Review of R Measurements

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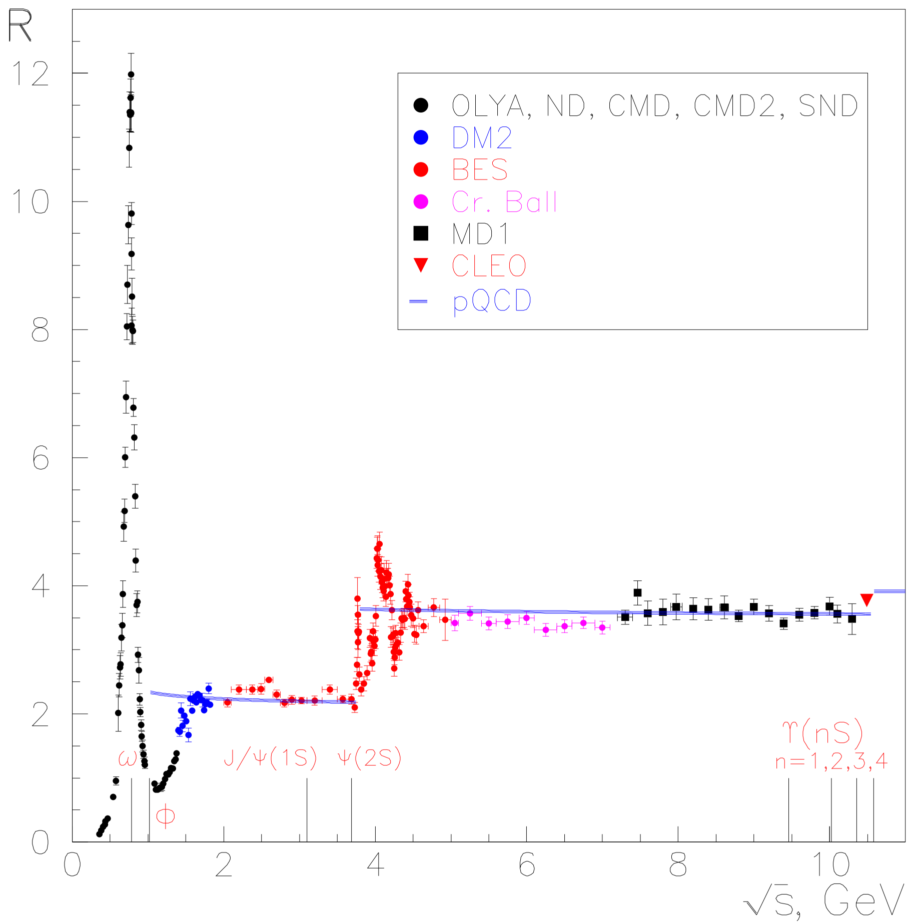
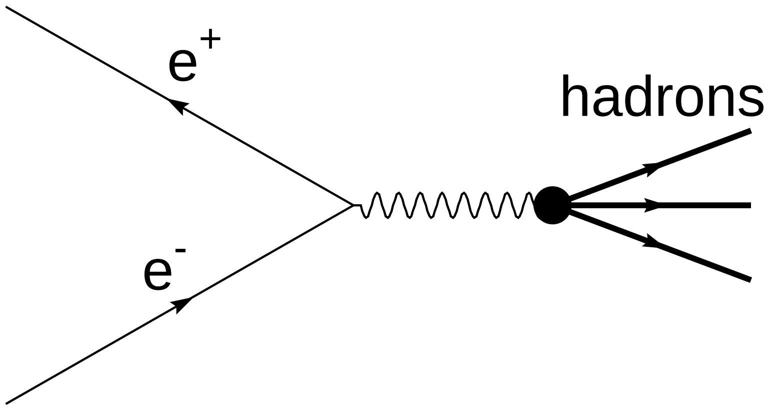
Outline

1. General
2. ISR measurements
3. Experiments at VEPP-2000
4. Conclusions

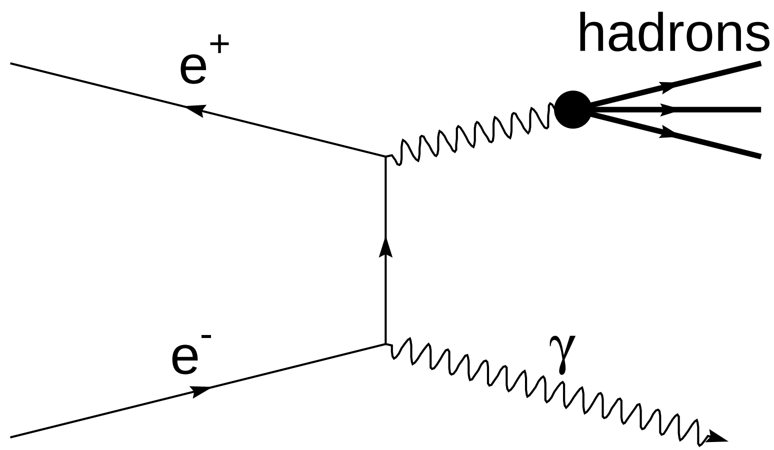
R Measurements below 10 GeV



Scan and ISR



Scan



ISR

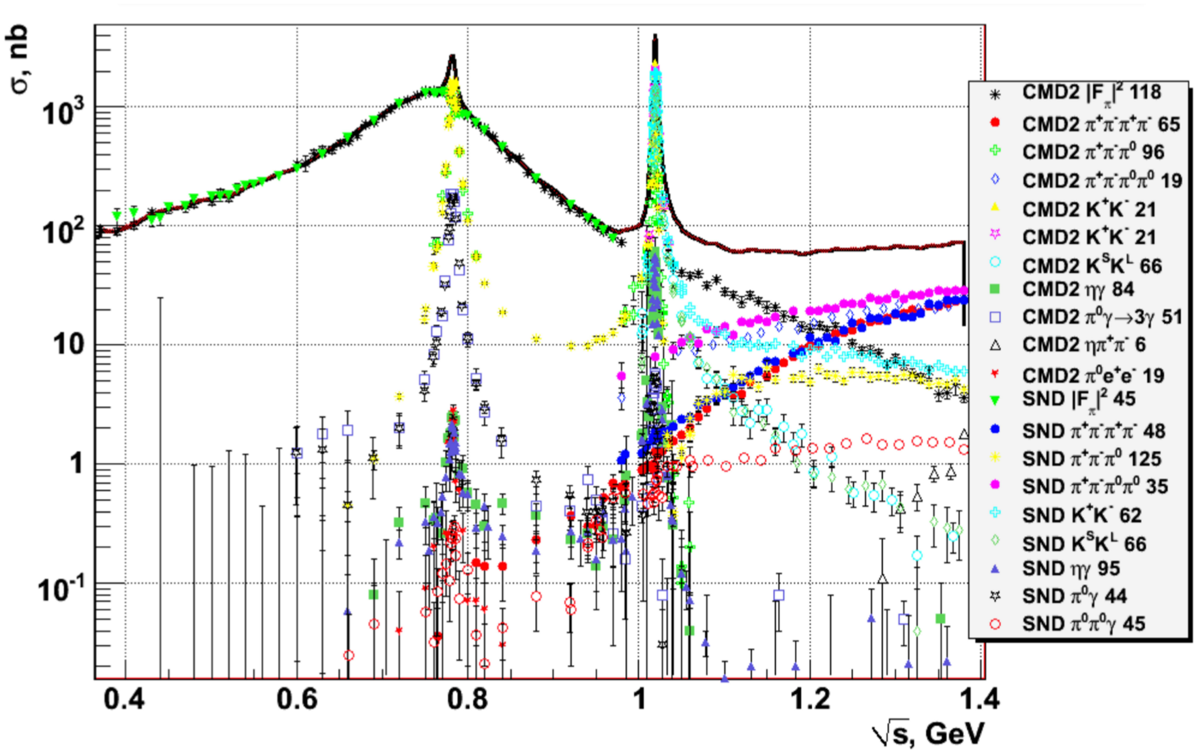
Scan can provide larger data samples at fixed energy

ISR benefits from the same systematics and flat acceptance,

but may suffer from more complicated radiative effects

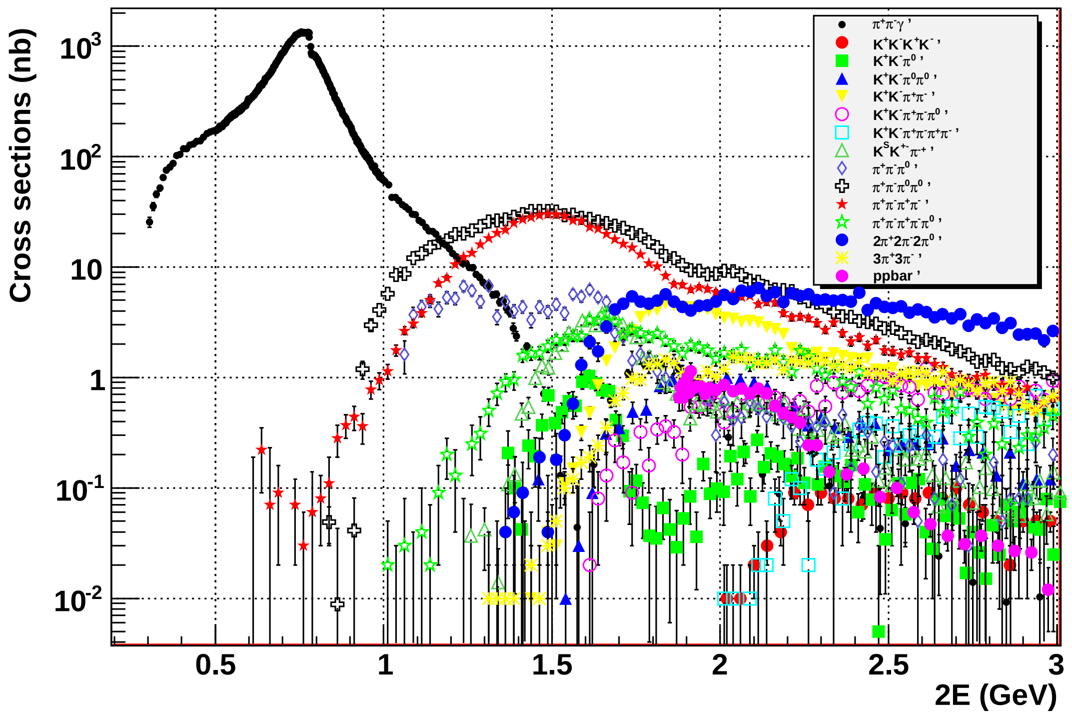
a much larger c.m. energy bin

Current Status of Exclusive Measurements – I



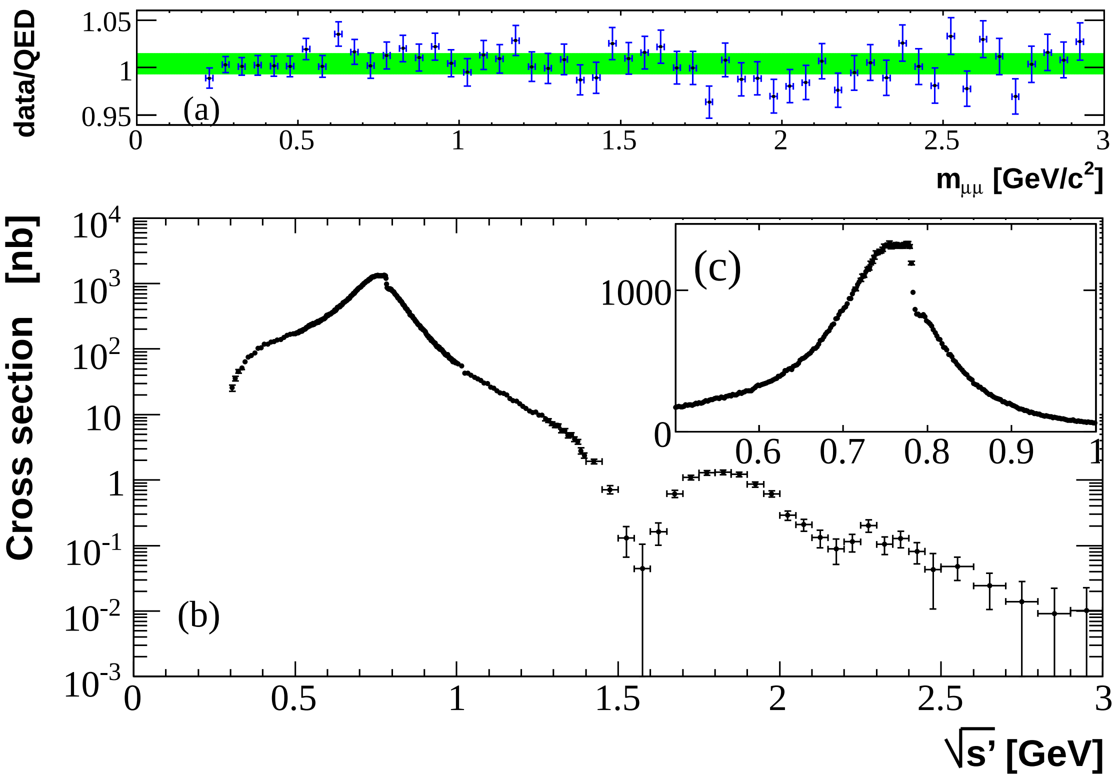
Impressive achievements of CMD-2, SND (scan at $\sqrt{s} < 1.4$ GeV)
and KLOE (ISR at $\sqrt{s} < 1.0$ GeV)

Current Status of Exclusive Measurements – II



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

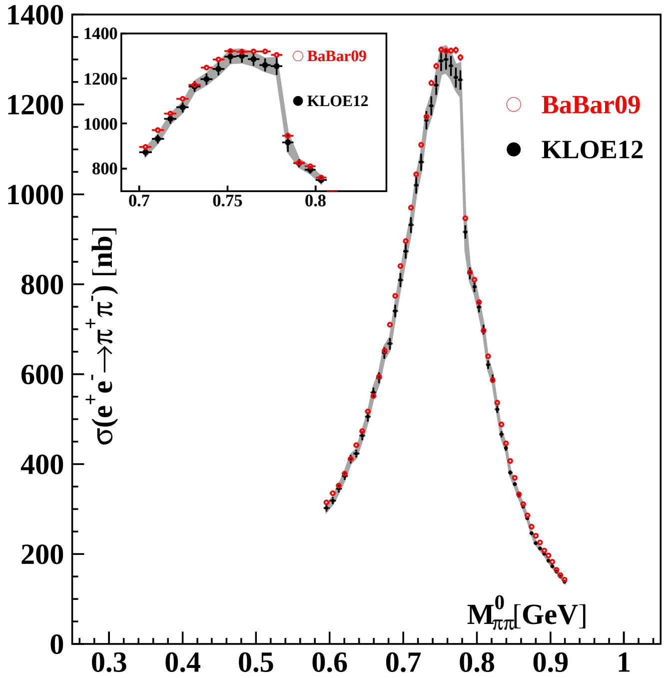
$e^+e^- \to \pi^+\pi^-$ at BaBar



The systematic error near the ρ is 0.5%

J.P. Lees et al., Phys. Rev. D86 (2012) 032013

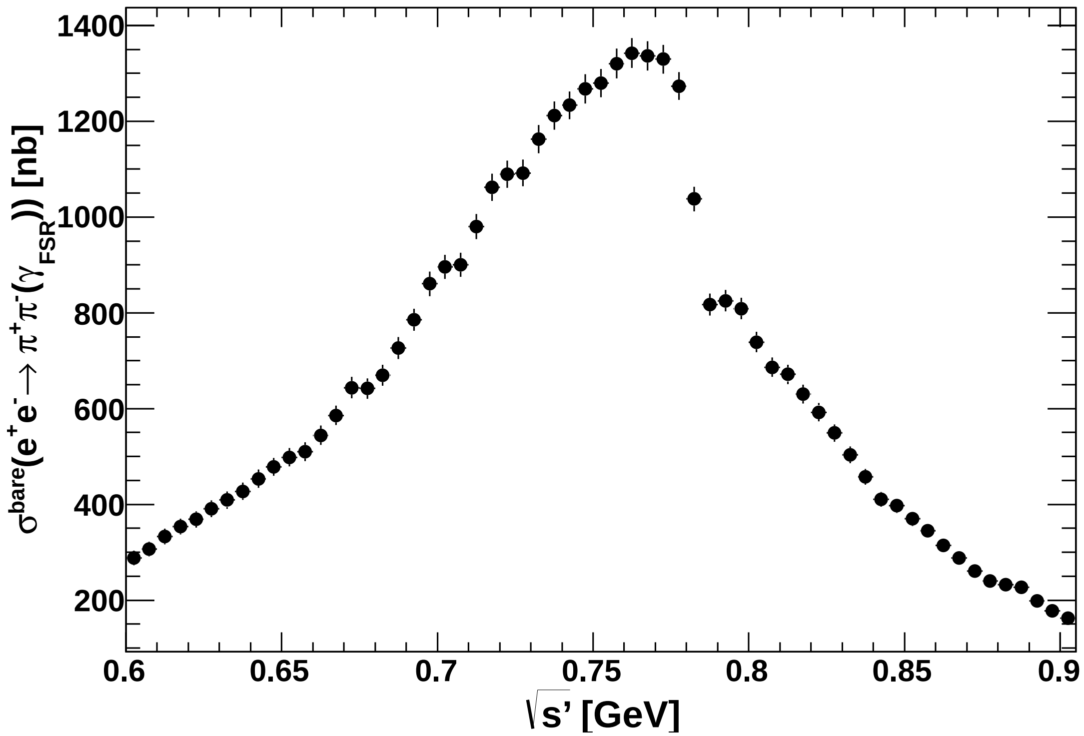
$e^+e^- \to \pi^+\pi^-$ at KLOE/KLOE-2



The systematic error is 0.7%

D. Babusci et al., Phys. Lett. B720 (2013) 336

$e^+e^- \to \pi^+\pi^-$ with ISR at BESIII – I

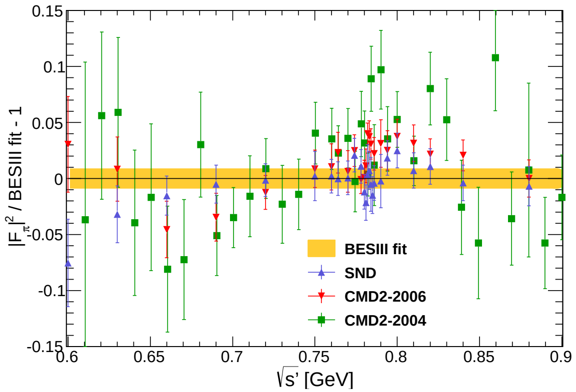


The achieved systematic error is 0.9%,

they plan using more data and work on smaller systematics

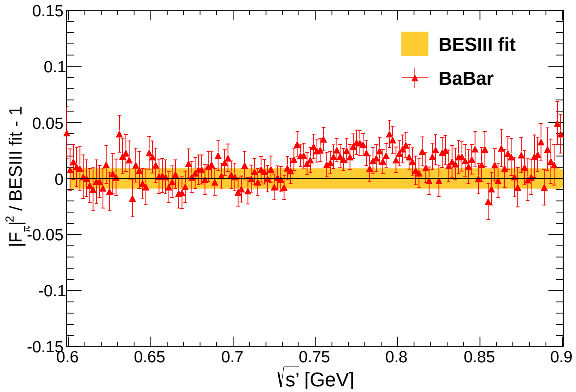
M. Ablikim et al., Phys. Lett. B761 (2016) 98

