Experiments at VEPP-2000

Simon Eidelman (for the CMD-3 and SND Collaborations)

Budker Institute of Nuclear Physics SB RAS and
Novosibirsk State University,
Novosibirsk, Russia

Outline

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

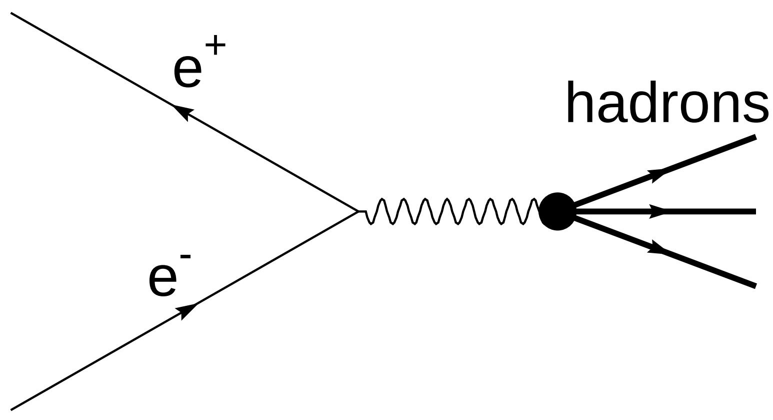
What Can We Learn from Low Energy e^+e^- Cross Sections?

1. Detailed study of exclusive processes $e^+e^- \to (2-7)h, h = \pi, K, \eta, p, \ldots$
   - Test of models and input to theory (ChPT, Vector Dominance, QCD, . . .)
   - Properties of vector mesons $(\rho', \omega', \phi', \ldots)$
   - 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 $R = \sigma(e^+e^- \to \text{ hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ at low energies and fundamental quantities
   - $(g_\mu - 2)/2$
   - $\alpha(M_Z^2)$
   - QCD sum rules (α_s, quark and gluon condensates)

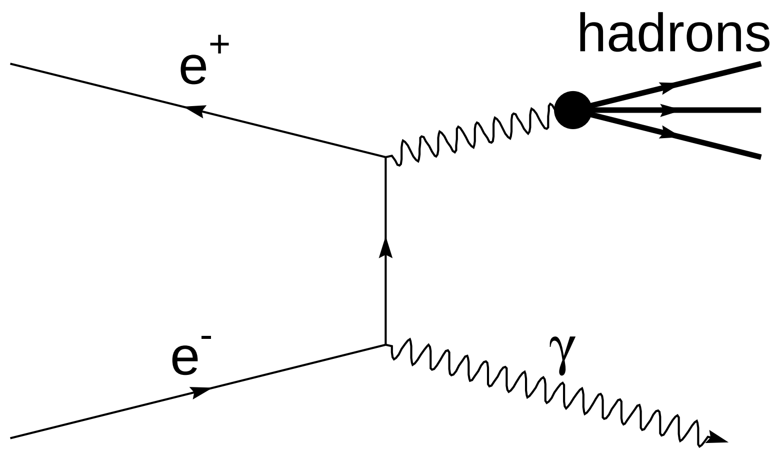
Contribution of Various Energy Ranges to $a_\mu^{\rm had,LO}$

$\sqrt{s}$, GeV	$a_\mu^{\rm had,LO}$
$\pi^+\pi^-$	507.80 ± 2.84
$\pi^+\pi^-\pi^0$	46.00 ± 1.73
K^+K^-	21.63 ± 0.73
$K_S^0K_L^0$	12.96 ± 0.39
m/h < 1.8	45.50 ± 3.44
1.8-3.7	$33.45 \pm 0.28(2.00)$
> 3.7	17.16 ± 0.31
Total	692.3 ± 4.2

