (2016) 032010

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

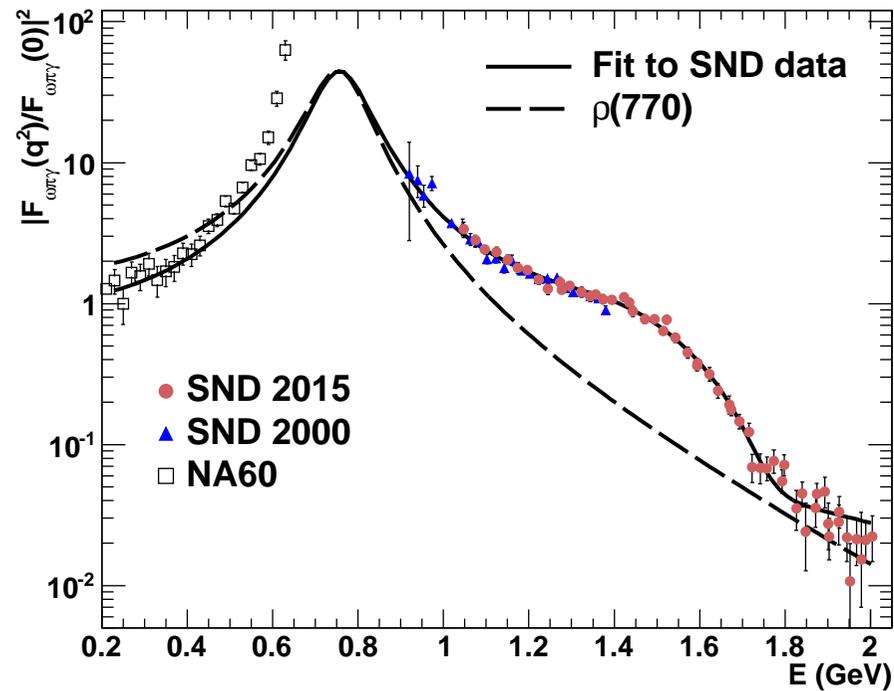


10.2k 5γ events, the systematic uncertainty varying from 2.7% to 5.2%

CVC test with $\mathcal{B}(\tau^- \rightarrow \omega\pi^- \nu_\tau)$: $(1.87 \pm 0.02 \pm 0.07)\%_{\text{CVC}}$ $(1.95 \pm 0.06)\%_{\text{WA16}}$

M.N. Achasov et al., arXiv:1610.00235

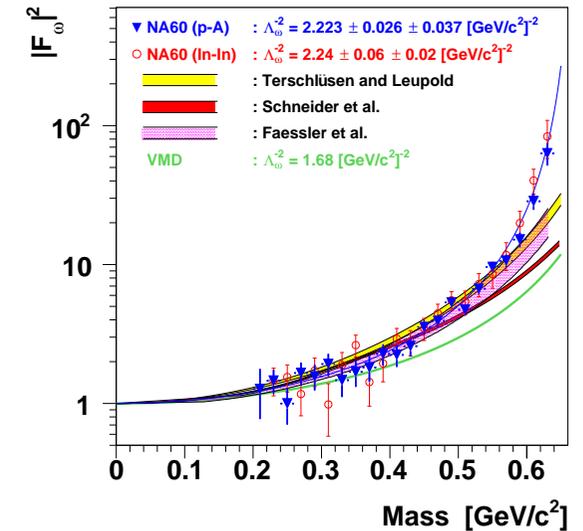
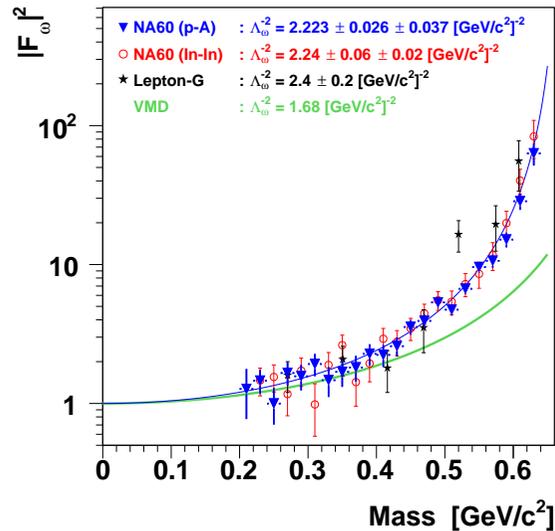
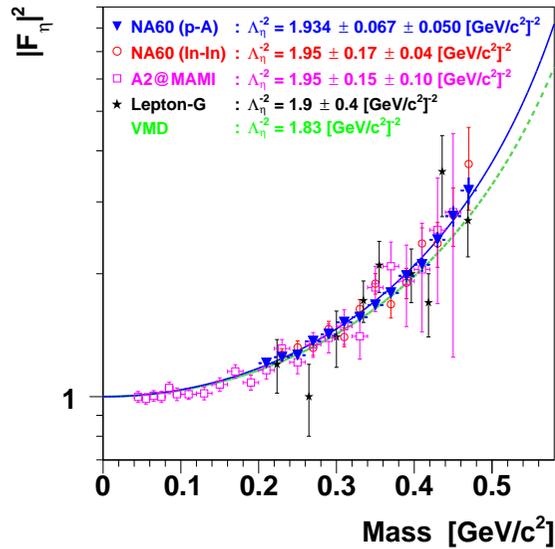
$$e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^0\pi^0\gamma \text{ at SND - II}$$