$e^+e^- \to \pi^+\pi^-$ with ISR at BESIII – II

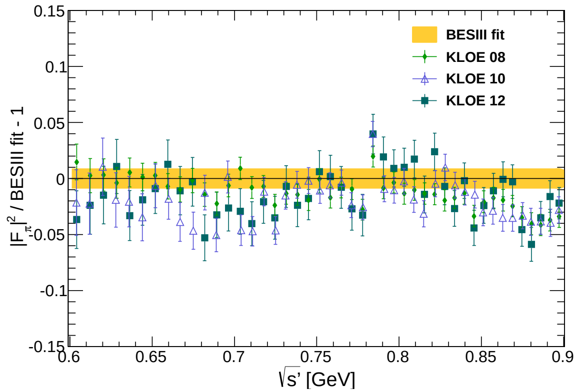


SND: JETP 103 (2006) 380

CMD-2: PLB 648 (2007) 28



BaBar: PRL 103 (2009) 231801



KLOE08: PLB 670 (2009) 285

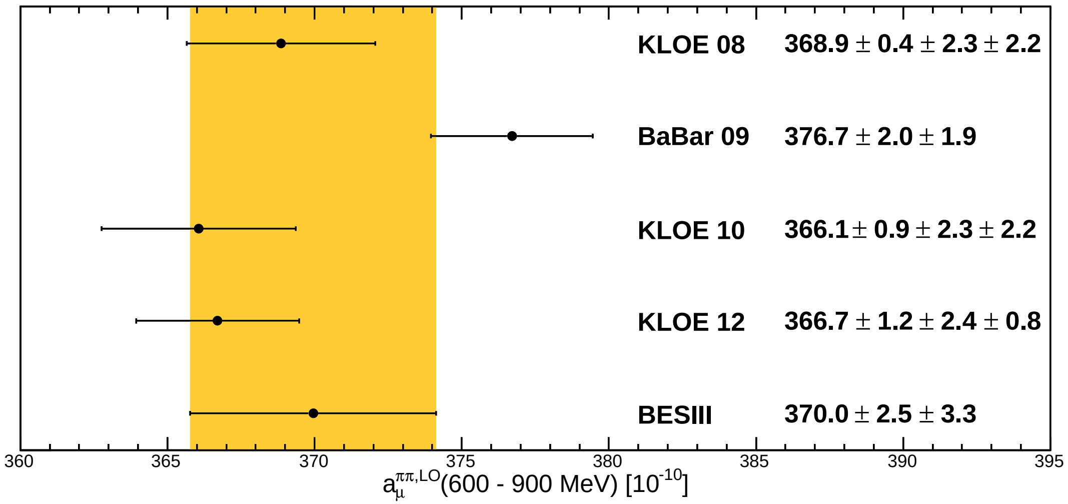
KLOE10: PLB 700 (2011) 102

KLOE12: PLB 720 (2013) 336

Agreement between different ISR results is far from perfect

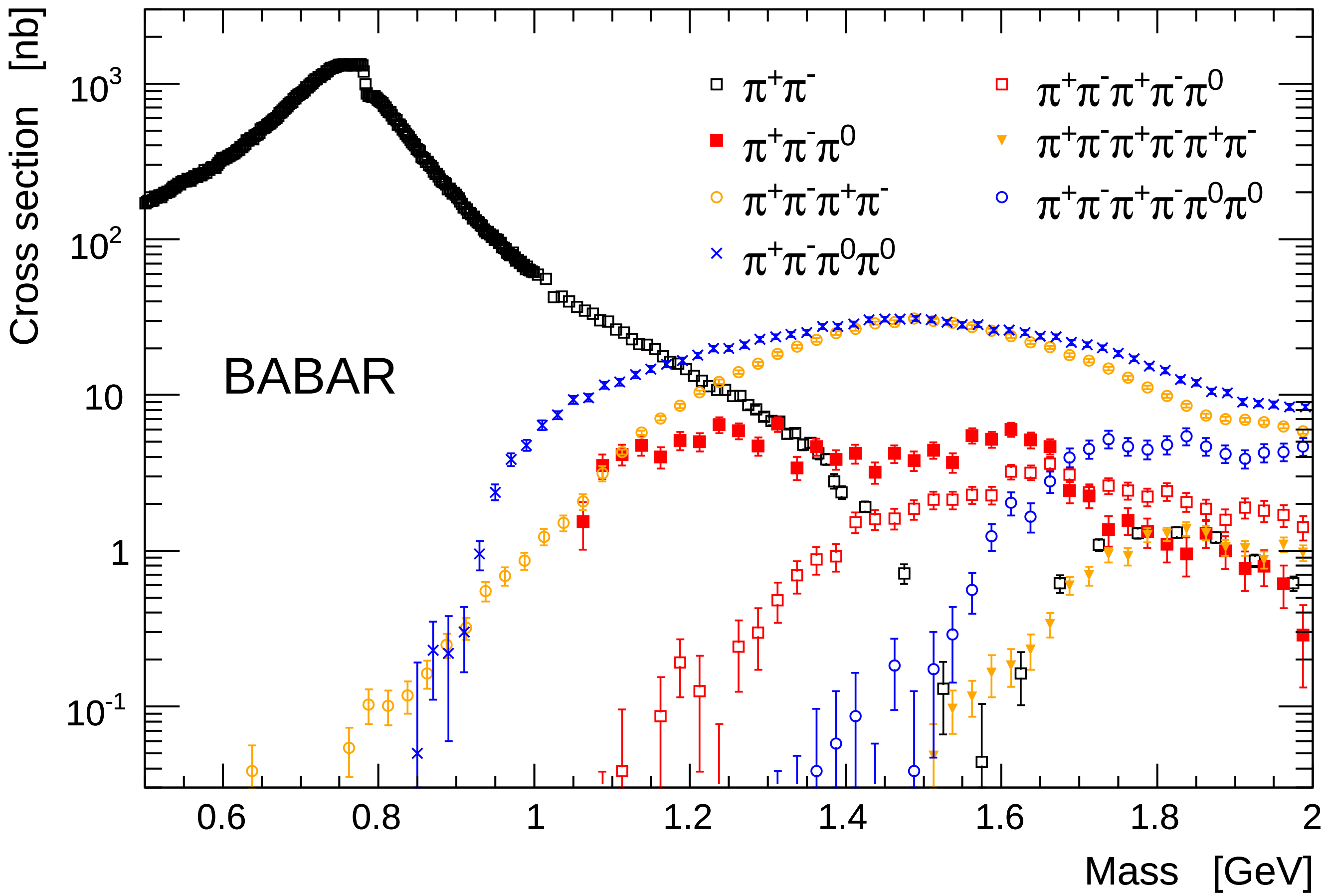
M. Ablikim et al., Phys. Lett. B761 (2016) 98

$e^+e^- \to \pi^+\pi^-$ with ISR at BESIII – III



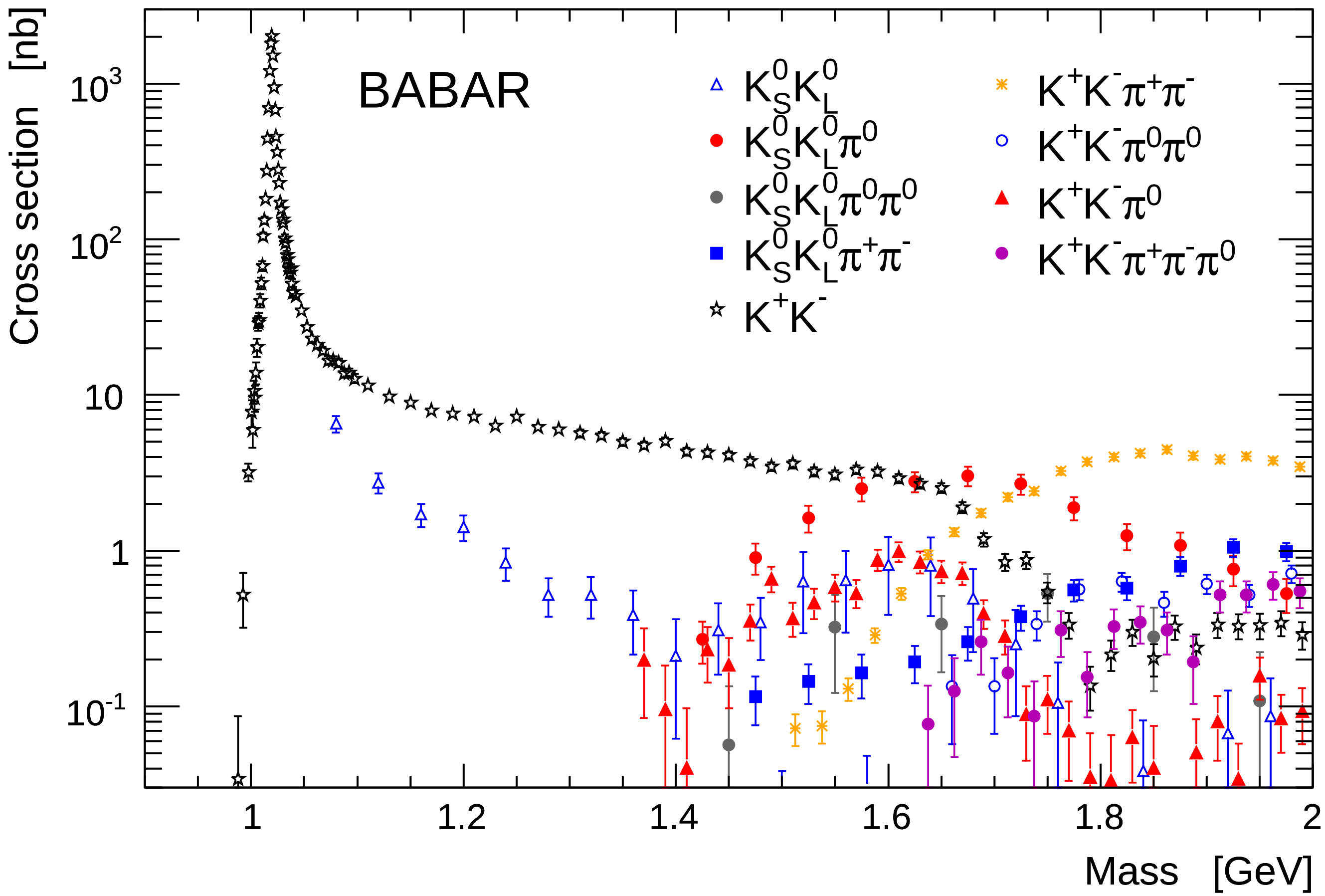
M. Ablikim et al., Phys. Lett. B761 (2016) 98

BaBar Results on the Processes with Pions



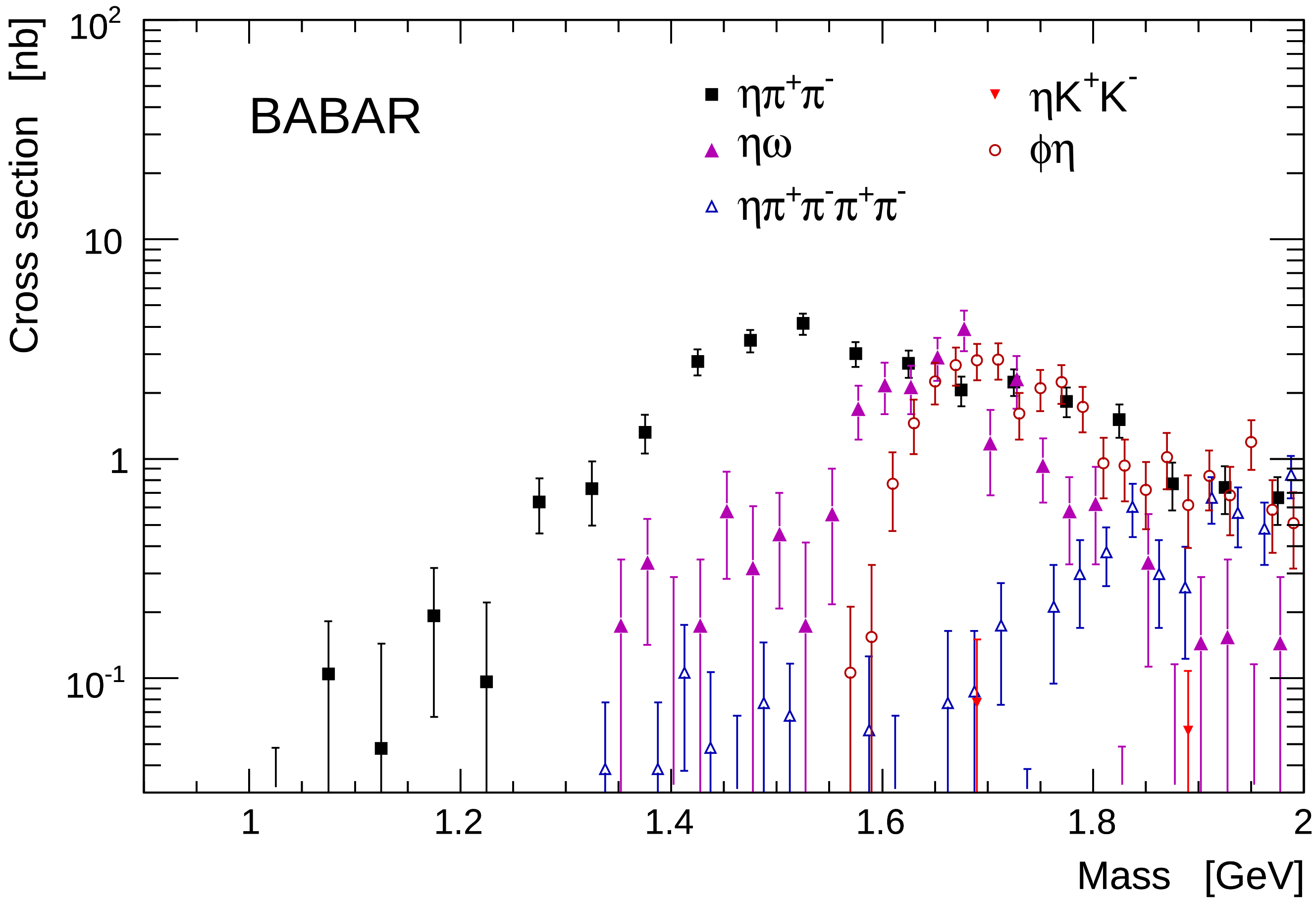
Systematic uncertainties range from 0.5% for $\pi^+\pi^-$ to (6-8)% for 6π