Scan and ISR



Scan

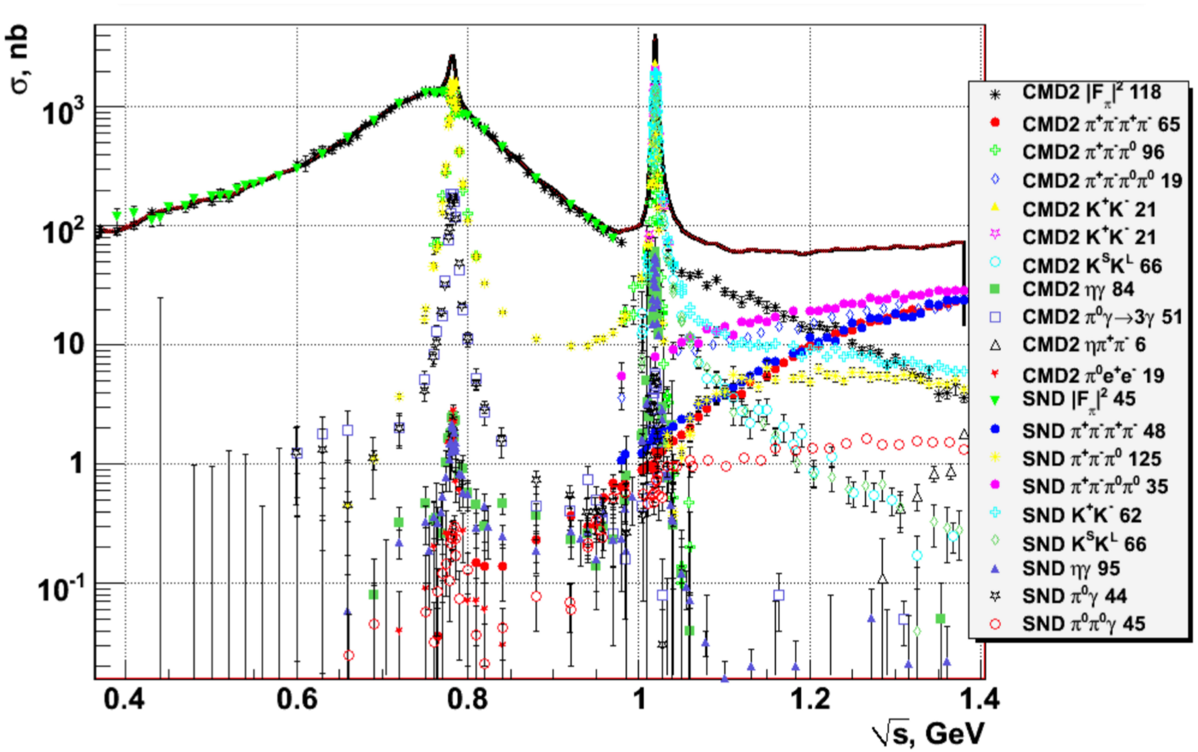


ISR

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

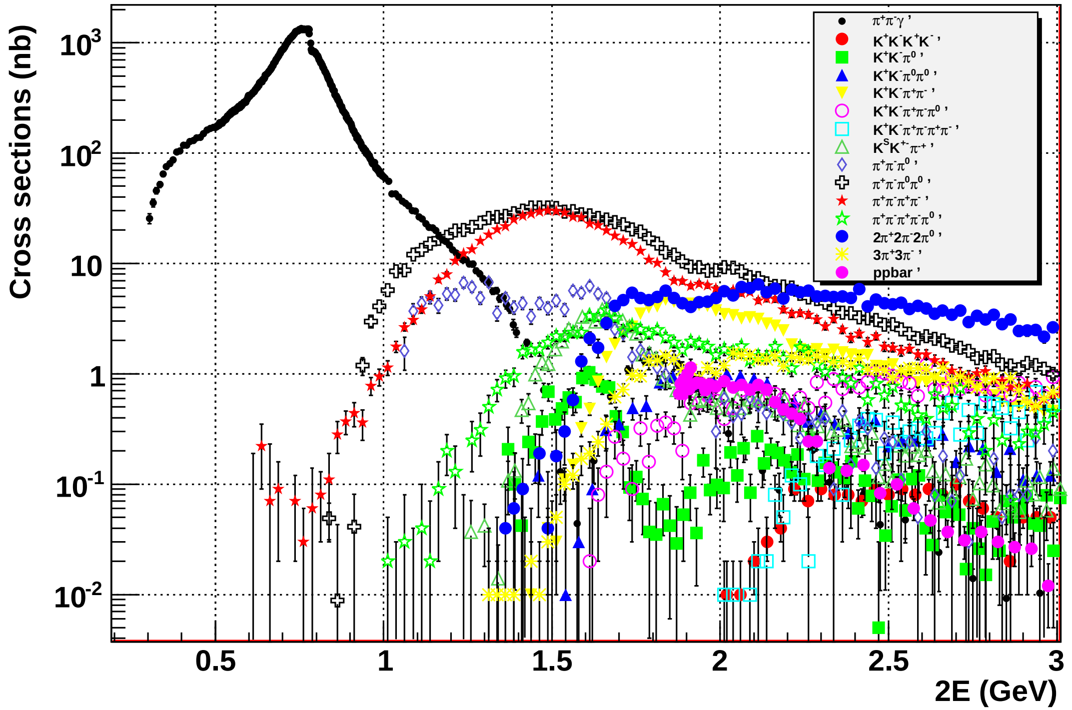
ISR benefits from the same systematics and flat acceptance,
may suffer from more complicated radiative effects, all neutrals hardly possible

Current Status of Exclusive Measurements – I