The fit curve is in obvious conflict with NA60 results at low energy

M.N. Achasov et al., arXiv:1610.00235

Transition Form Factors from NA60

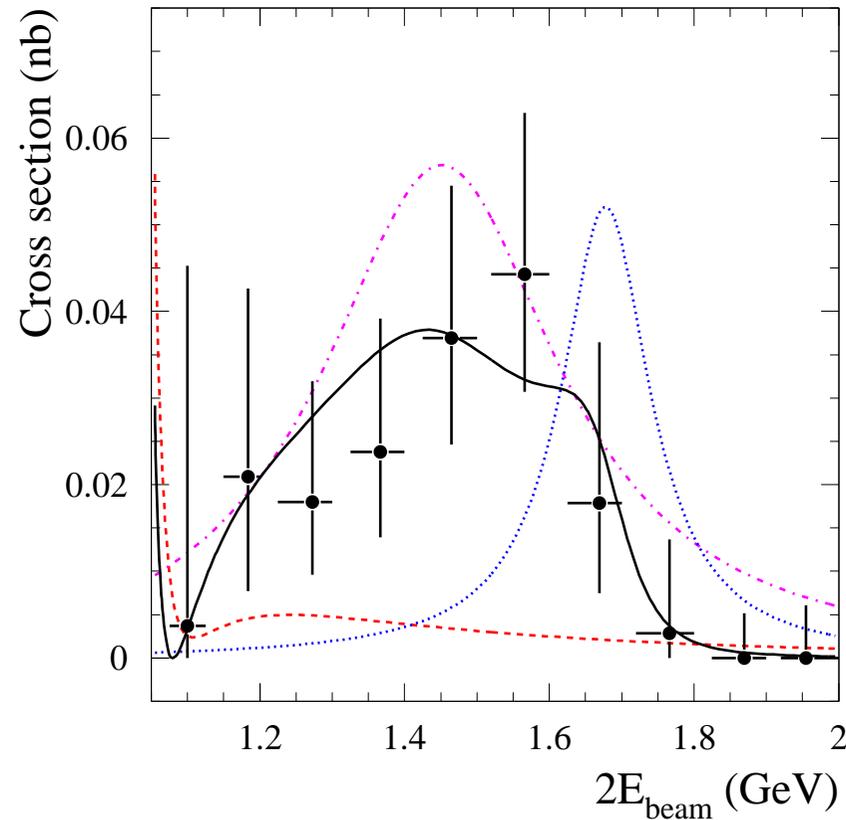


R. Arnaldi et al. (NA60), Phys. Lett. B757 (2016) 437 (p-A)
 TFF of NA60 is in obvious conflict with theory near the kinematic limit

A2 data on $\eta \rightarrow e^+e^-\gamma$ and $\omega \rightarrow \pi^0 e^+e^-$ agree with theory,