BaBar Results on the Processes with Kaons

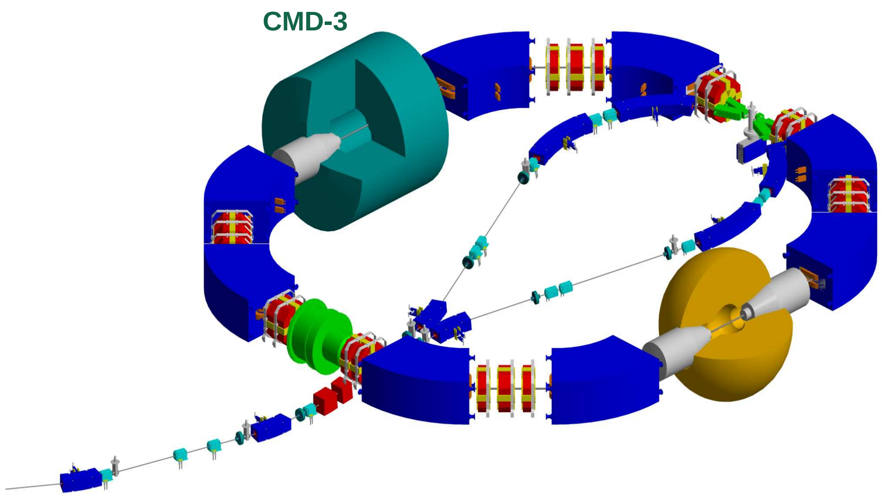


Systematic uncertainties range from 0.7% for K^+K^- to (6-8)% for $K\bar{K}n\pi$

BaBar Results on the Processes with η Mesons

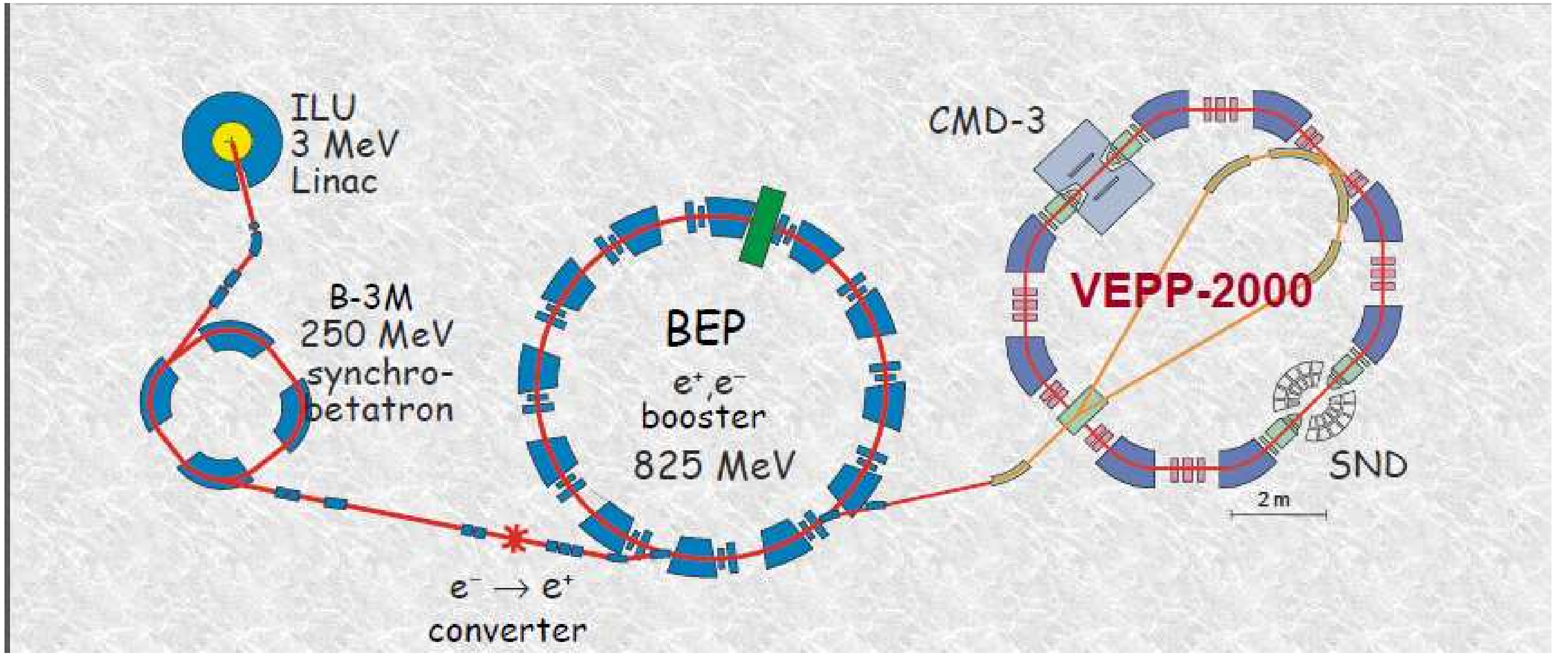


VEPP-2000 – I



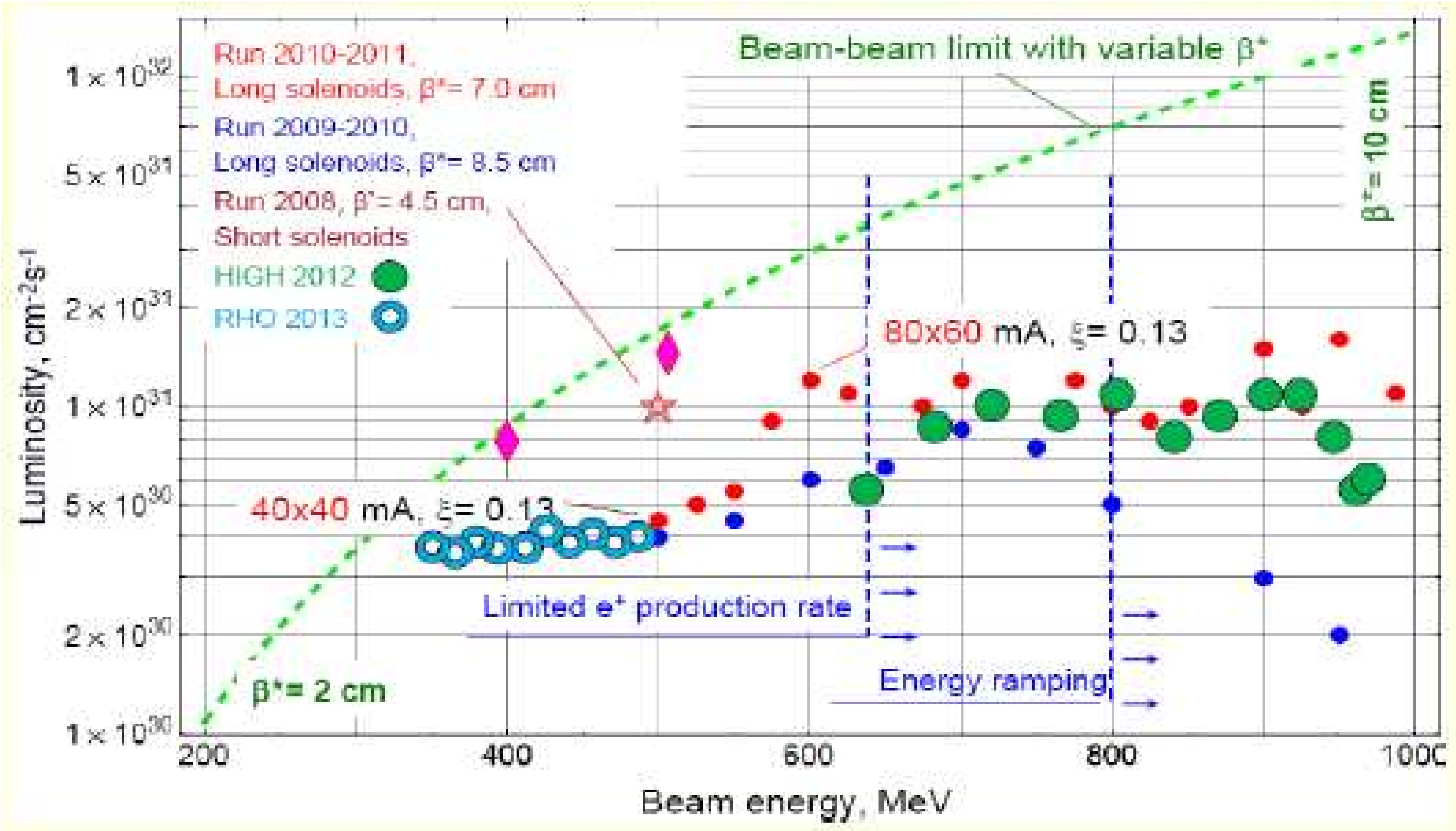
Collider	Operation	$\sqrt{s}$, MeV	$\mathcal{L}, 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
VEPP-2M	1975-2000	[360,1400]	3
VEPP-2000	2010-	$[2m_\pi, 2000]$	100

VEPP-2000 – II

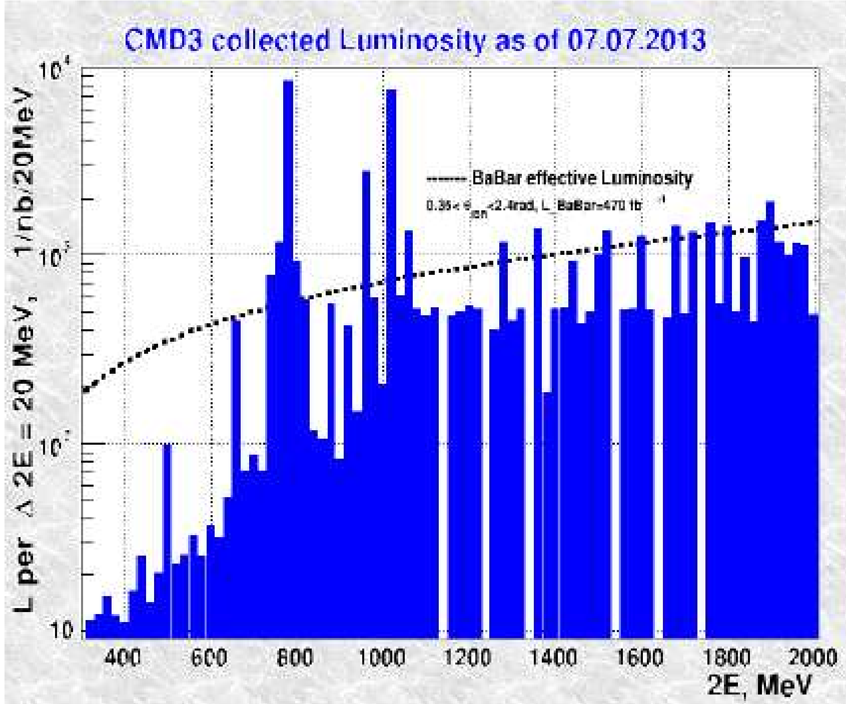


New optics with round beams ⇒ higher luminosity, precise beam energy measurement using LCBS

VEPP-2000 – III



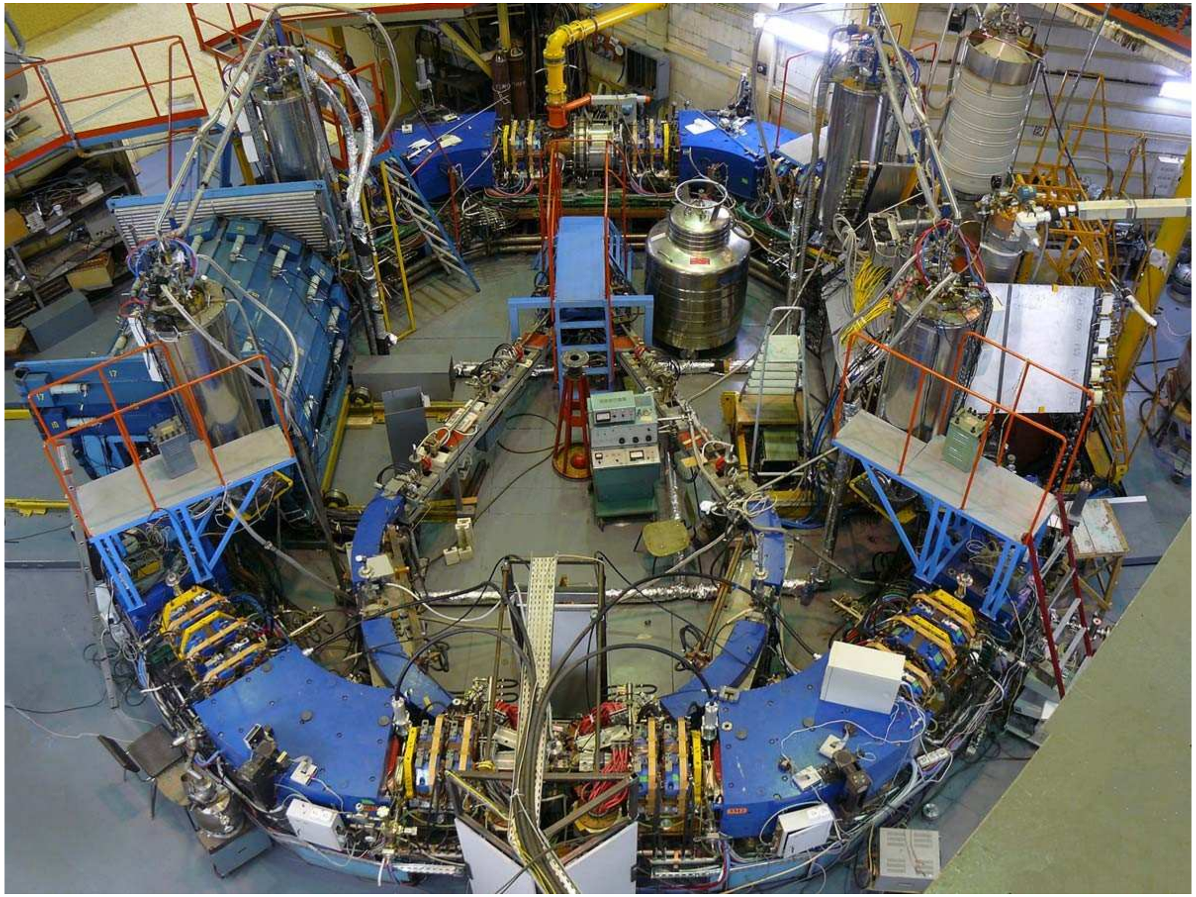
Data Taking at VEPP-2000 in 2011-2013



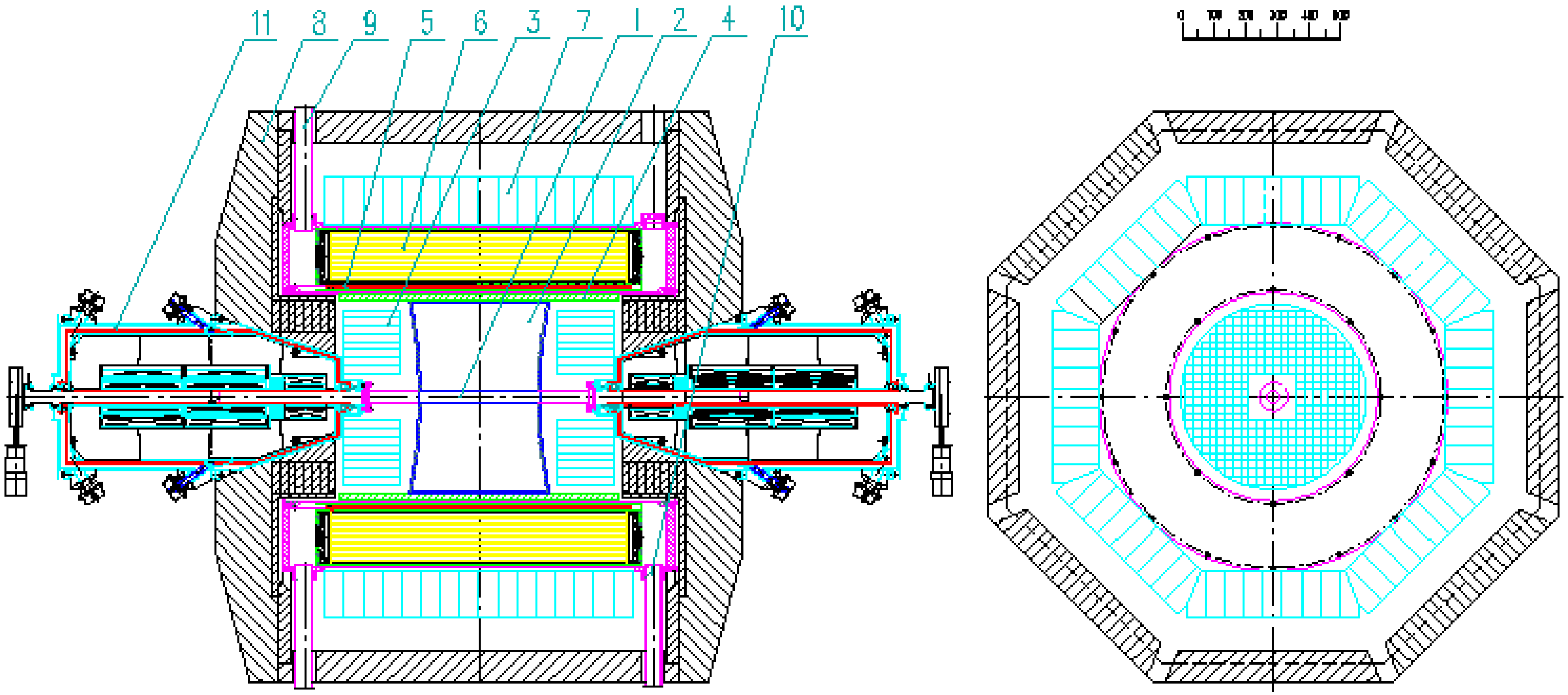
Collected L ~ 60 pb^{-1} per detector

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

VEPP-2000 and Detectors

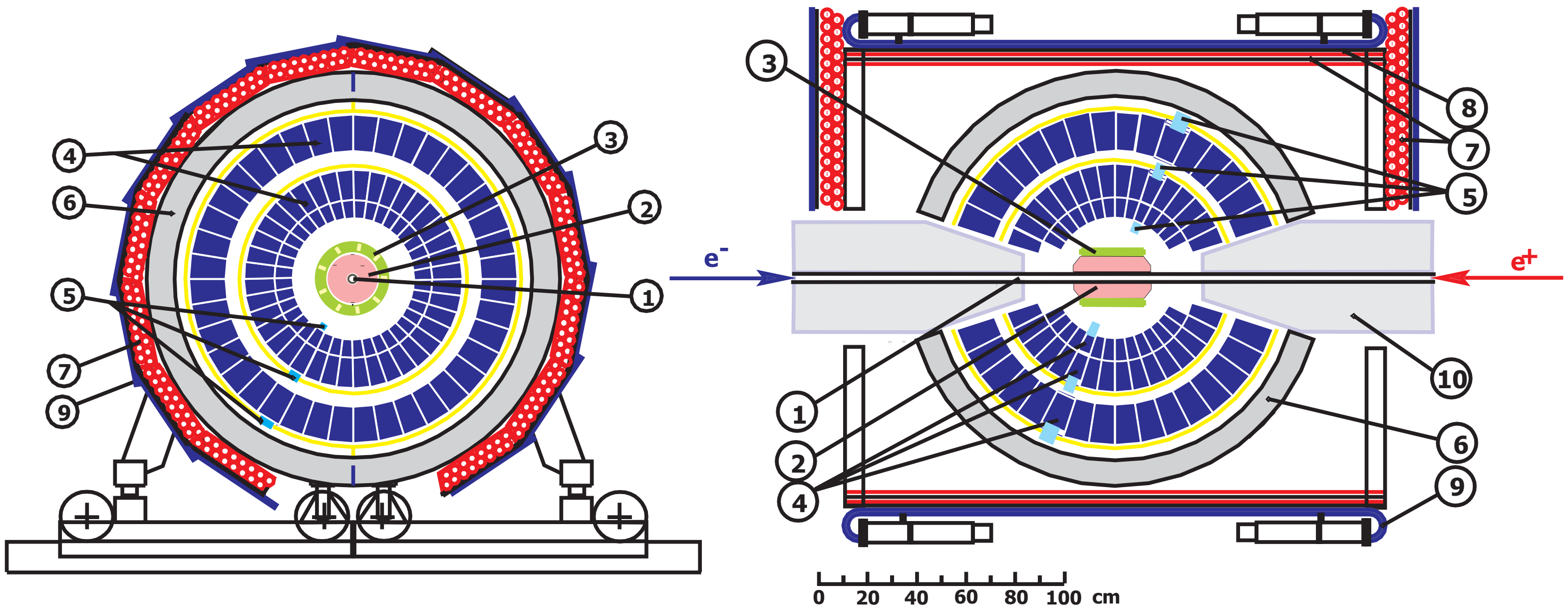


CMD-3



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

SND

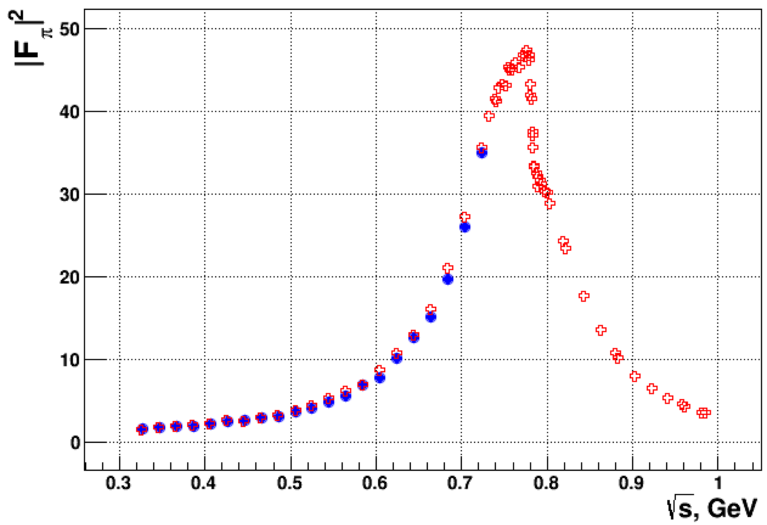


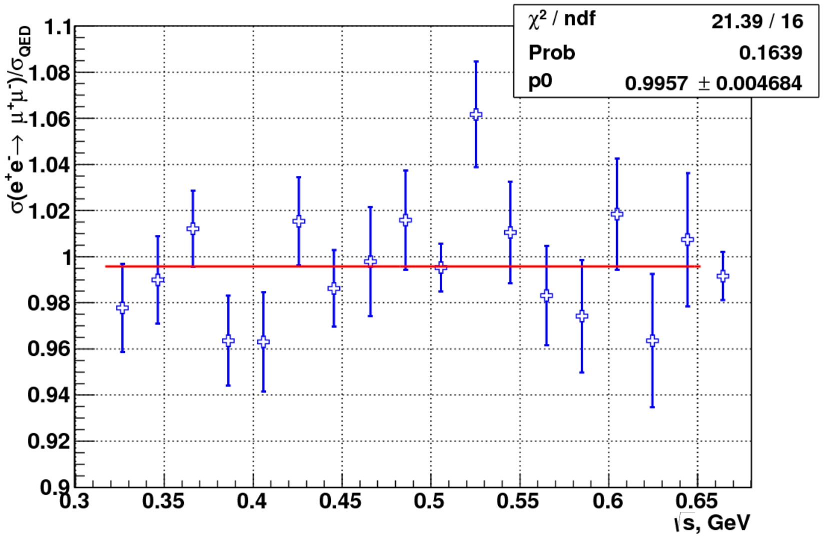
High-resolution NaI calorimeter with excellent tracking and PID