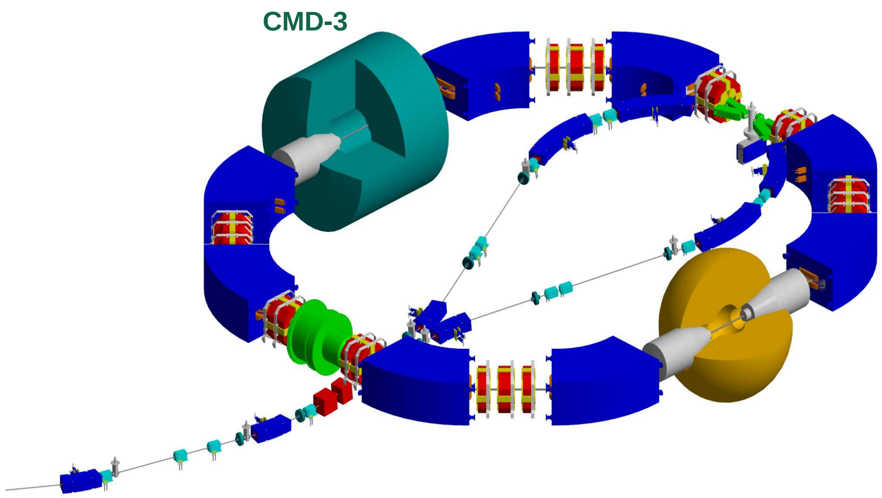
Impressive achievements of CMD-2, SND (scan at $\sqrt{s} < 1.4$ GeV)
and KLOE (ISR at $\sqrt{s} < 1.0$ GeV)

Current Status of Exclusive Measurements – II



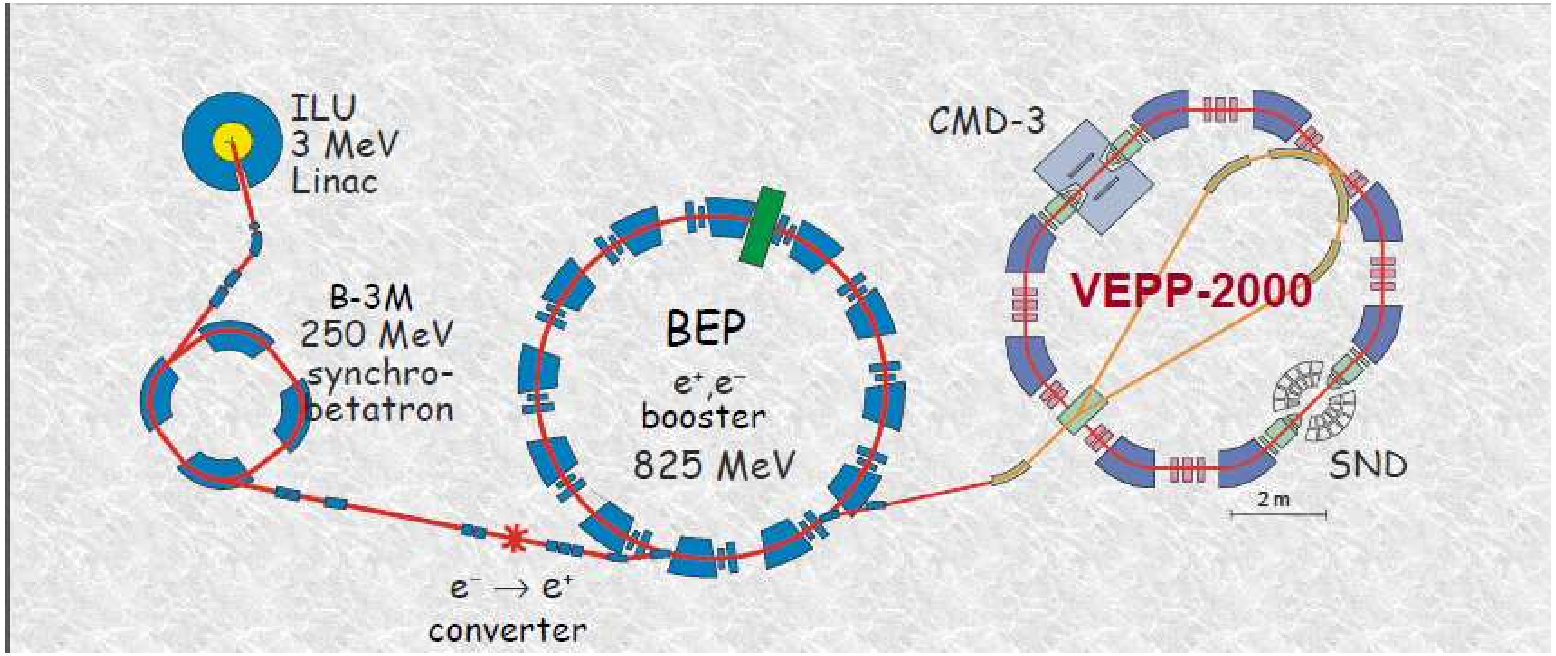
BaBar used ISR to study the energy range $\sqrt{s} < 3.0$ GeV,
Belle and BESIII may contribute as well to ISR measurements