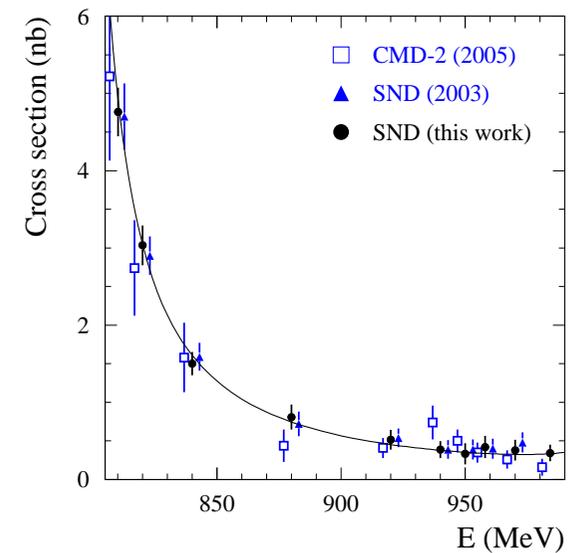
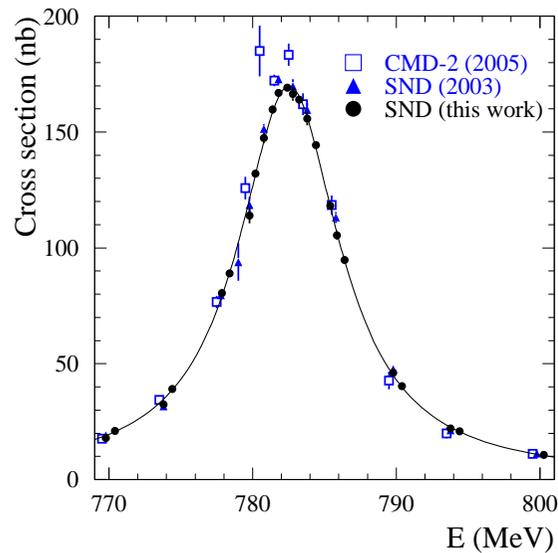
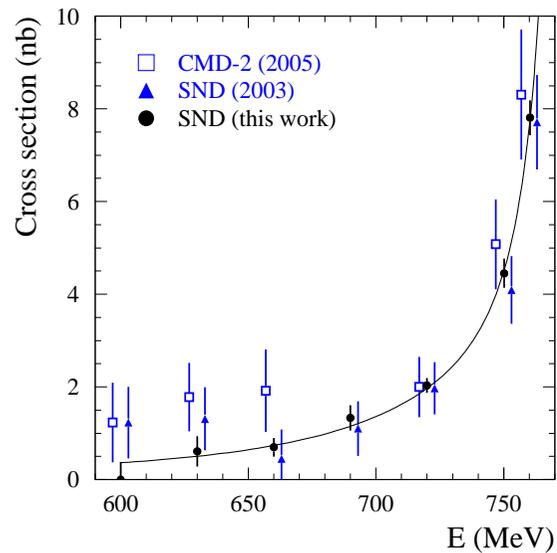
P. Adlarson et al., arXiv:1609.04503