Performance of VEPP-2000 and Detectors in 2011-2013

- The maximum luminosity is $2 \cdot 10^{31}$ cm^{-1}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 pb^{-1} per detector, a factor of 6 higher than before from ϕ to 2 GeV, the number of multihadronic events per 1 pb^{-1} $\sim 50k$
- In 2013 we reached 2×160 MeV, the smallest $\sqrt{s}$ ever
- Both detectors perform reasonably well with reconstruction of both tracks and photons and redundancy $(\eta \to 2\gamma, \pi^+\pi^-\pi^0, 3\pi^0, \pi^+\pi^-\gamma,\ \omega \to \pi^+\pi^-\pi^0, \pi^0\gamma)$
- At high energies lumi is limited by a deficit of positrons and maximum energy of the booster (825 MeV now)
- During the shutdown (2014-2016) to upgrade the booster (energy increase to 1 GeV) and commission the new injection complex to reach 10^{32} cm^{-1}s^{-1}

$e^+e^- \to \pi^+\pi^-$ at CMD-3 – I

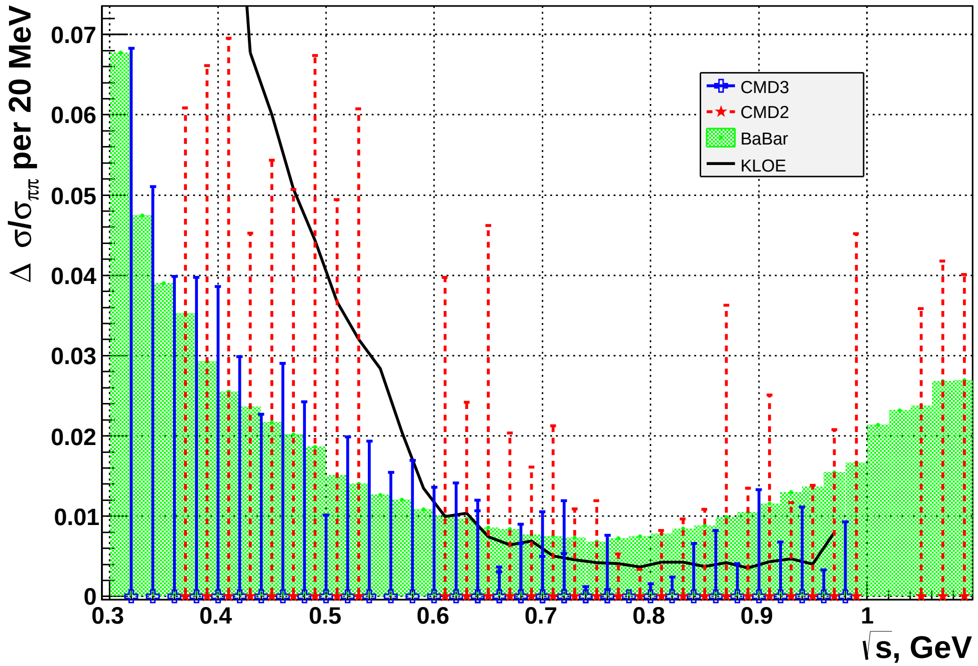




Identification at low energy - by DC with separation of $\mu^+\mu^-$

At high energy - by energy deposition in calorimeters

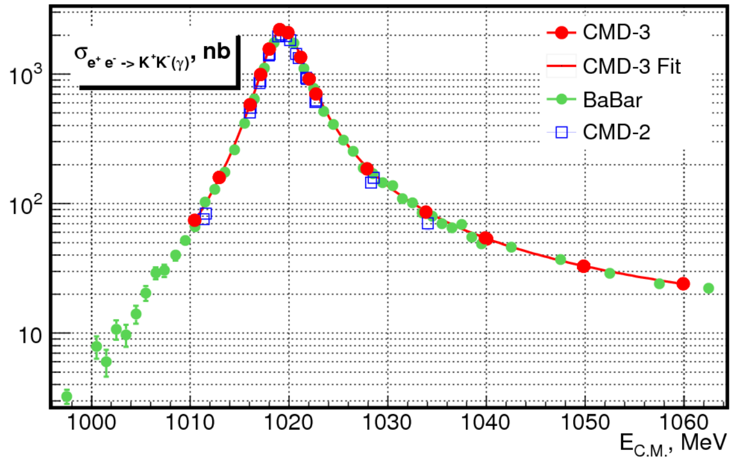
$e^+e^- \to \pi^+\pi^-$ at CMD-3 – II

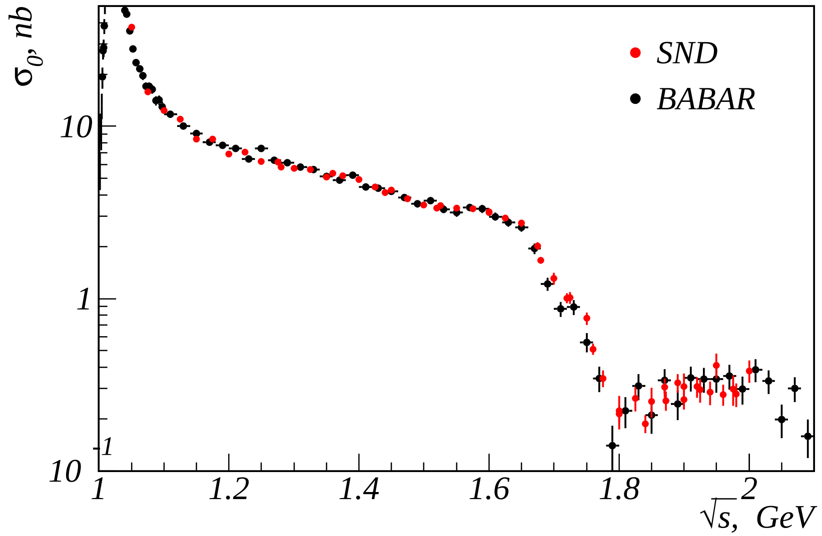


Statistical precision better than that of BaBar

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

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



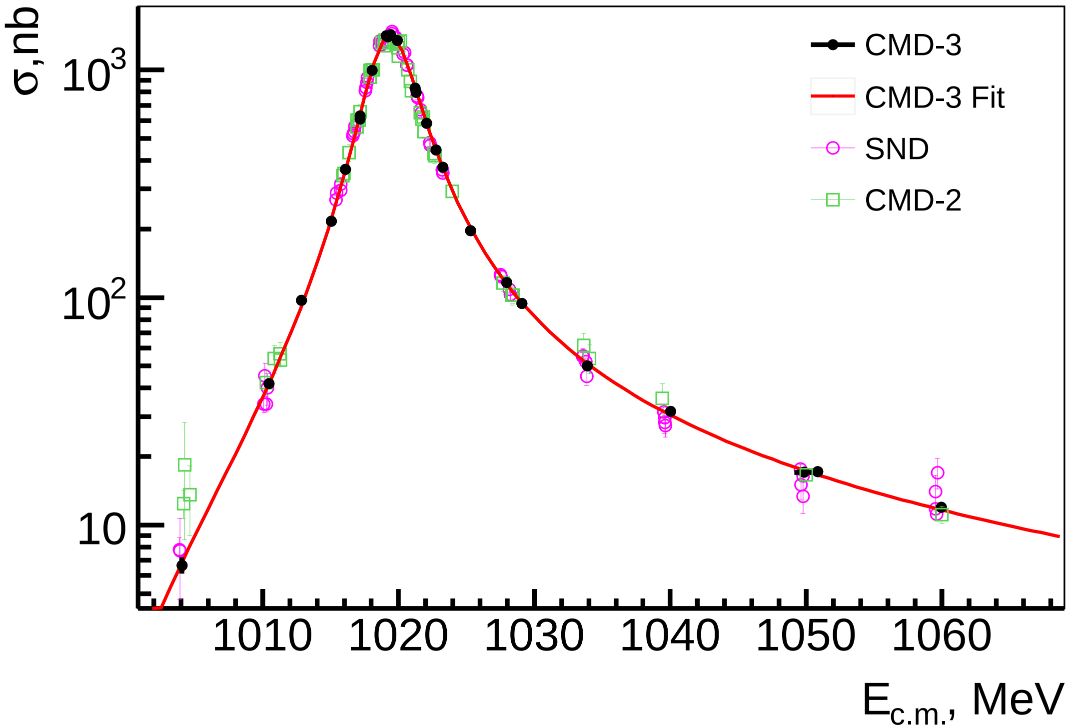


BaBar claims aggressive systematics of 0.72% at the ϕ, increasing to 7% at 2 GeV

CMD-3 hopes to reach (1-2)% at the ϕ and not much worse at higher energy,

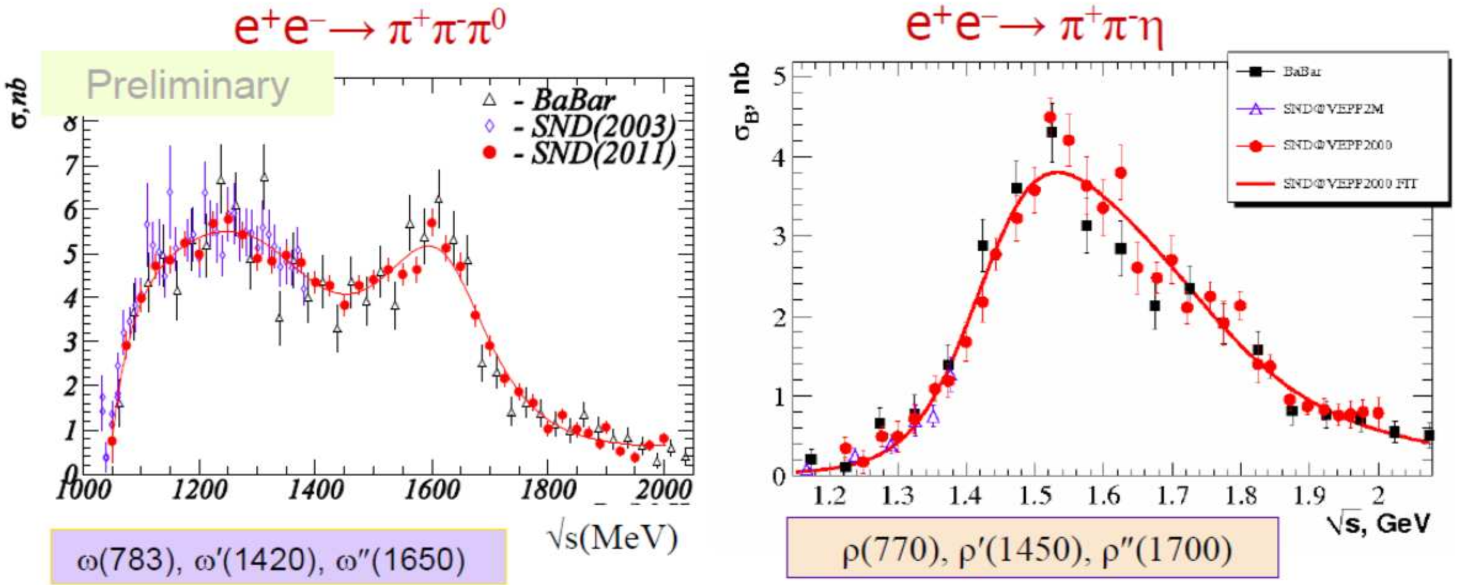
E.A. Kozyrev et al., Phys. Lett. B759 (2018) 64

$e^+e^- \to \phi \to K_S^0 K_L^0$ at CMD-3



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

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

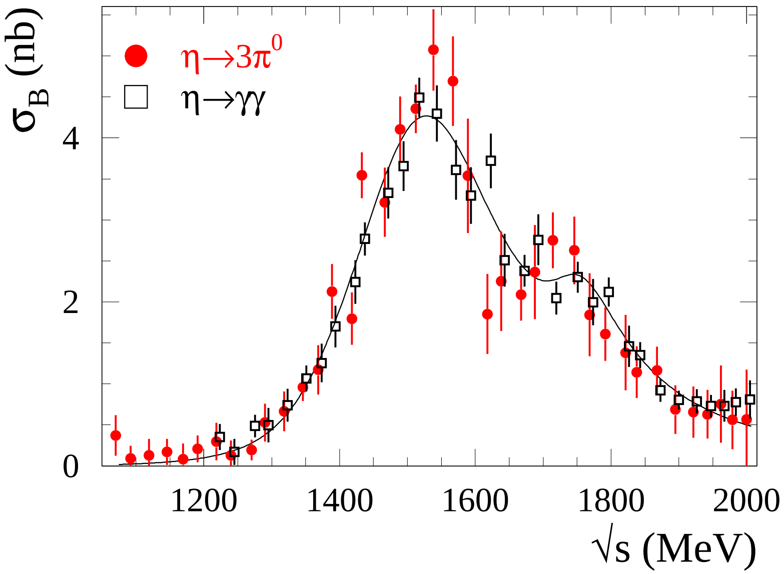


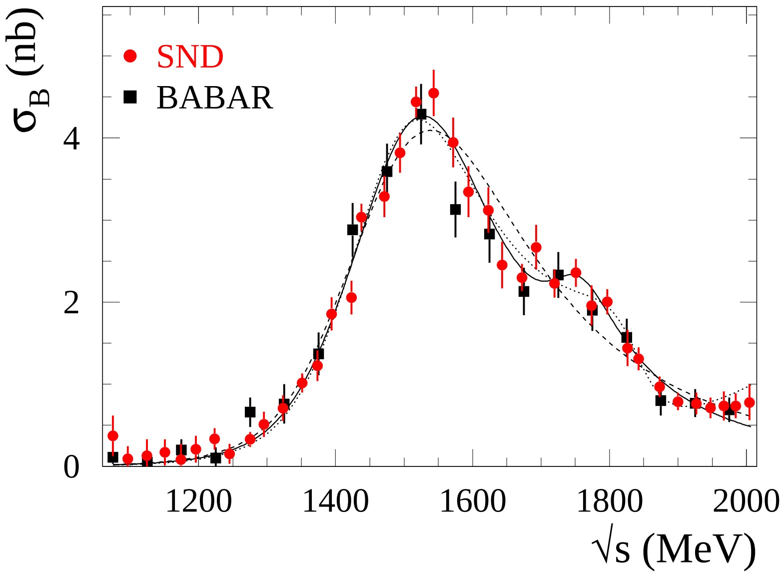
At each $\sqrt{s}$ full information on invariant masses