VEPP-2000 – I



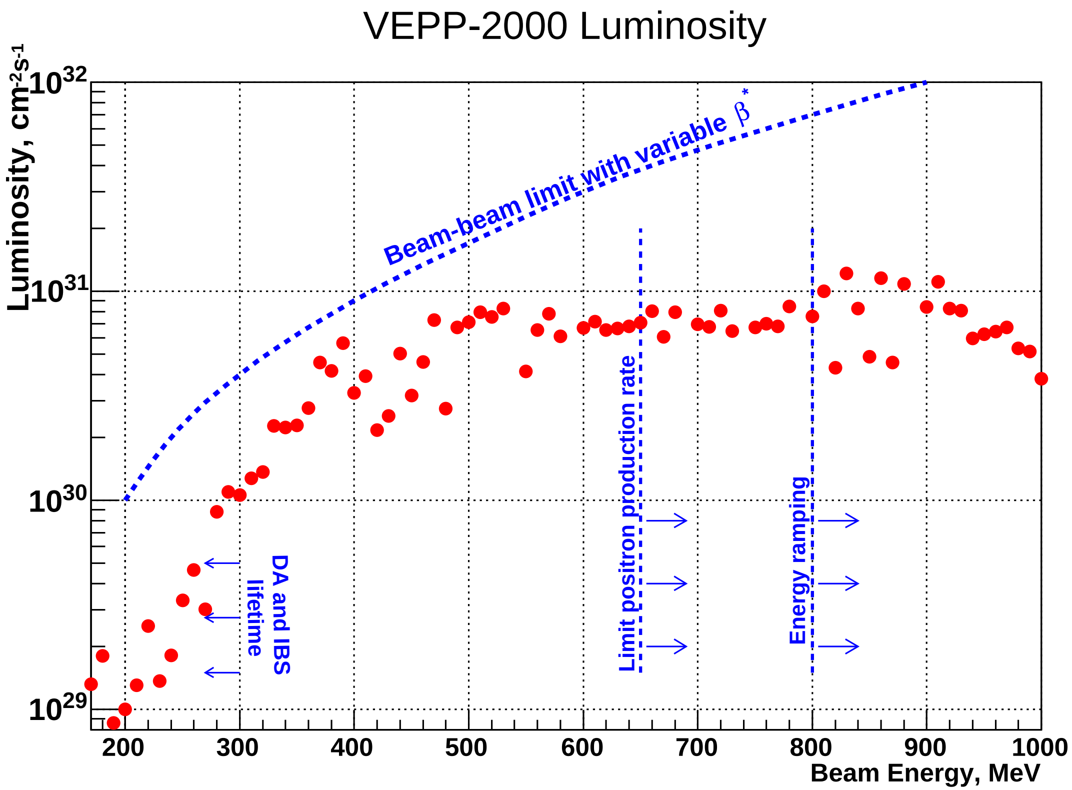
Collider	Operation	$\sqrt{s}$, MeV	$\mathcal{L}$, $10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
VEPP-2M	1975-2000	[360,1400]	3
VEPP-2000	2010-	$[2m_\pi, 2000]$	100

VEPP-2000 – II

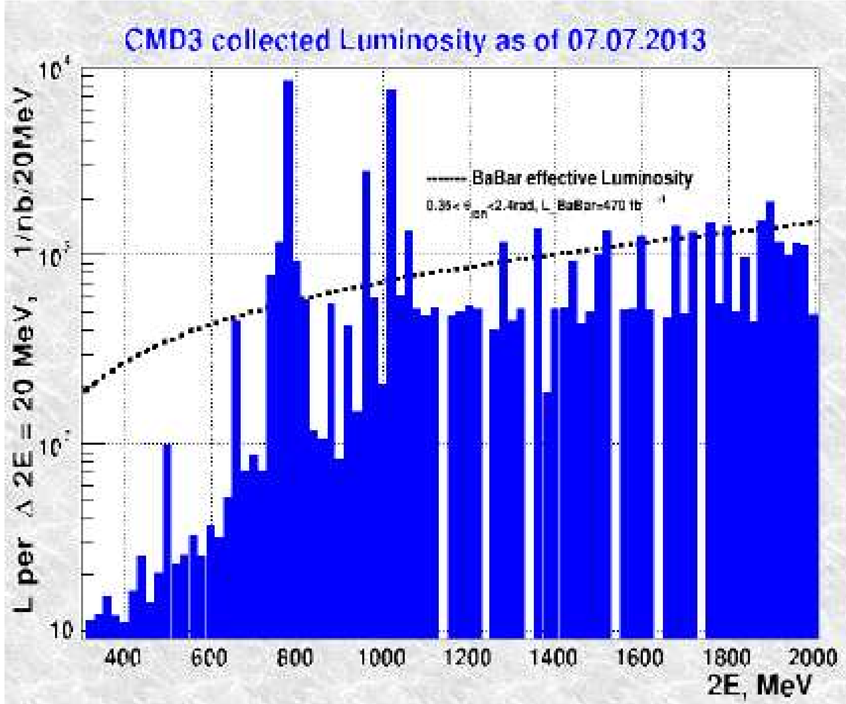


New optics with round beams ⇒ higher luminosity, precise beam energy measurement using LCBS