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



The first measurement of radiative decays above 1.4 GeV

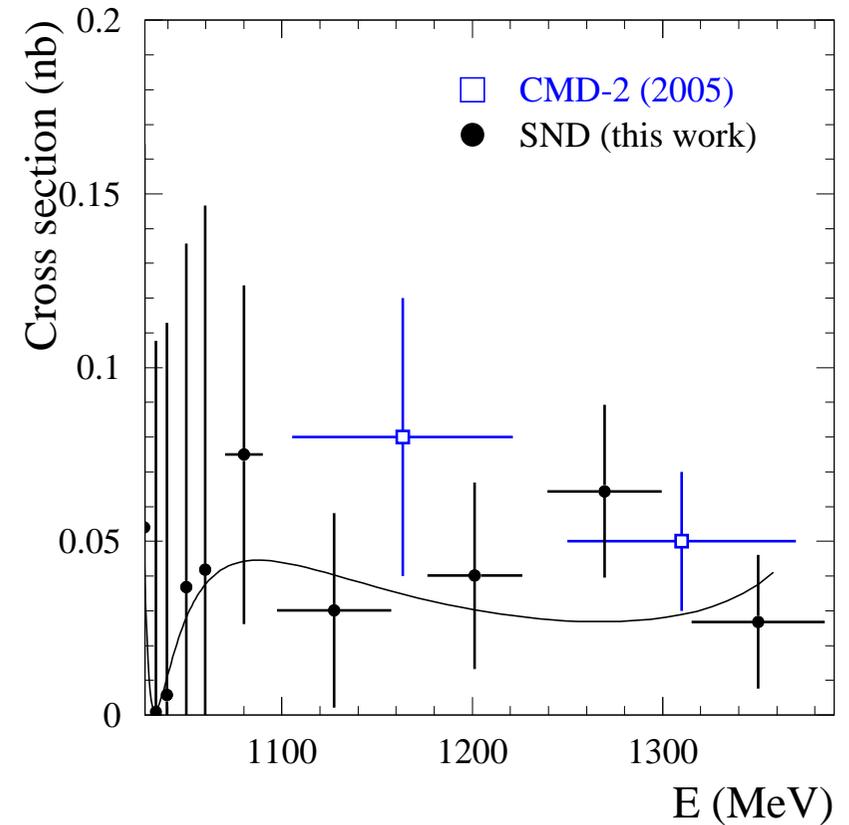
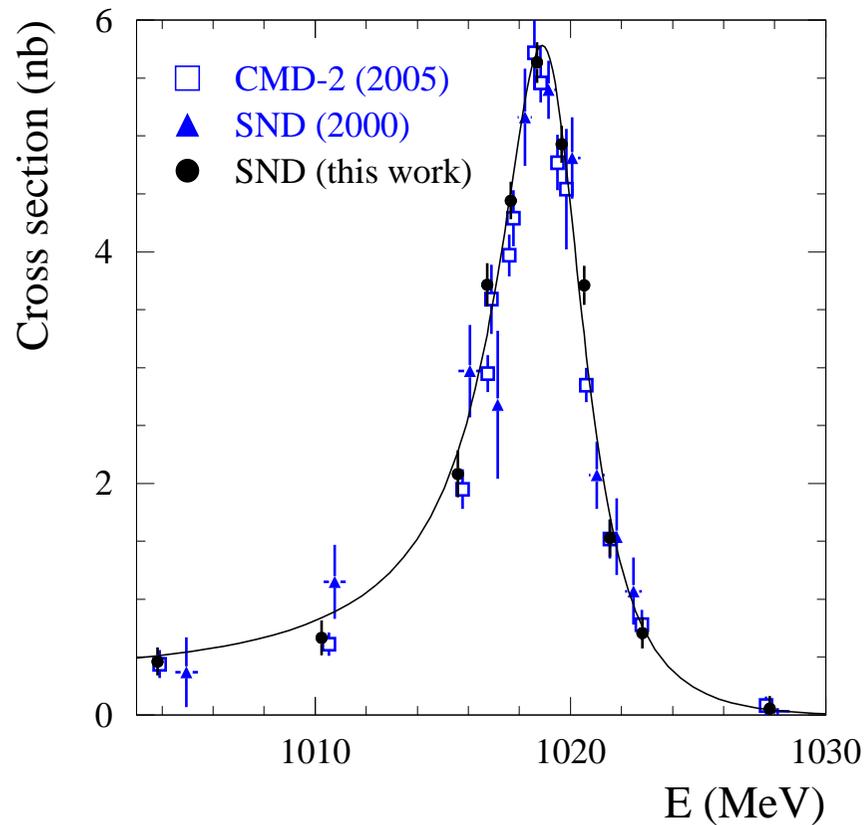
M.N. Achasov et al., Phys. Rev. D 90 (2014) 032002

$$e^+e^- \rightarrow \pi^0\gamma \text{ at SND at VEPP-2M - I}$$


The most precise measurement below 1.4 GeV

SND points seem to be below CMD-2

M.N. Achasov et al., Phys. Rev. D 93 (2016) 092001

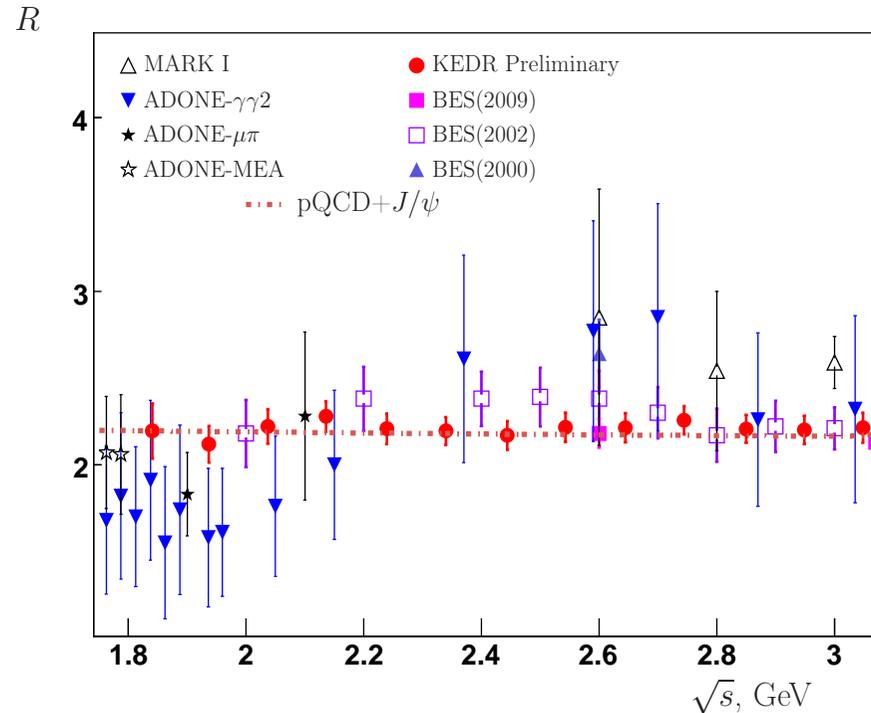
$$e^+e^- \rightarrow \pi^0\gamma \text{ at SND at VEPP-2M - II}$$