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

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

$e^+e^- \to \pi^+\pi^-\eta,\ \eta \to 3\pi^0$ at SND

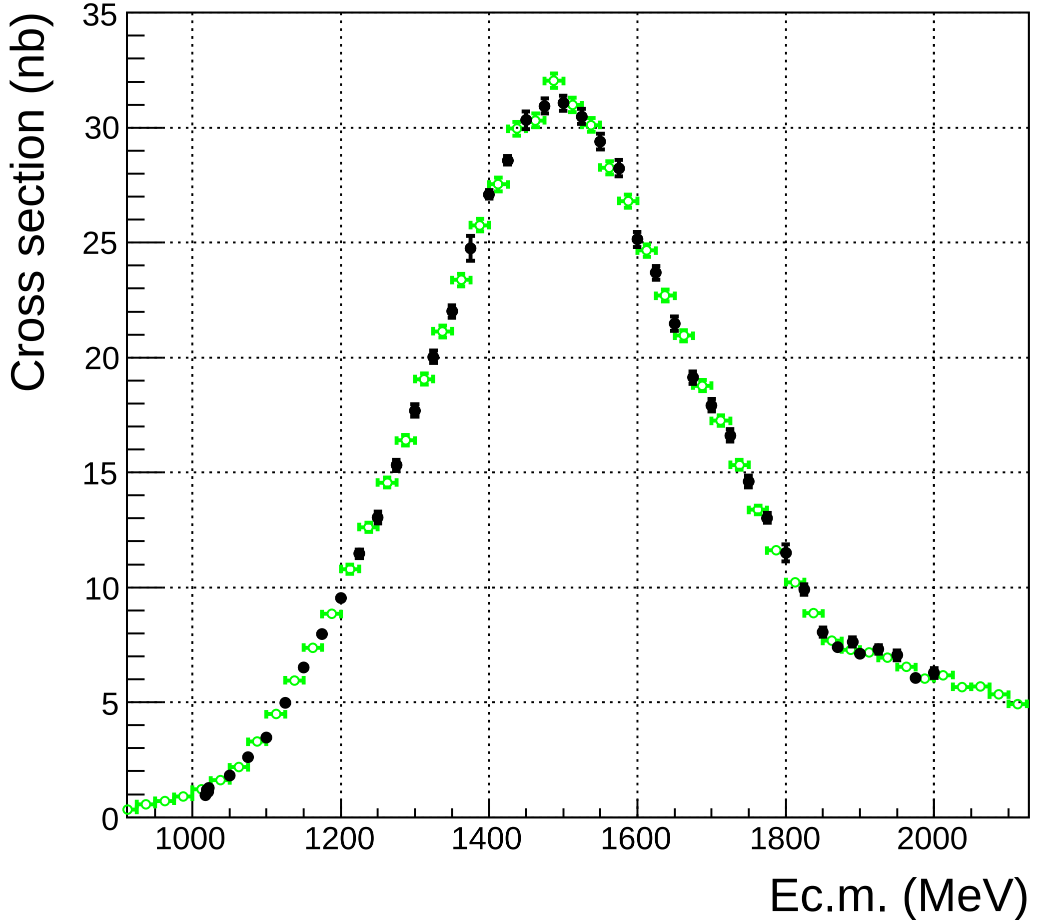




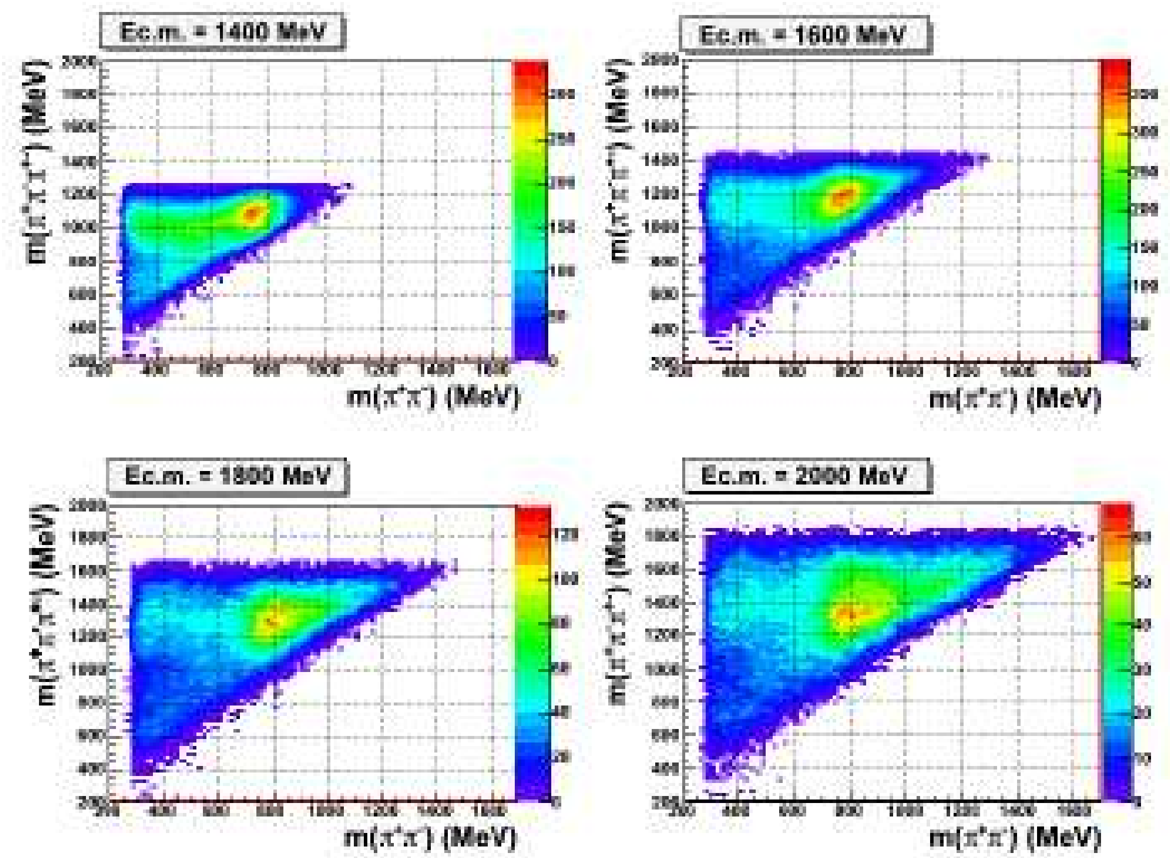
Results are compatible with BaBar and more precise

M.N. Achasov et al., Phys. Rev. D 97 (2018) 012008

$e^+e^- \to 2\pi^+2\pi^-$ at CMD-3



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

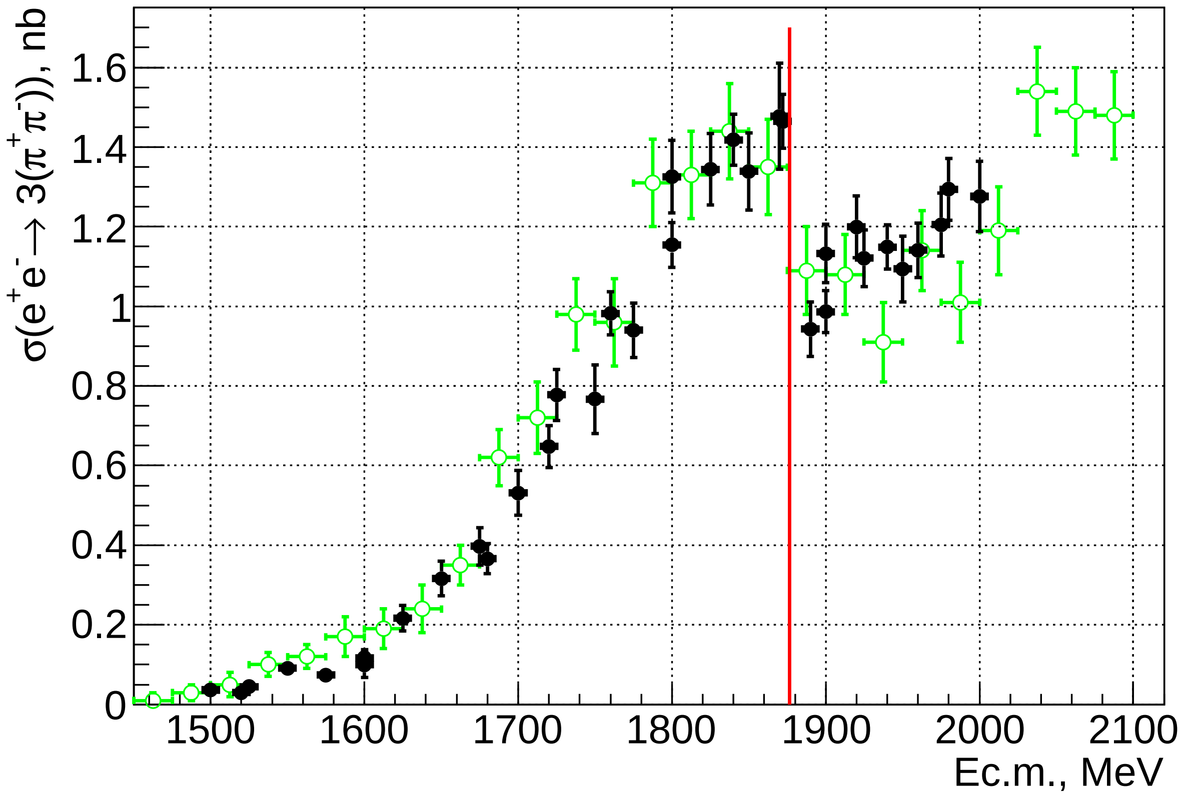


A ρ^0 is always present, $a_1^\pm(1260)\pi^\mp(a_2^\pm(1320)\pi^\mp)$ significant, at higher $\sqrt{s}$ other mechanisms like $\rho^0 f_0$, $\rho^0 f_2(1270)$ appear

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

1. $\int Ldt$ =22 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 ρ^0/event:
   - $\rho(1450)(\pi^+\pi^-)_{\text{S-wave}} \to a_1(1260)^{\pm}\pi^{\mp}\pi^+\pi^- \to \rho^0 2(\pi^+\pi^-) \to 3(\pi^+\pi^-)$
   - $\rho(770)(2\pi^+2\pi^-)_{\text{S-wave}} \to 3(\pi^+\pi^-)$
     3 options for $2\pi^+2\pi^-$: phase space, $f_0(1370)$, $f_0(1500)$
   - $\rho(770)f_2(1270) \to 3(\pi^+\pi^-)$
   - 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%

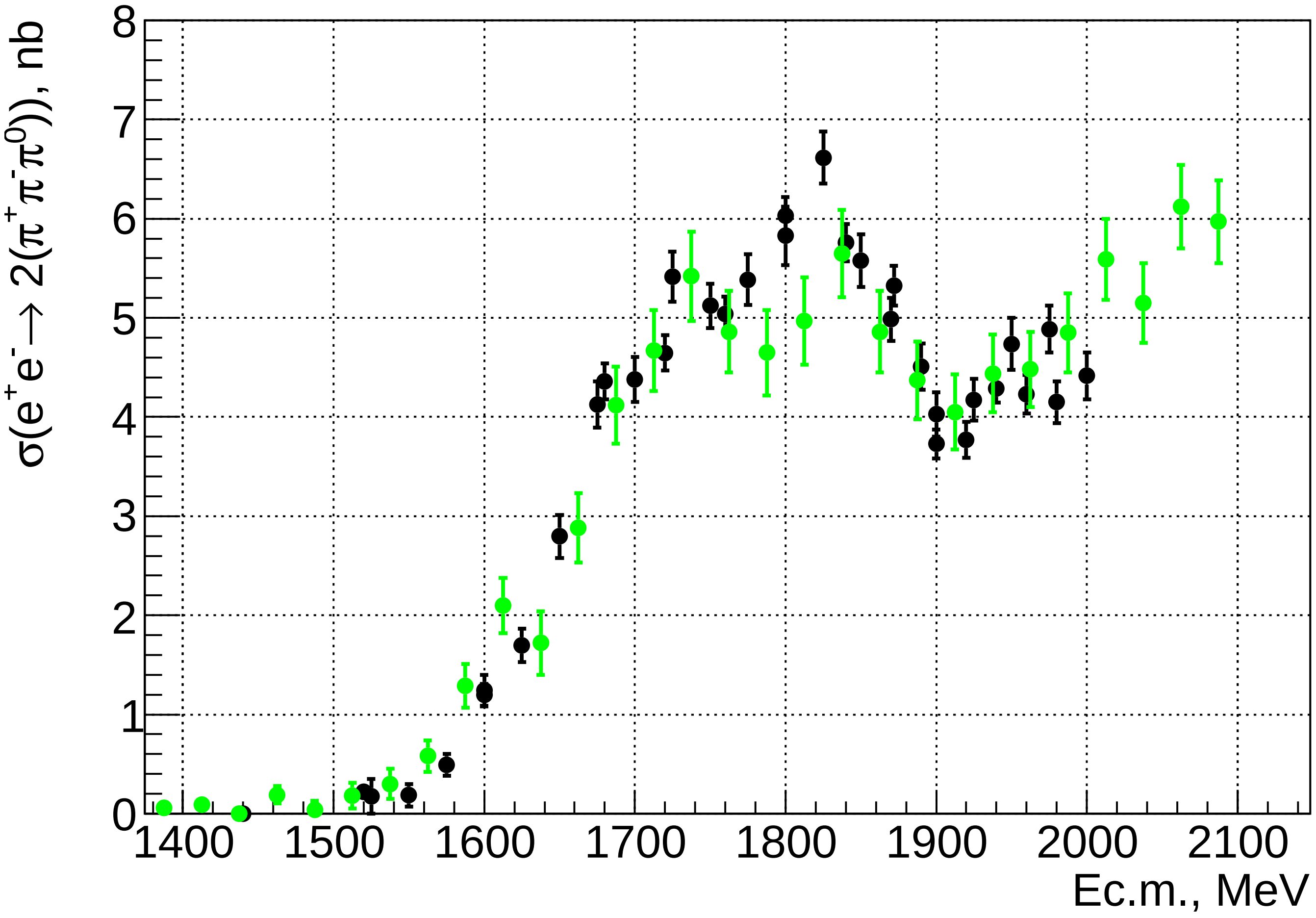
$e^+e^- \to 3\pi^+3\pi^-$ at CMD-3– II



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

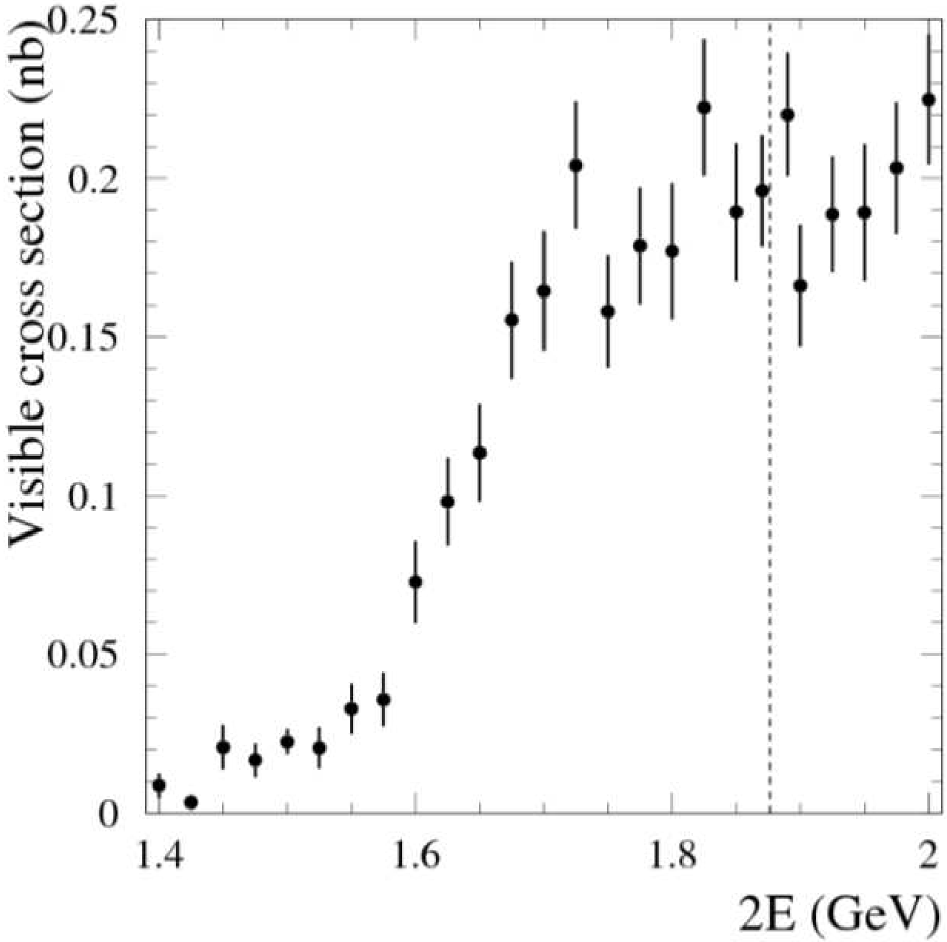
R.R. Akhmetshin et al., Phys. Lett. B 723 (2013) 82

$e^+e^- \to 2\pi^+2\pi^-2\pi^0$ at CMD-3



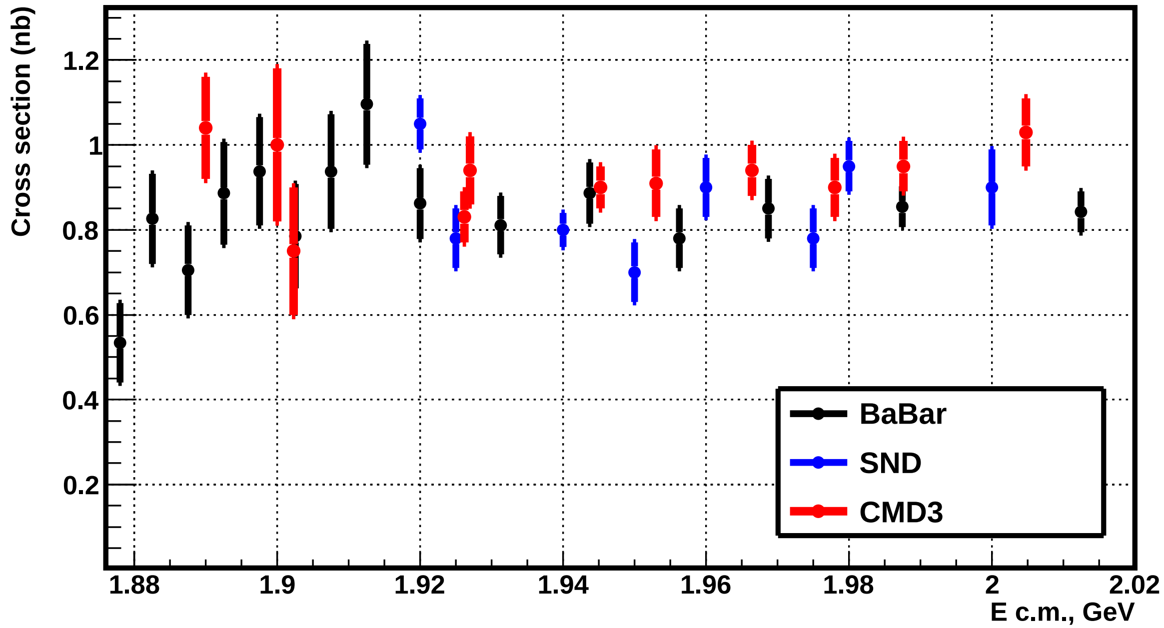
The dip structure near $N\bar{N}$ threshold also seen

$e^+e^- \to \pi^+\pi^-4\pi^0$ at SND



First ever measurement of the process

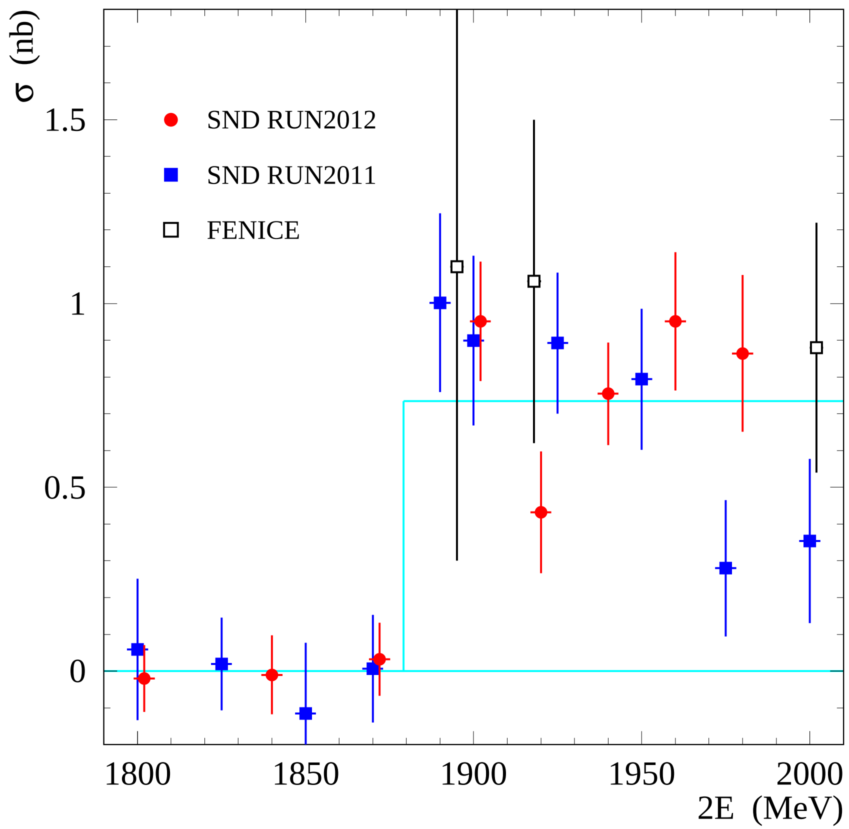
$p\bar{p}$ Production at VEPP-2000



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

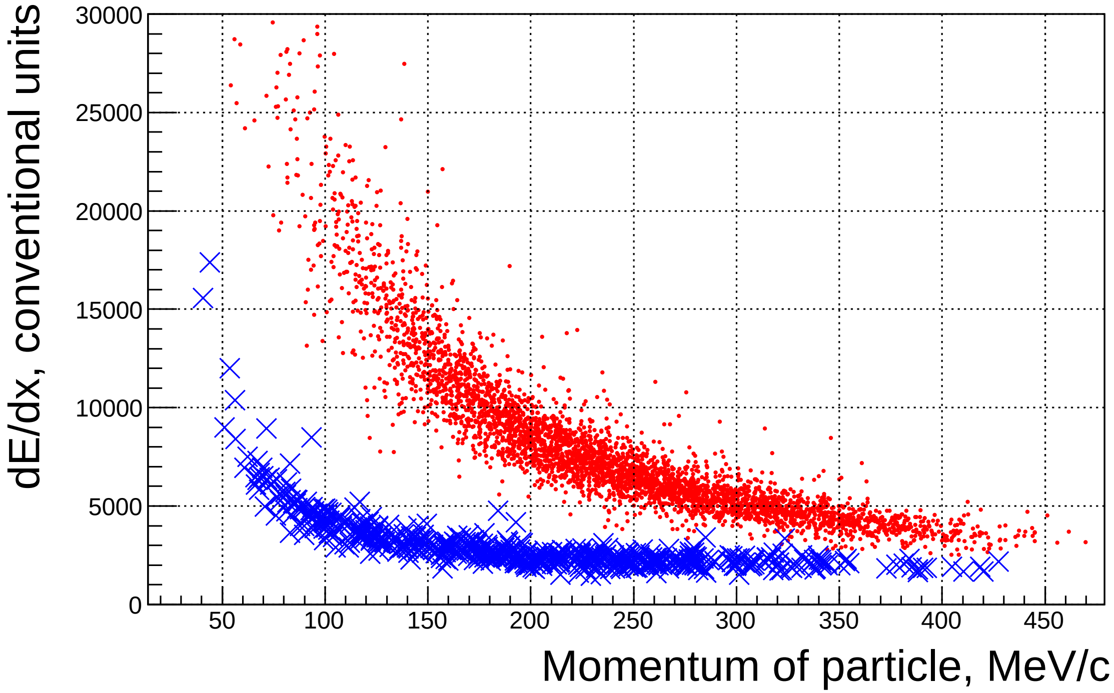
R.R. Akhmetshin et al., Phys. Lett. B759 (2016) 634