VEPP-2000 – III



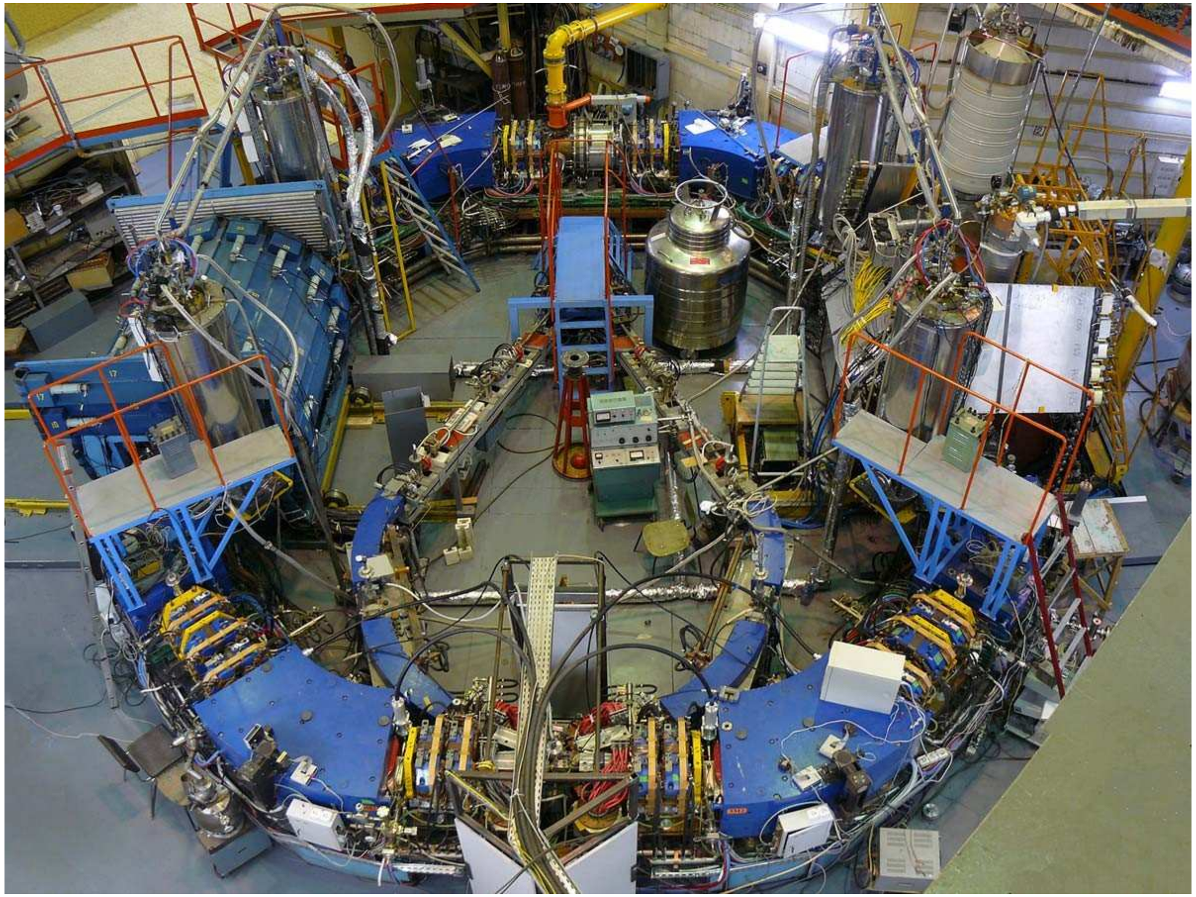
Data Taking at VEPP-2000



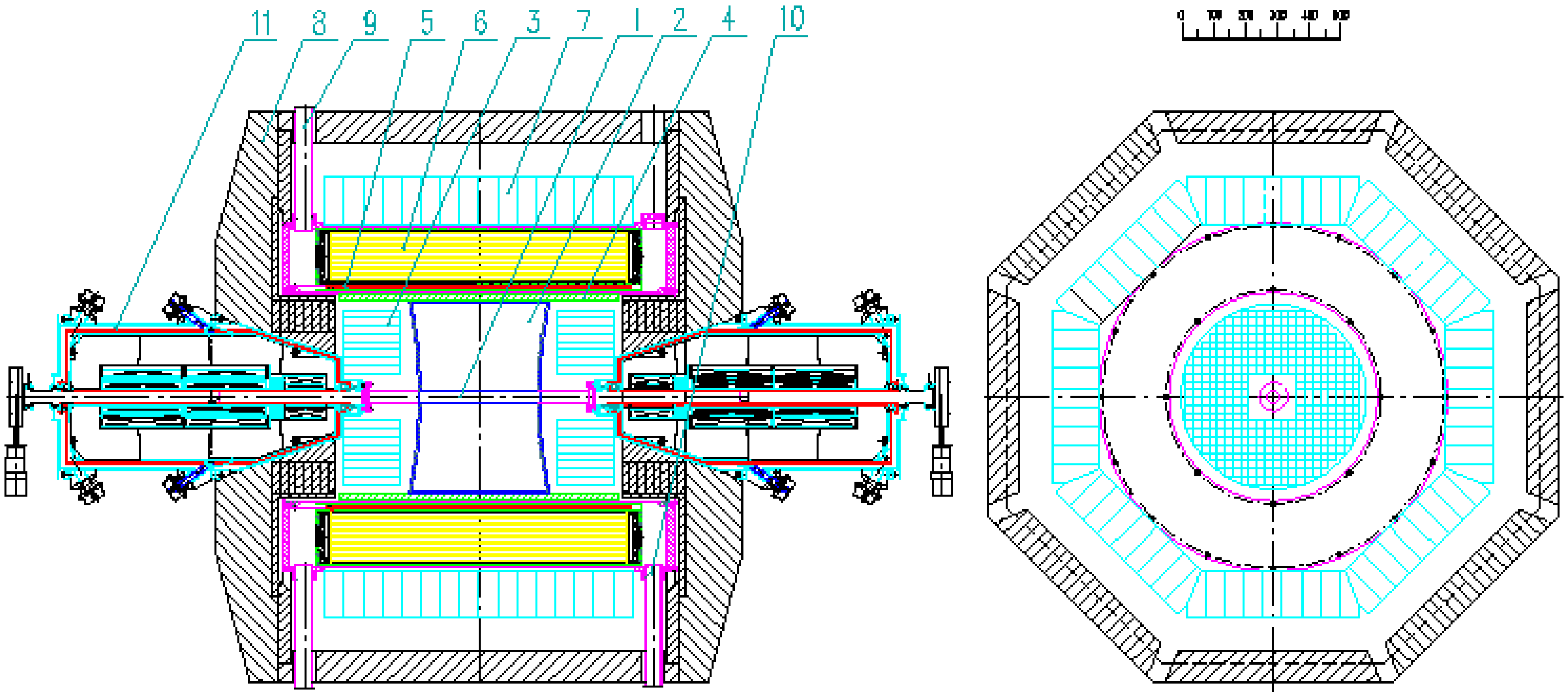
Collected L ~ 60 pb^{-1} per detector

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

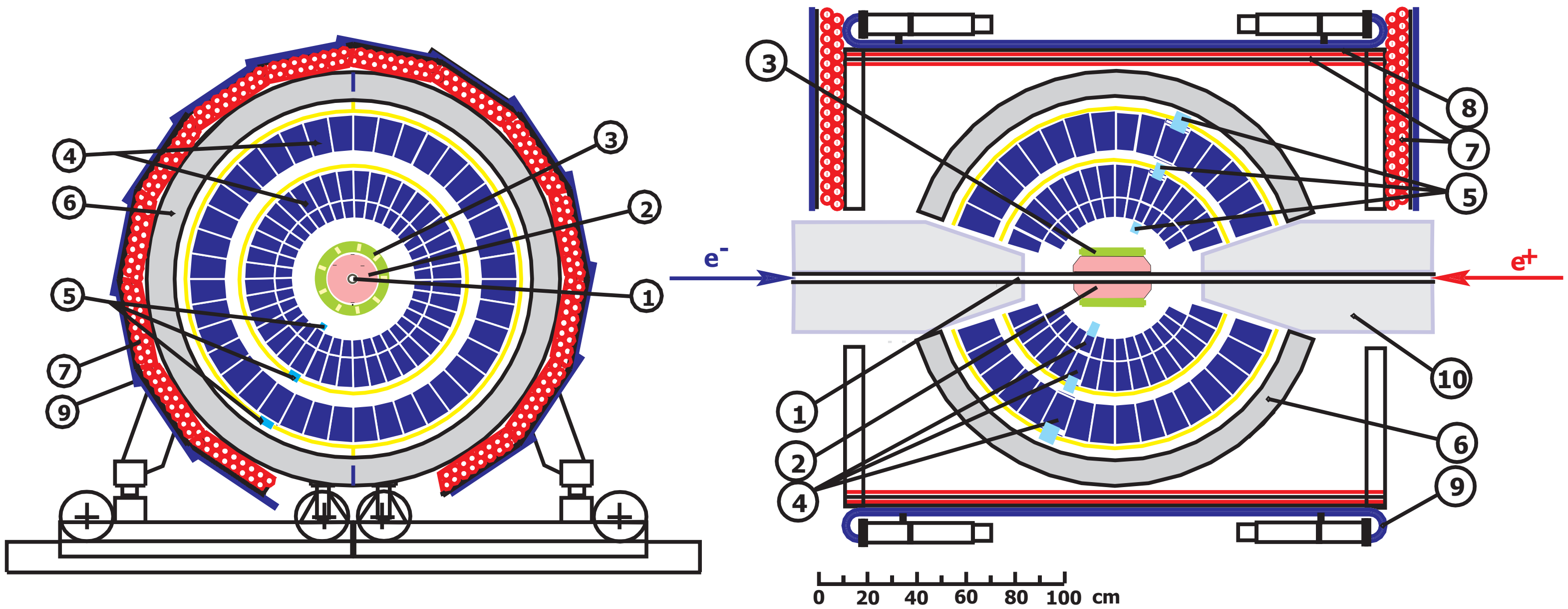


CMD-3



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

SND

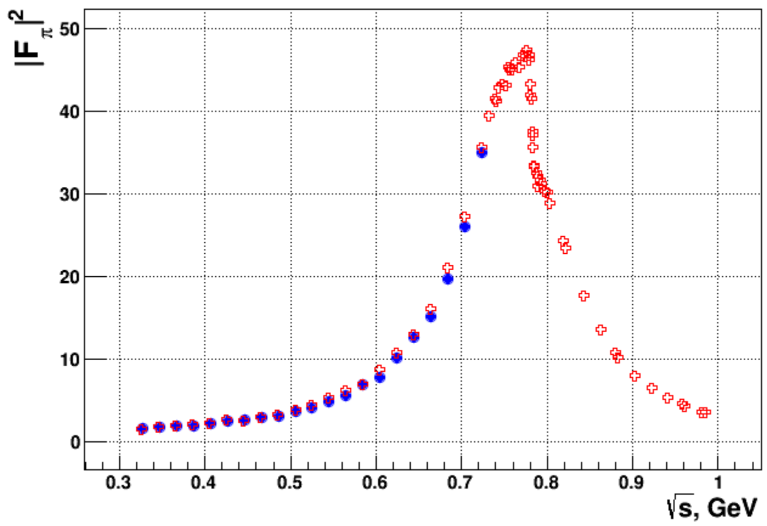


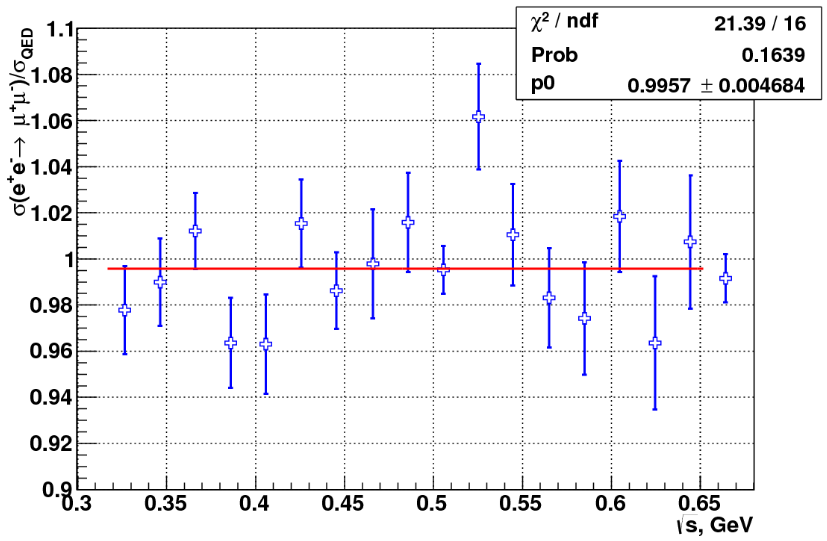
High-resolution NaI calorimeter with excellent tracking and PID

Performance of VEPP-2000 and Detectors

- 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
- At high energies luminosity 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} cm^{-1}s^{-1}
- Both detectors perform reasonably well with reconstruction of both tracks and photons and redundancy ($\eta \to 2\gamma, \pi^+\pi^-\pi^0, 3\pi^0, \pi^+\pi^-\gamma$, $\omega \to \pi^+\pi^-\pi^0, \pi^0\gamma$)