More precise measurements needed above the ϕ
M.N. Achasov et al., Phys. Rev. D 93 (2016) 092001

Search for $e^+e^- \rightarrow \eta', \eta$ at VEPP-2000

- CMD-3 looks for $e^+e^- \rightarrow \eta' \rightarrow \eta\pi^+\pi^-$,
R.R. Akhmetshin et al., Phys. Lett. B740 (2015) 273
- SND combines their data on $e^+e^- \rightarrow \eta' \rightarrow \eta\pi^+\pi^-, \eta\pi^0\pi^0$ with CMD-3:
 $\mathcal{B}(\eta' \rightarrow e^+e^-) < 5.6 \cdot 10^{-9}$ at 90%CL,
M.N. Achasov et al., Phys. Rev.D91 (2015) 092010
- The unitarity limit $\mathcal{B}(\eta' \rightarrow e^+e^-) > 3.75 \cdot 10^{-11}$
- SND used 110 nb^{-1} for a feasibility study of $e^+e^- \rightarrow \eta, \eta \rightarrow 3\pi^0$,
 $\eta \rightarrow 2\gamma, \pi^+\pi^-\pi^0$ dominated by QED background,
 $\mathcal{B}(\eta \rightarrow e^+e^-) < 3 \cdot 10^{-6}$ at 90%CL,
M.N. Achasov et al., JETP Lett. 102 (2015) 266
- The best limit is by HADES in Phys. Lett. B731 (2014) 265,
 $\mathcal{B}(\eta \rightarrow e^+e^-) < 2.3 \cdot 10^{-6}$ at 90%CL,
The HADES limit can be improved after a 2-week run
- The unitarity limit is $\mathcal{B}(\eta \rightarrow e^+e^-) > 1.8 \cdot 10^{-9}$

R Measurement between 1.84 and 3.05 GeV at KEDR



$\overline{R} = 2.209 \pm 0.020 \pm 0.046$ agrees with $R_{\text{pQCD}} = 2.18 \pm 0.02$

based on $\alpha_s(m_\tau) = 0.333 \pm 0.013$ derived from hadronic τ decays

R at KEDR from 1.8 to 2 GeV can be compared to the sum of CMD-3 σ 's

V.V. Anashin et al., arXiv:1610.2827

Future

- Two new measurements of a_μ are expected in 3-5 years:
E989 at Fermilab plans to improve the uncertainty from 0.5ppm to 0.14 ppm, they plan to start running in 2017
J-PARC has the same precision goal, data taking planned in 2019-2021
- What is expected for the theoretical prediction?
Progress in low energy e^+e^- annihilation expected, improving the LO error from 4.2 to 2.0, so 2.6 from the LbL dominates, in the new approach 1.0 may be achieved (?) giving 2.2 in total
First principles (lattice) give promising results, but far from final
C.M. Carloni Calame et al., Phys. Lett. B 746 (2015) 325,
 $a_\mu^{\text{had,LO}}$ from $\alpha(t)$ in the spacelike region of Bhabha
- With the same central values of a_μ^{exp} and a_μ^{th}
the today difference will correspond to about 10σ !!

Conclusions

- VEPP-2000 ran smoothly with CMD-3 and SND at $0.32 < \sqrt{s} < 2.00$ GeV, the achieved accuracy is comparable or better than in ISR measurements, sometimes disagreement with ISR and old results seen
- 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 σ 's due to scans in Novosibirsk and ISR from KLOE-2, BaBar, Belle, BESIII and Belle2
- Various high-statistics experiments will substantially improve the accuracy of vacuum polarization calculations for $(g_\mu - 2)/2$
- Higher statistics ($\sim 1\text{fb}^{-1}$) \Rightarrow a detailed study of dynamics, thus a study of mesons with various quantum numbers
- Good prospects for a study of transition form factors and hLbL
- Meanwhile a $\sim 3.5\sigma$ deviation of a_μ^{SM} from a_μ^{exp} persists:
New Physics or various experimental and interpretation errors?