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



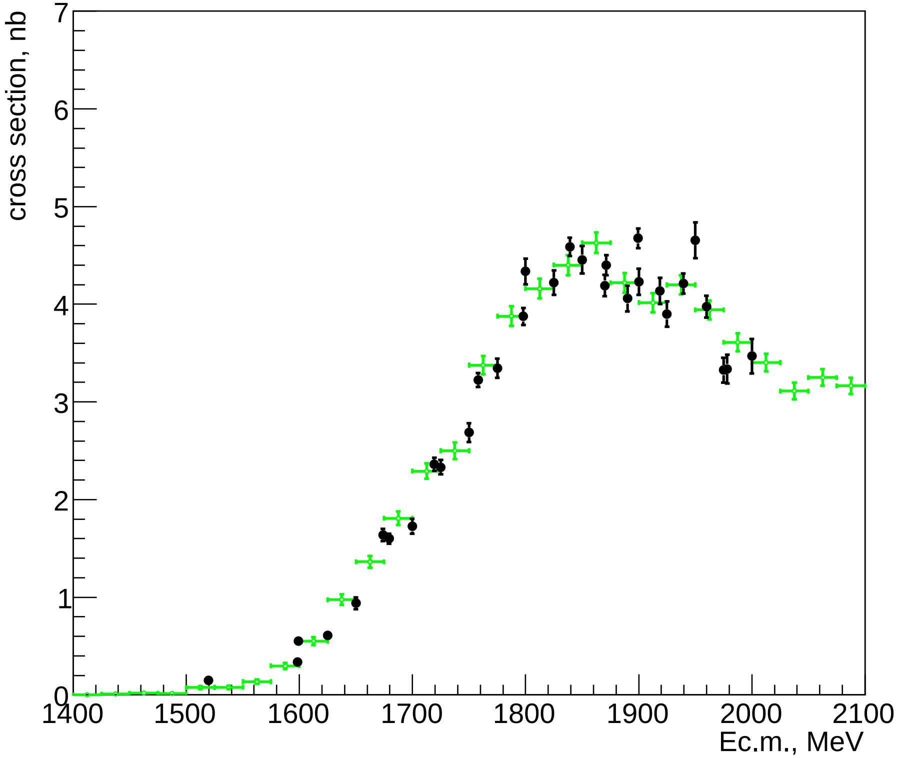
The first and more precise measurement after FENICE
M.N. Achasov et al., Phys. Rev. D 90 (2014) 112007

Multibody Final States with Charged Kaons



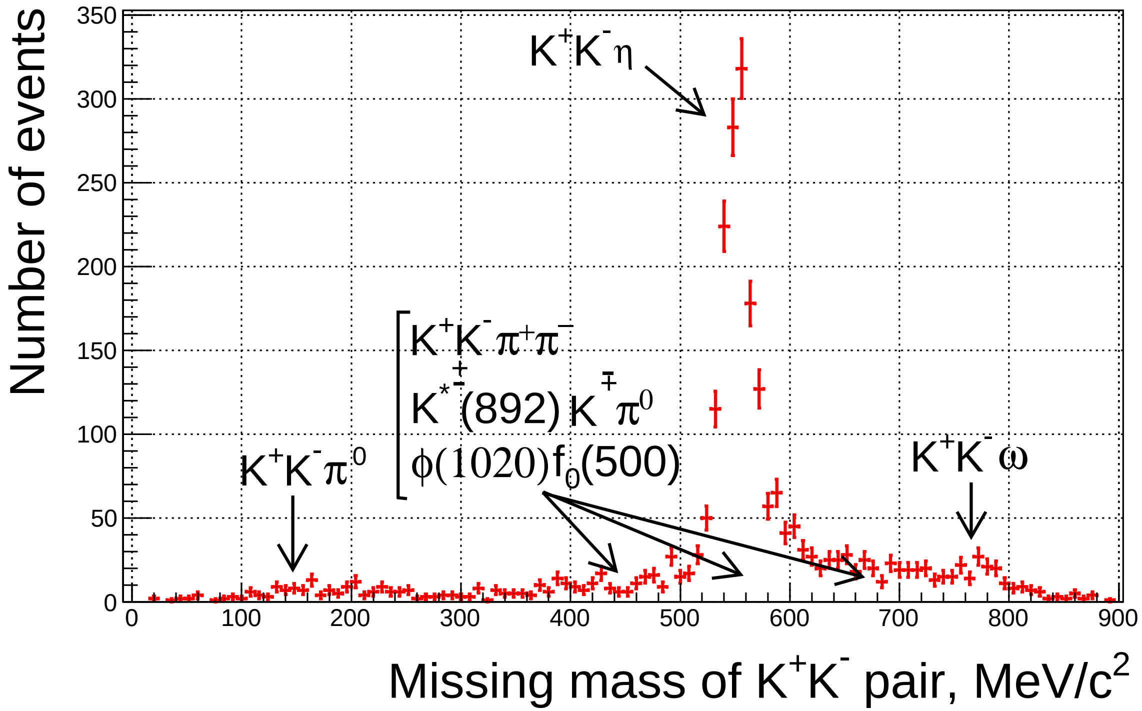
Ionization losses in DC (dE/dx) provide good K/π separation

$e^+e^- \to K^+K^-\pi^+\pi^-$ at CMD-3



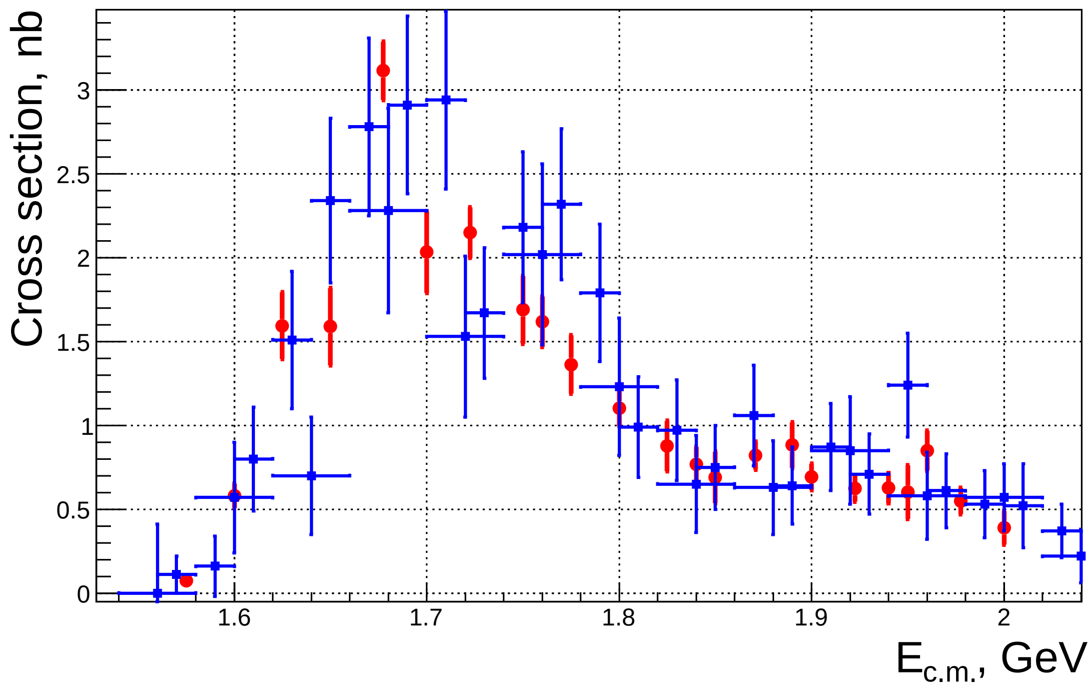
From more than 10000 events many different mechanisms seen:
$K_1(1270)\bar{K} \to K\bar{K}\rho,\ K^*(892)\bar{K}\pi,\ K_1(1400)\bar{K} \to K^*(892)\bar{K}\pi,\ \phi\pi^+\pi^-$
D.N. Shemyakin et al., Phys. Lett. B756 (2016) 153

$e^+e^- \to K^+K^-\eta$ at CMD-3 – I



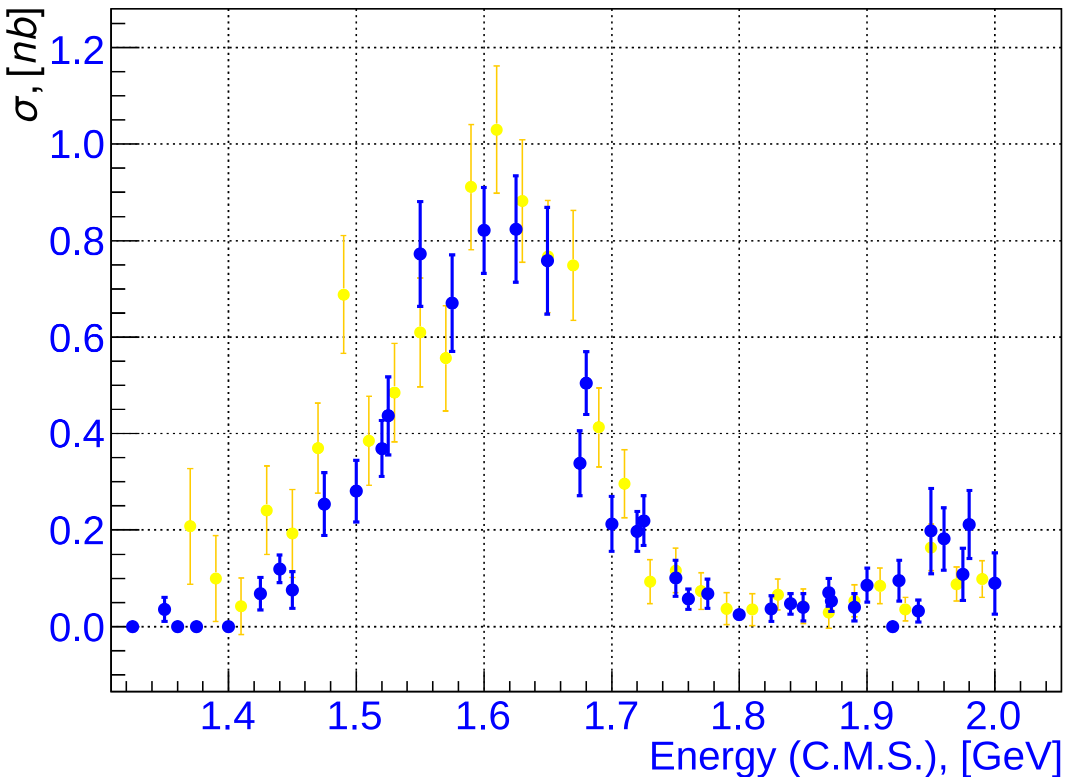
Missing mass to K^+K^- clearly shows the dominant signal and BGs

$e^+e^- \to K^+K^-\eta$ at CMD-3 – II



Cross section is consistent with and more precise than BaBar

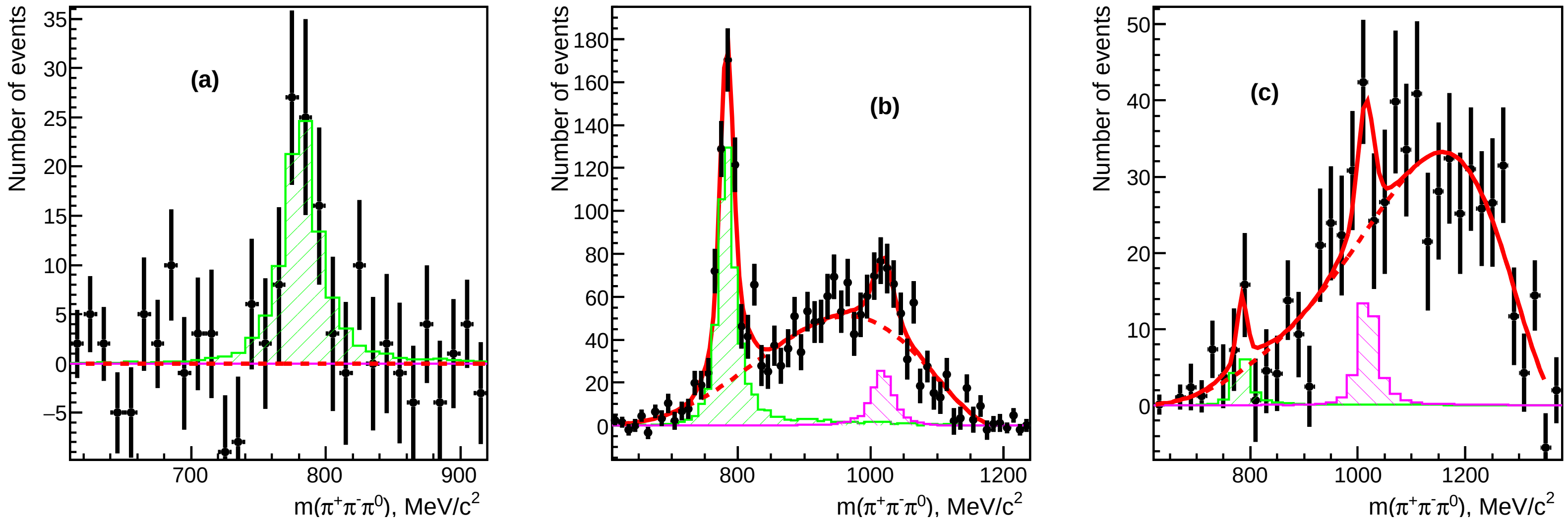
$e^+e^- \to K^+K^-\pi^0$ at CMD-3



From 600 events the $\phi\pi^0$ and $K^{*\pm}(892)K^{\mp}$ mechanisms seen

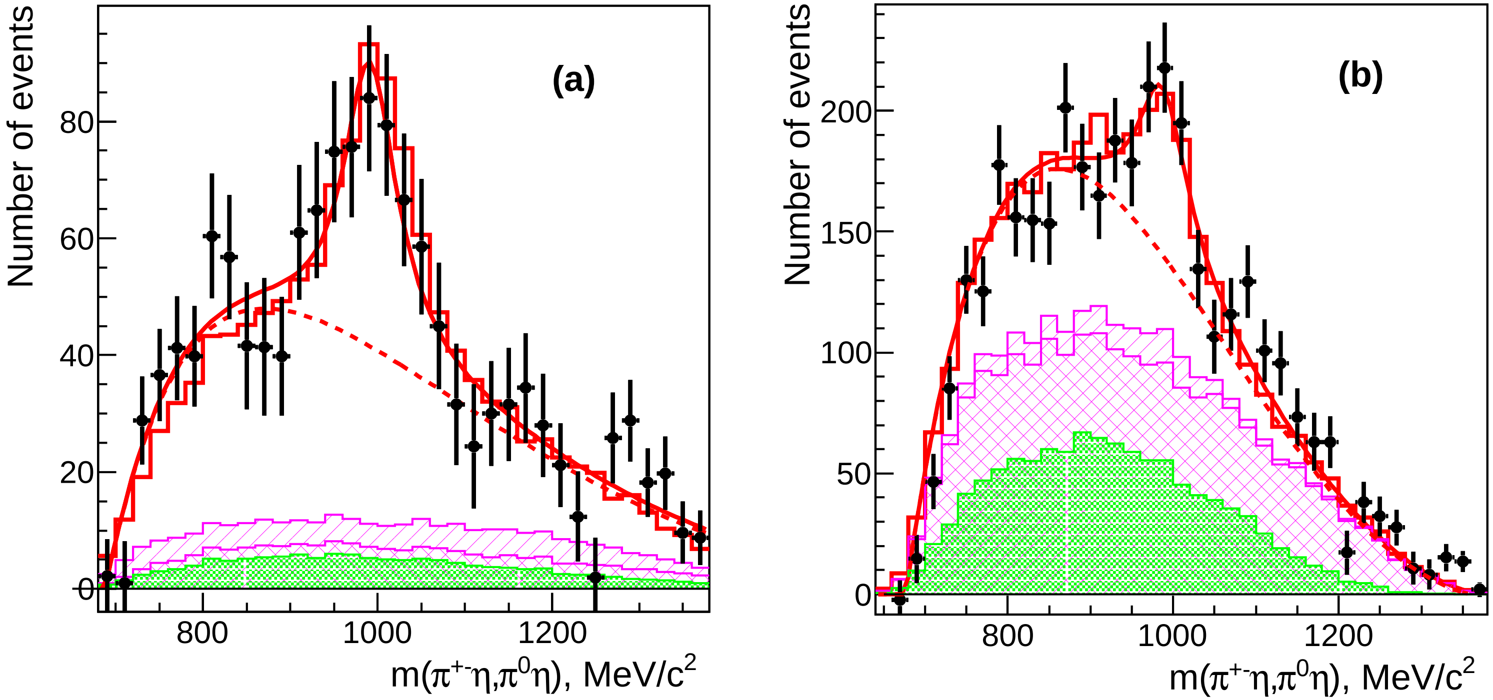
Cross section is consistent with and more precise than BaBar