$e^+e^- \to \pi^+\pi^-$ at CMD-3 – I

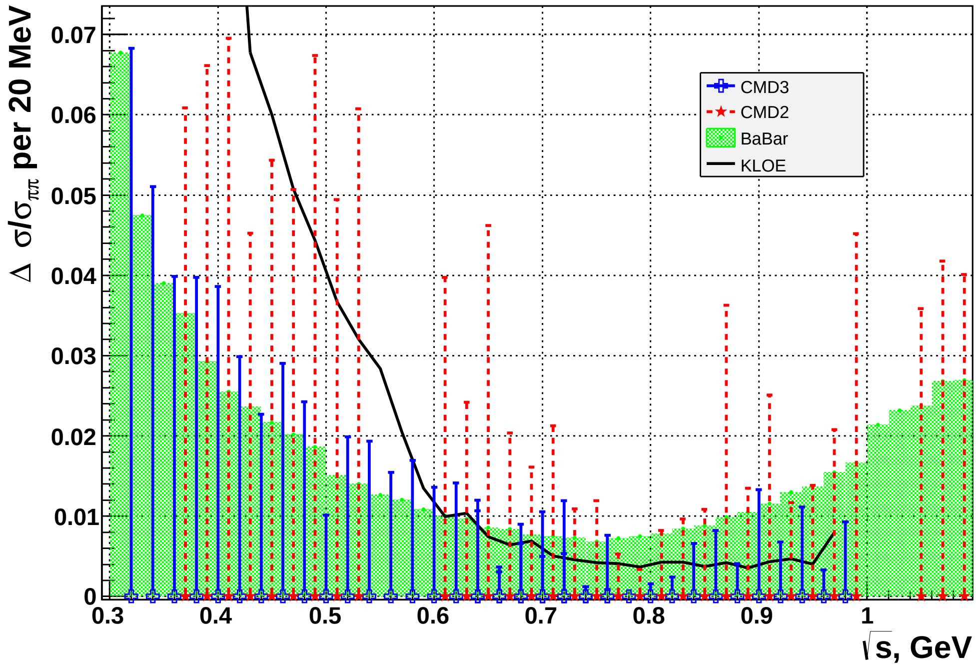




Identification at low energy - by DC with separation of $\mu^+\mu^-$

At high energy - by energy deposition in calorimeters

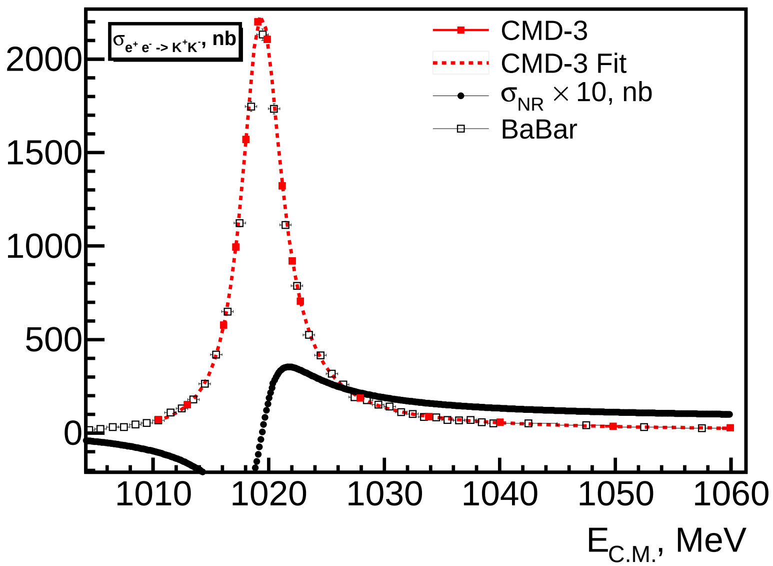
$e^+e^- \to \pi^+\pi^-$ at CMD-3 – II

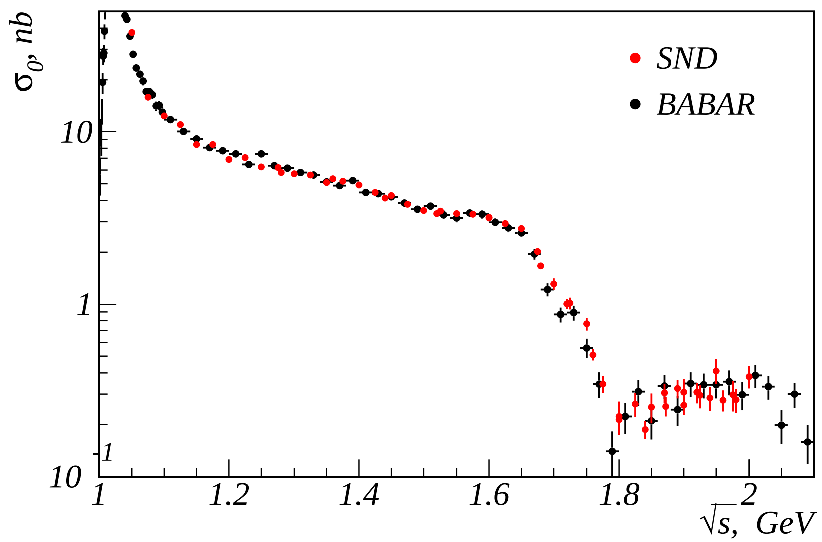


Statistical precision better than that of BaBar

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

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

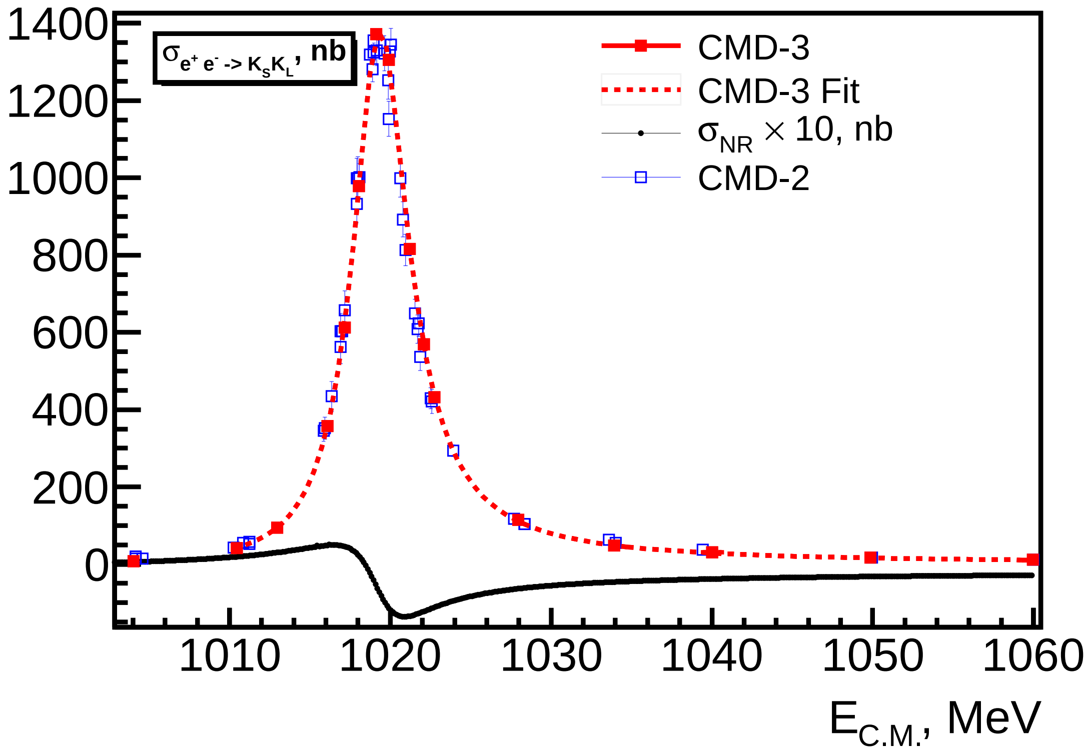




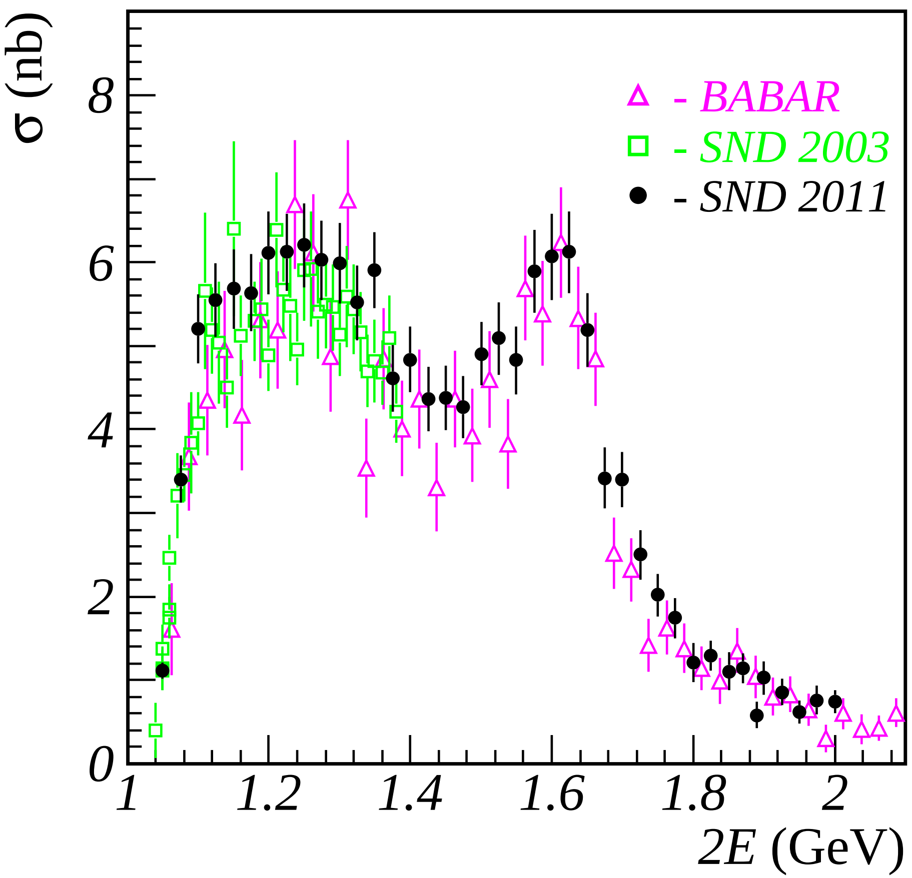
BaBar claims aggressive systematics of 0.72% at the ϕ, increasing to 7% at 2 GeV