$e^+e^- \to \pi^+\pi^-\pi^0\eta$ at CMD-3 – I



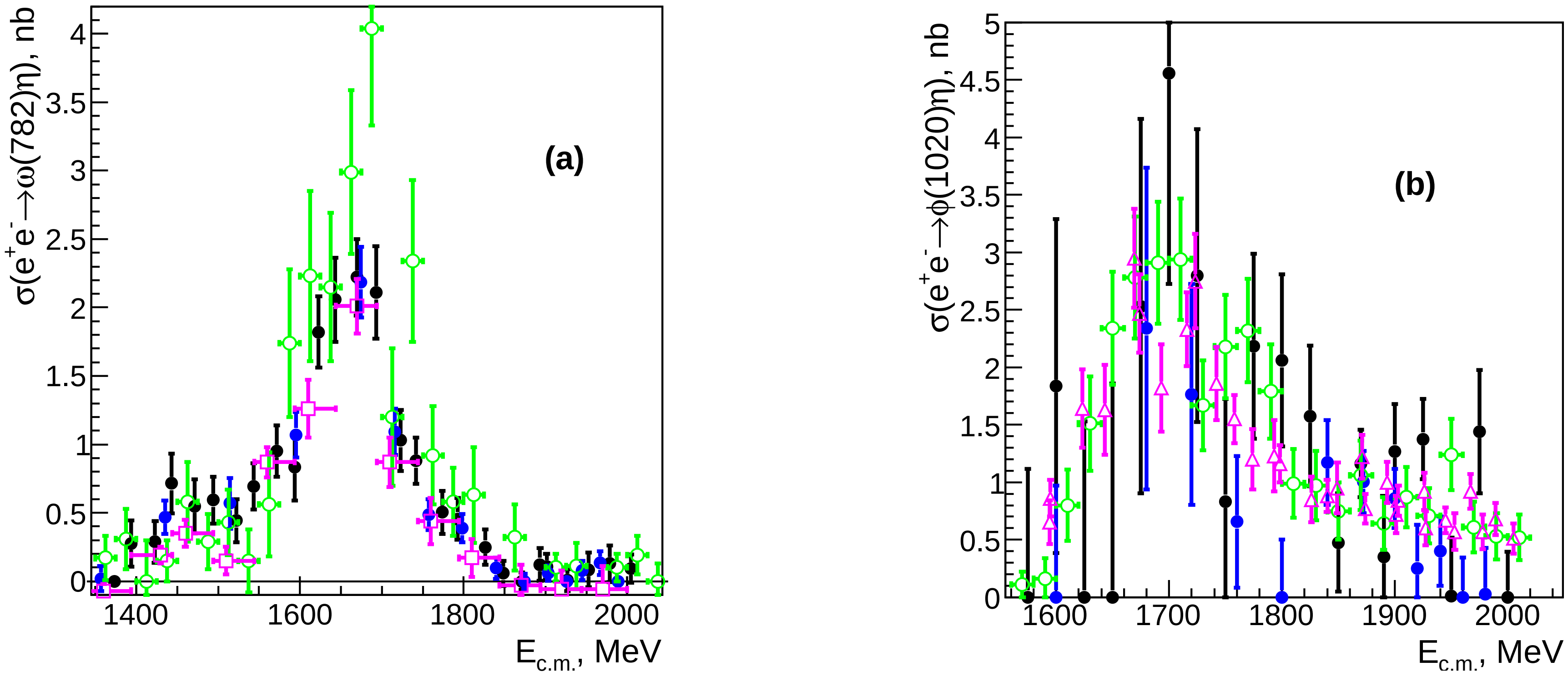
R.R. Akhmetshin et al., Phys. Lett. B773 (2017) 150

$e^+e^- \to \pi^+\pi^-\pi^0\eta$ at CMD-3 – II



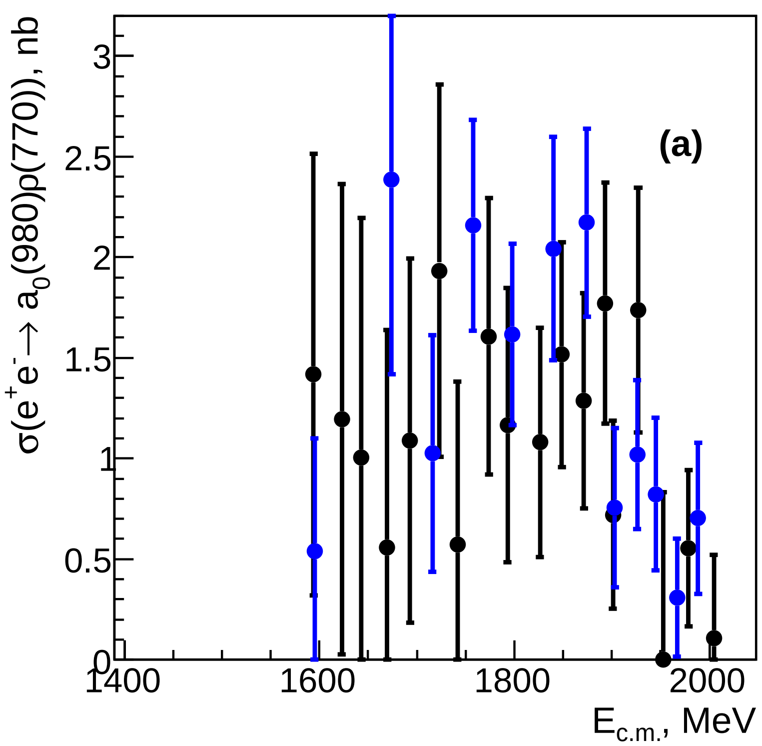
R.R. Akhmetshin et al., Phys. Lett. B773 (2017) 150

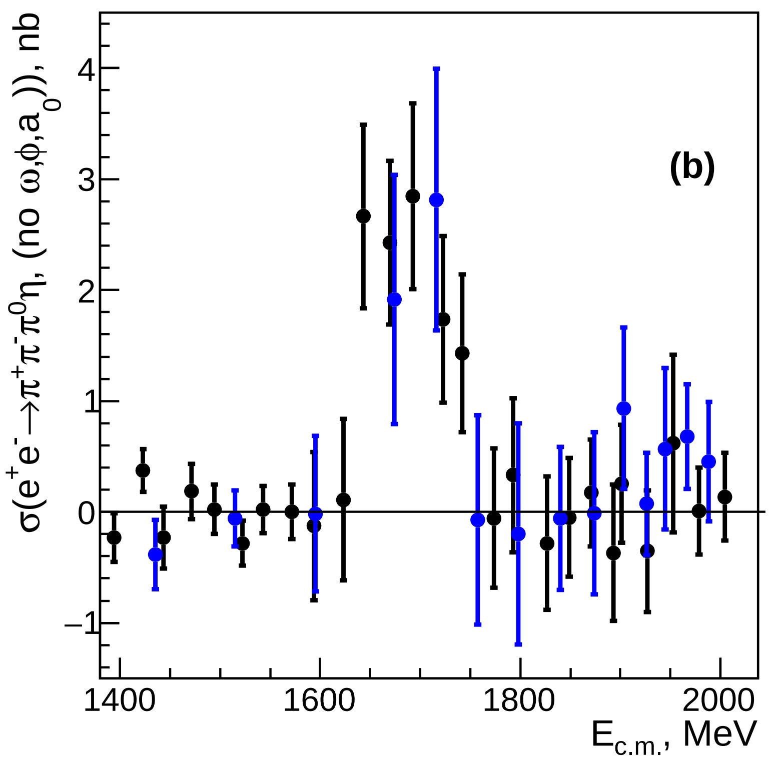
$e^+e^- \to \pi^+\pi^-\pi^0\eta$ at CMD-3 – III



R.R. Akhmetshin et al., Phys. Lett. B773 (2017) 150

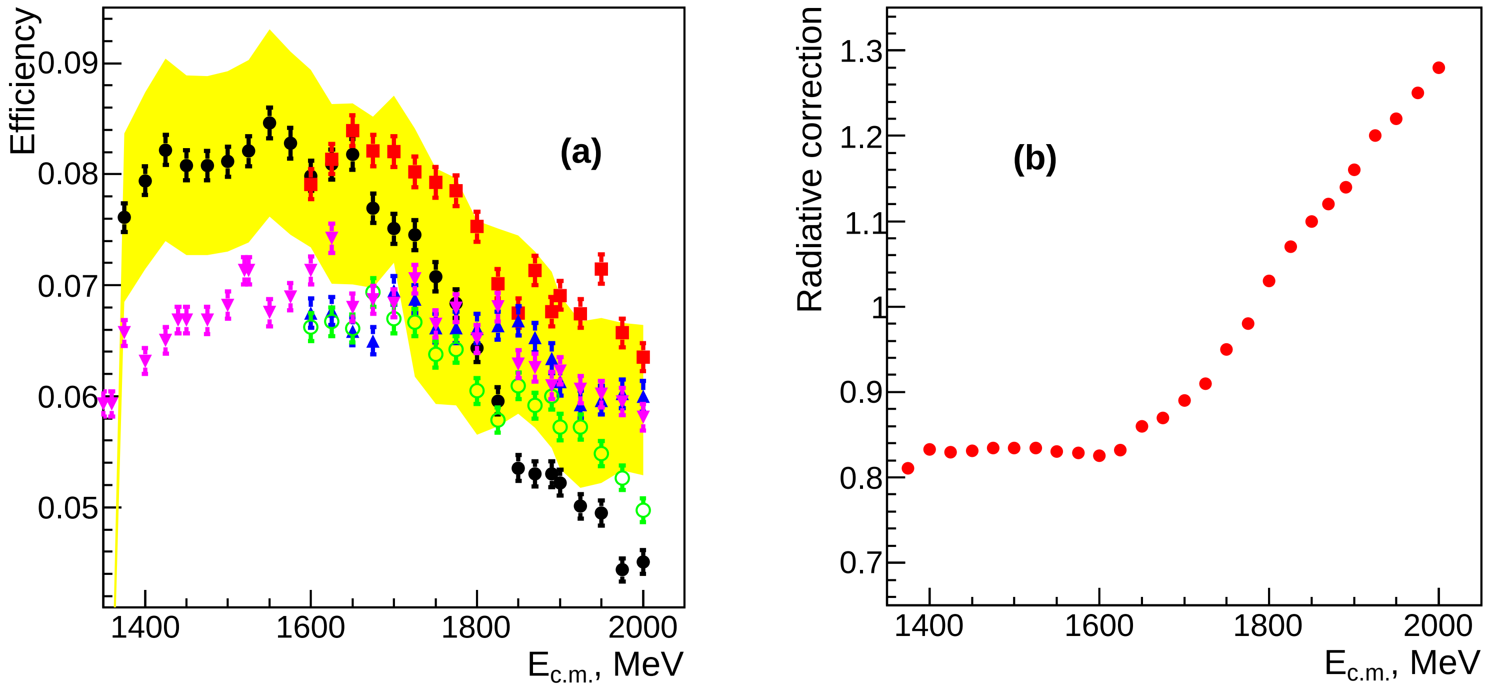
$e^+e^- \to \pi^+\pi^-\pi^0\eta$ at CMD-3 – IV





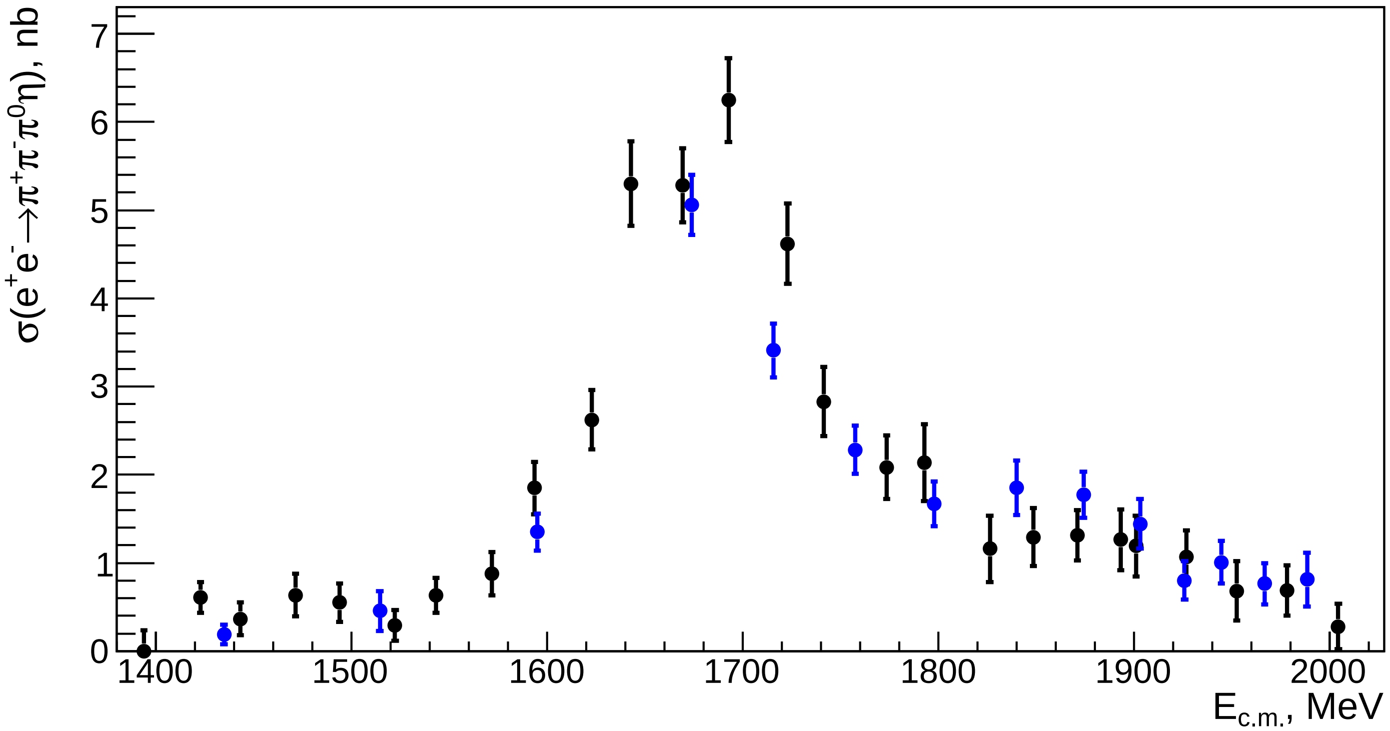
R.R. Akhmetshin et al., Phys. Lett. B773 (2017) 150

$e^+e^- \to \pi^+\pi^-\pi^0\eta$ at CMD-3 – V



R.R. Akhmetshin et al., Phys. Lett. B773 (2017) 150

$e^+e^- \to \pi^+\pi^-\pi^0\eta$ at CMD-3 – VI

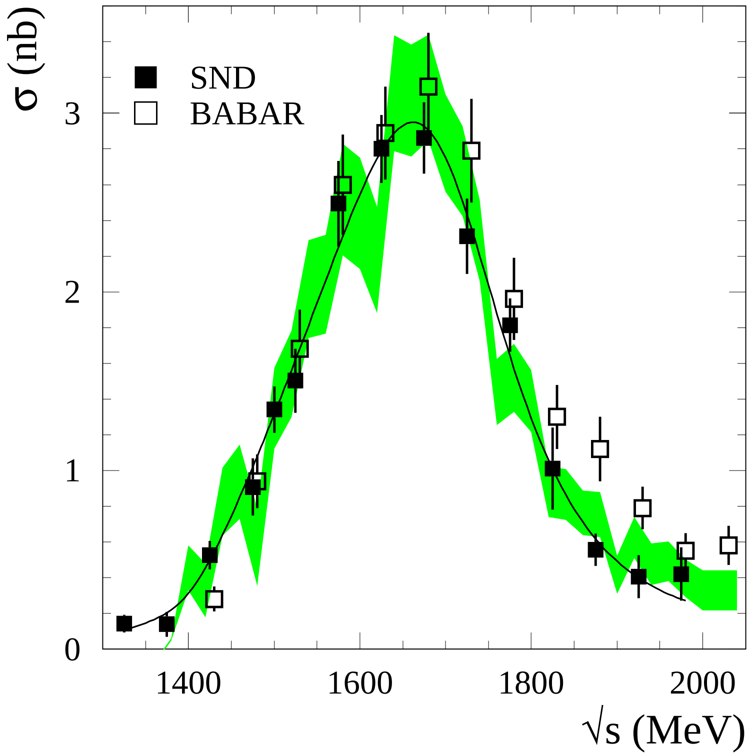


About 2800 events selected, $\omega\eta$, $\omega\phi$, $a_0\rho$, others seen

Using $\epsilon_{\rm av}$ for 4 channels σ is obtained for the first time

R.R. Akhmetshin et al., Phys. Lett. B773 (2017) 150

$e^+e^- \to K_S^0 K_L^0 \pi^0$ at SND

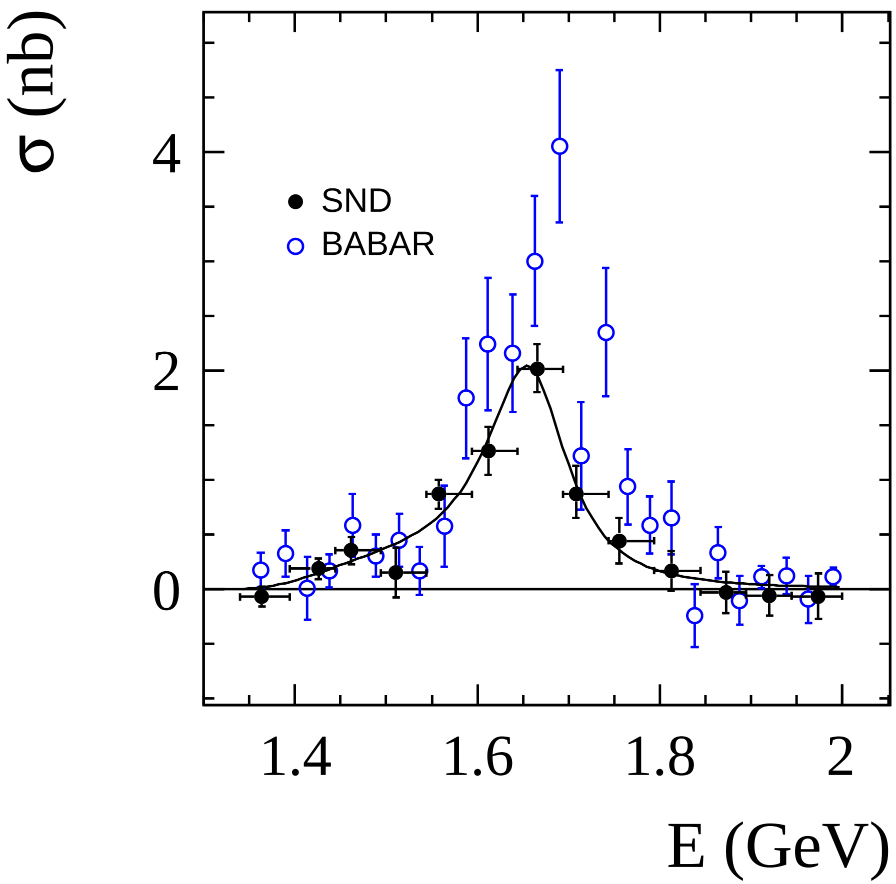


$\sim$ 700 events selected, syst. error 12%

Significant disagreement with BaBar above 1.6 GeV

M.N. Achasov et al., 1711.07143

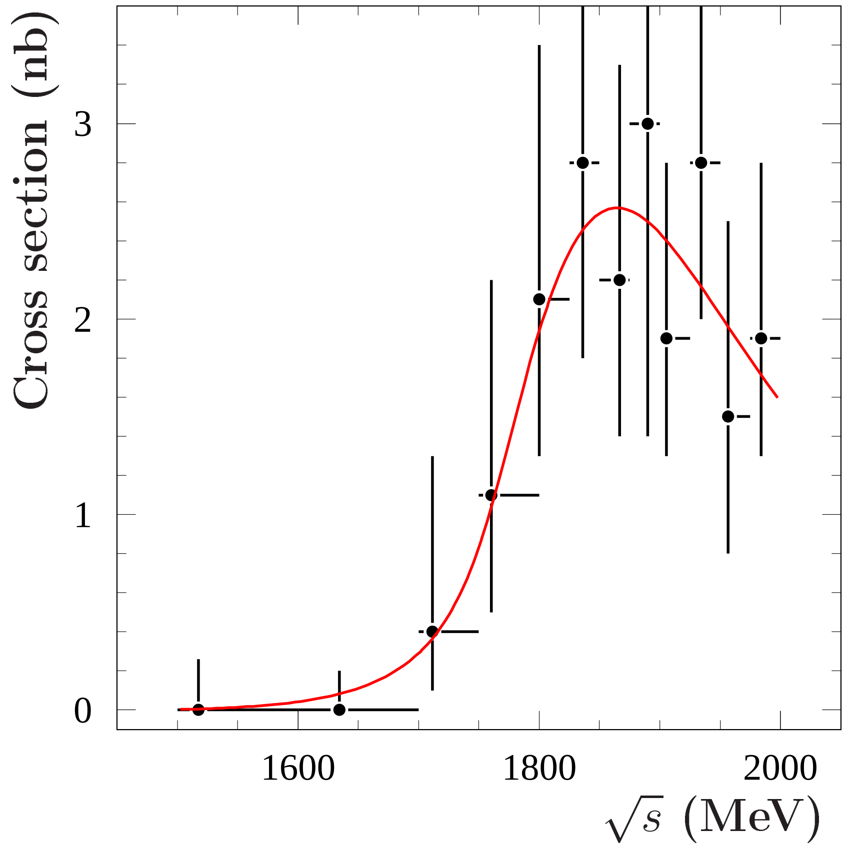
$e^+e^- \to \omega\eta$ at SND



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

M.N. Achasov et al., Phys. Rev. D94 (2016) 092002

$e^+e^- \to \omega\eta\pi^0$ at SND

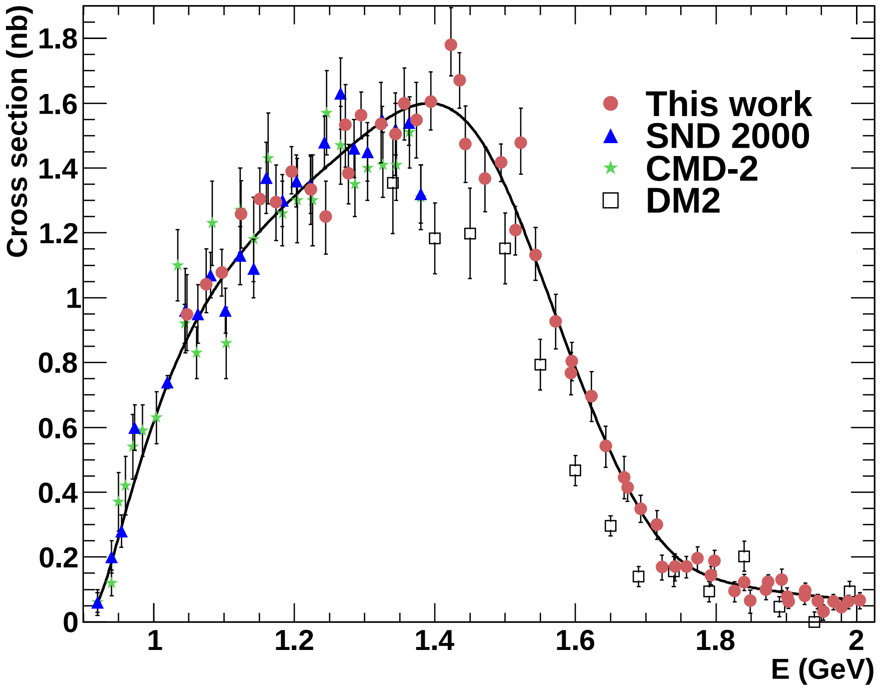


First ever observation with 62 $\pi^0\pi^0\gamma\eta$ events

The $\omega a_0(980)$ mechanism dominates

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

$e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$ at SND

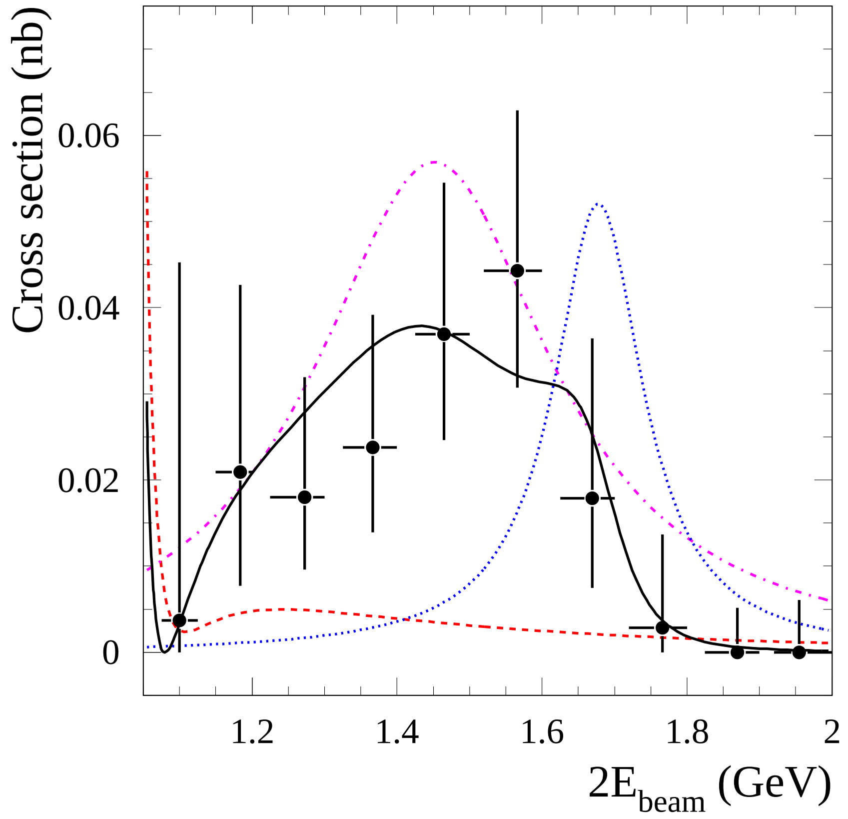


10.2k 5γ events, the systematic uncertainty varying from 2.7% to 5.2%

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

M.N. Achasov et al., Phys. Rev. D94 (2016) 112001

$e^+e^- \to \eta\gamma$ at SND



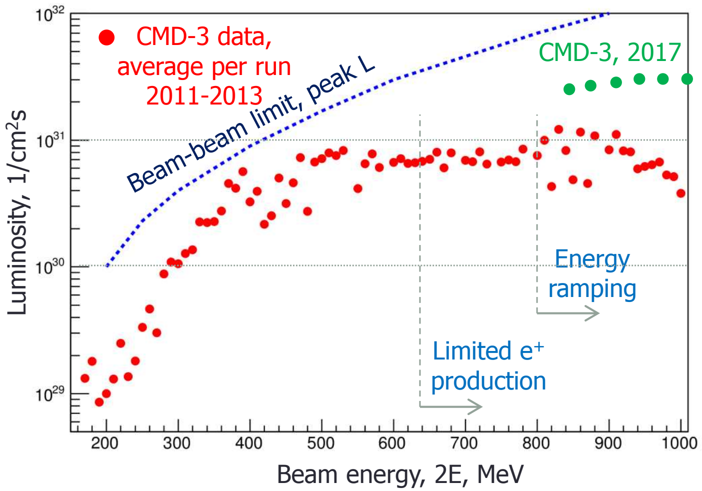
The first measurement above 1.4 GeV, Phys. Rev. D90 (2014) 032002

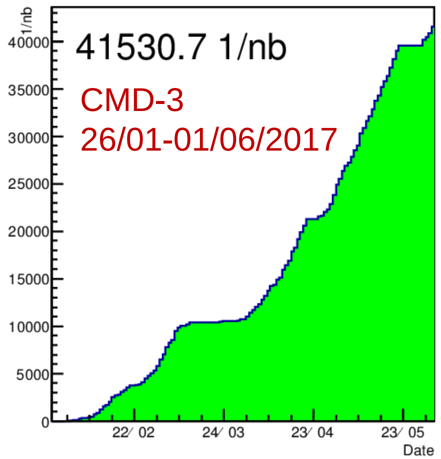
Dominated by the $\rho(1450)$ and $\phi(1680)$ mesons

VEPP-2000 Upgrade – I

1

2017 data taking





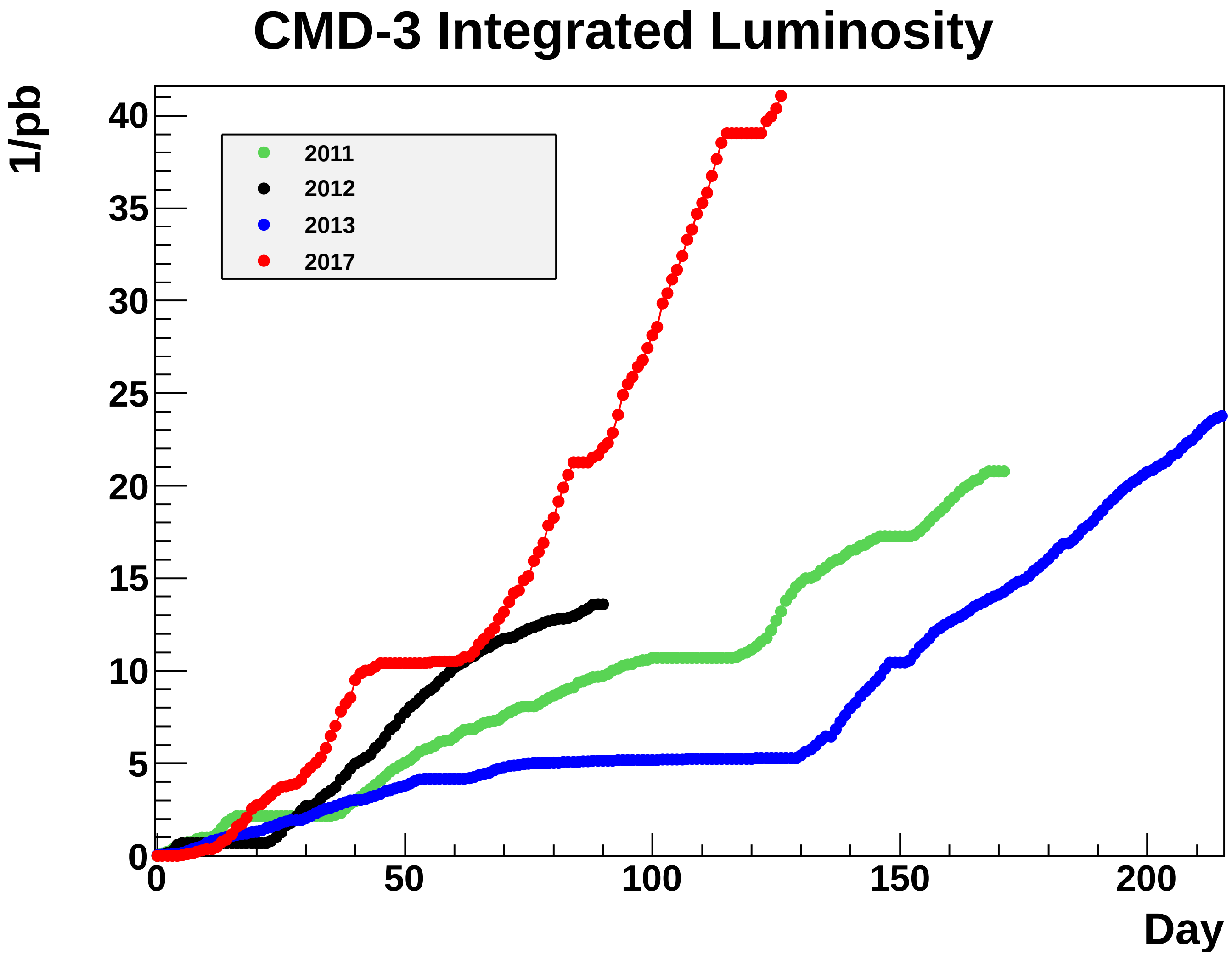
In 2011-2013, the luminosity was limited by a deficit of positrons (from $E > 650$ MeV) and limited energy of the booster (from $E > 825$ MeV).

In 2017: big improvement in luminosity at high energy, still way to go

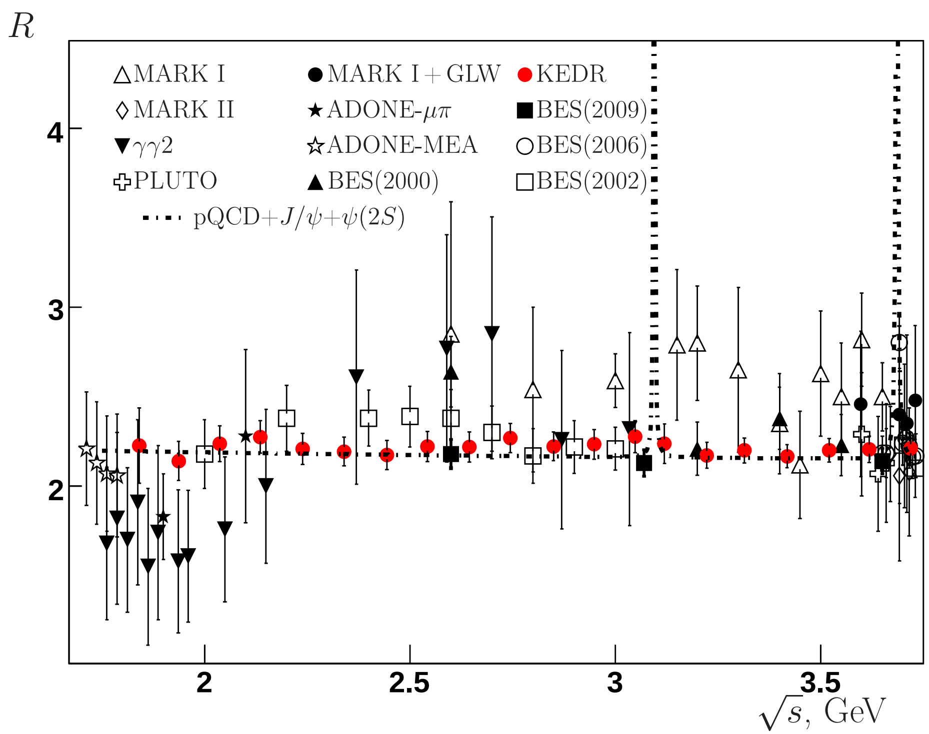
About 40 pb-1 collected

2.007 GeV ($e^+e^- \to D^{0*}$)	4 $1/pb$
$p\bar{p}$ and $n\bar{n}$ threshold	14 $1/pb$
Overall:	
1.65 – 2.007 GeV	41.5 $1/pb$

VEPP-2000 Upgrade – II



R Measurement between 1.84 and 3.72 GeV at KEDR – I



$\sqrt{s}$, GeV	N	δ_{tot}, %	δ_{syst}, %	Reference
1.84-3.05	13	3.9	2.4	Phys.Lett. B775 (2017) 174
3.12-3.72	7	3.3	2.1	Phys.Lett. B753 (2016) 533

R Measurement between 1.84 and 3.72 GeV at KEDR – II

$\sqrt{s}$, GeV	$\overline{R}$	$R_{\rm pQCD}$
1.84-3.05	$2.209 \pm 0.020 \pm 0.046$	2.18 ± 0.02
3.12-3.72	$2.189 \pm 0.022 \pm 0.042$	2.16 ± 0.01

Using $\alpha_s(m_\tau) = 0.333 \pm 0.013$ from hadronic τ decays

- R at KEDR from 1.8 to 2 GeV can be compared to the sum of CMD-3 σ's
- New precise measurement of $\Gamma_{ee}\mathcal{B}_{\rm had}$ at J/ψ
- New precise measurement of $\Gamma_{ee}\mathcal{B}_{\mu\mu}$ at $\psi(2S)$

Future

- Two new measurements of a_μ are expected in 3-5 years improving the uncertainty a factor of 4 each
- What is expected for the HVP from $e^+e^- \to$ hadrons?
  Progress in low energy e^+e^- annihilation expected from VEPP-2000 scans, from ISR with KLOE-2, BESIII, BaBar and BelleII
- New exciting approaches:
  C.M. Carloni Calame et al., Phys. Lett. B 746 (2015) 325,
  from $\alpha(t)$ in the spacelike region of Bhabha
  G. Abbiendi et al., Eur. Phys. J. C77 (2017) 139,
  from $\alpha(t)$ in the spacelike region of $\mu e \to \mu e$
- New theory g-2 initiative, June 2018 - meeting in Mainz

Conclusions

- VEPP-2000 is running smoothly with CMD-3 and SND, their accuracy is comparable or better than in 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 σ's due to scans in Novosibirsk and ISR from KLOE2, BaBar, Belle, BES3 and Belle2, are there discrepancies and/or missing modes?
- Experiments with large data samples 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
- Meanwhile a $\sim (3.5 - 4.0)\sigma$ deviation of $a_\mu^{\rm SM}$ from $a_\mu^{\rm exp}$ persists: New Physics or various experimental and interpretation errors?