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

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



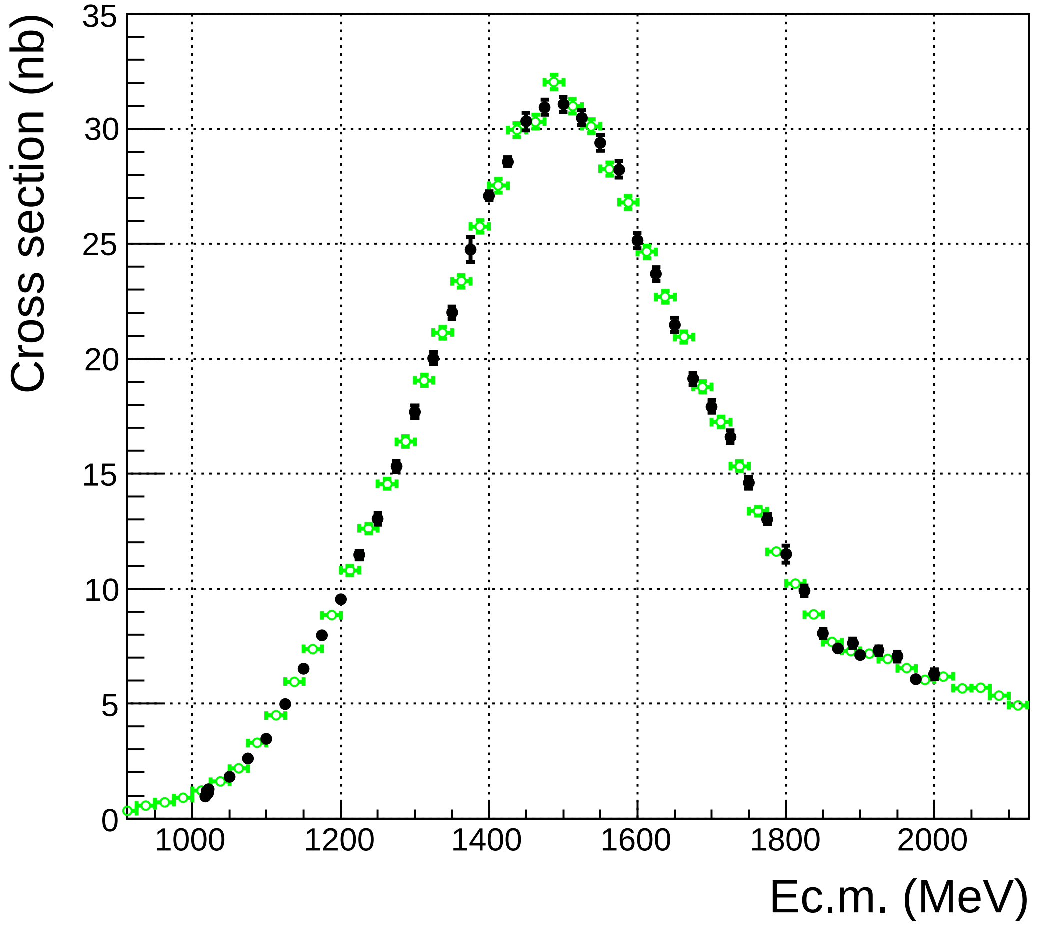
$e^+e^- \to \pi^+\pi^-\pi^0$ at SND



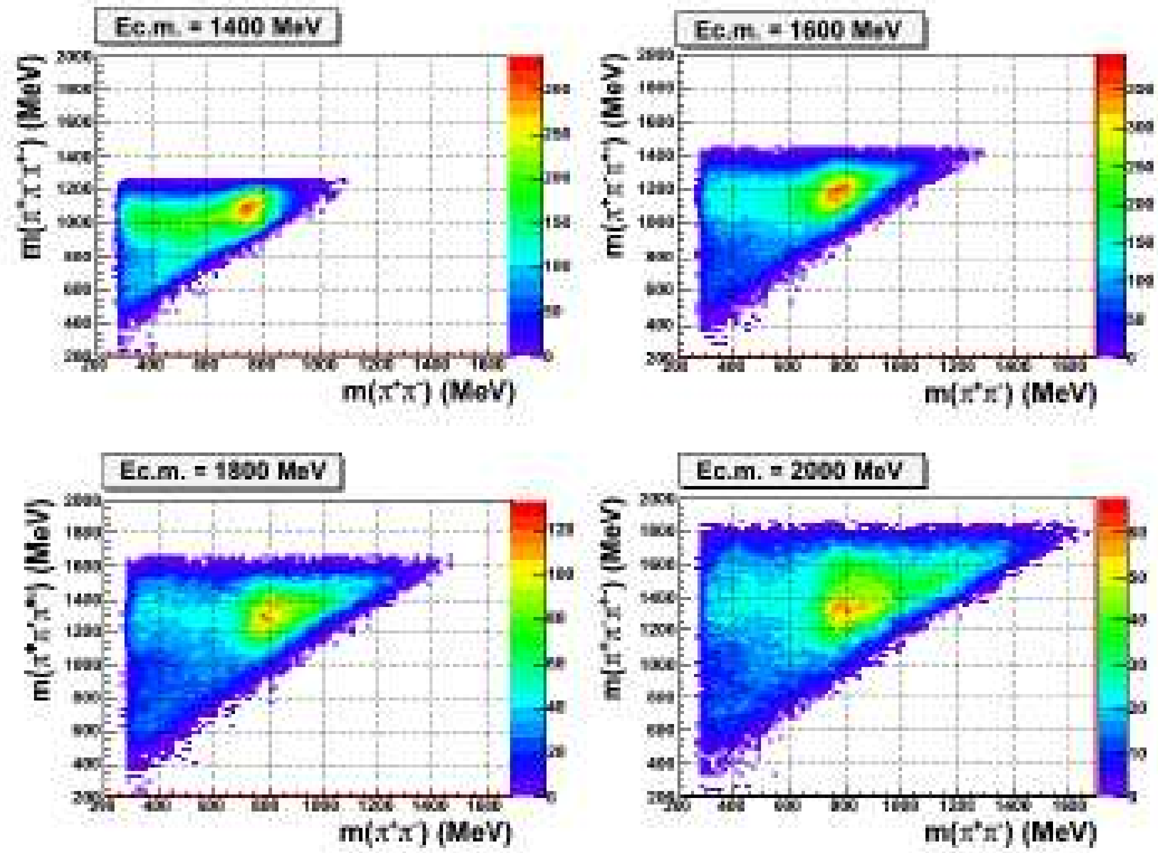
Two ω' clearly seen: $\omega(1420)$ and $\omega(1650)$

It's interesting to disentangle the $\rho\pi$ and direct 3π modes

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

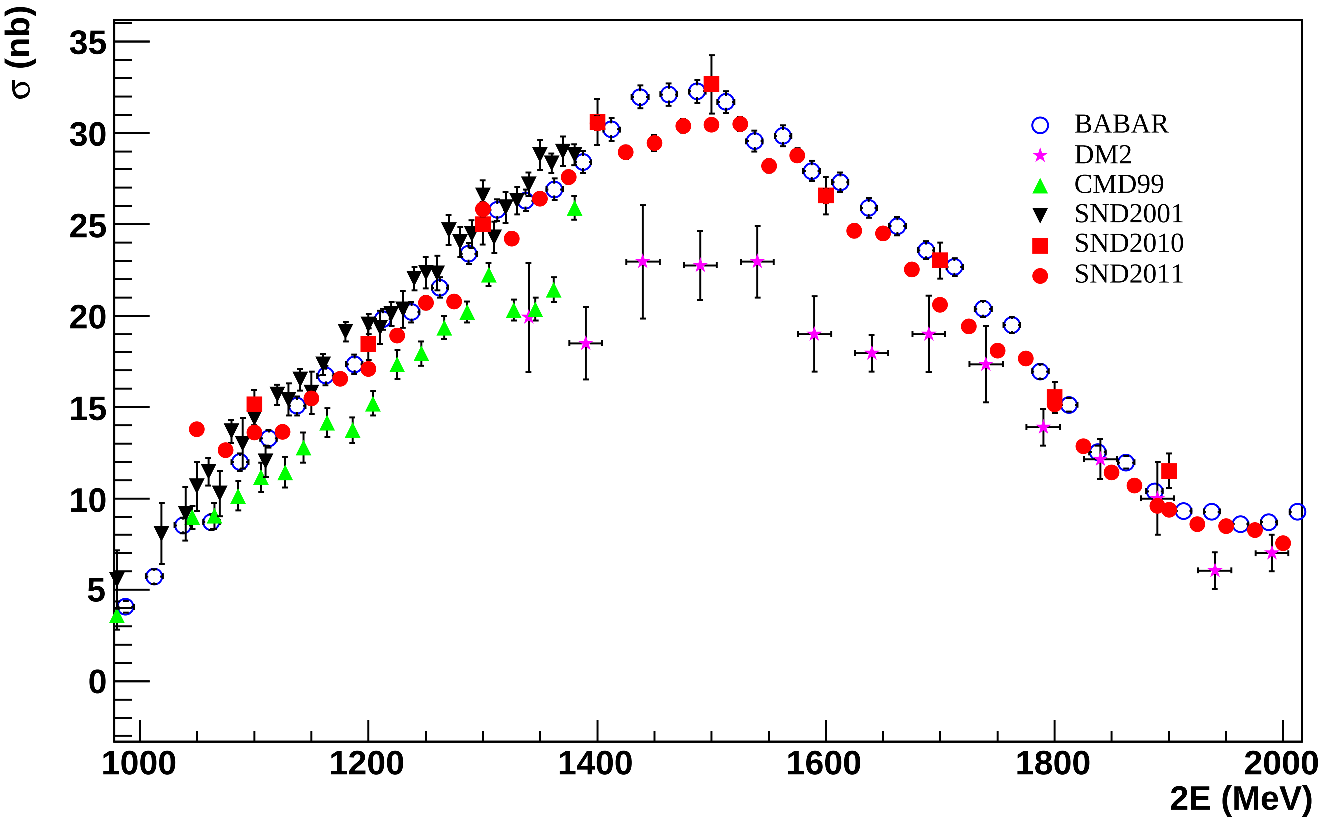


Dynamics of $e^+e^- \to 2\pi^+2\pi^-$ at CMD-3



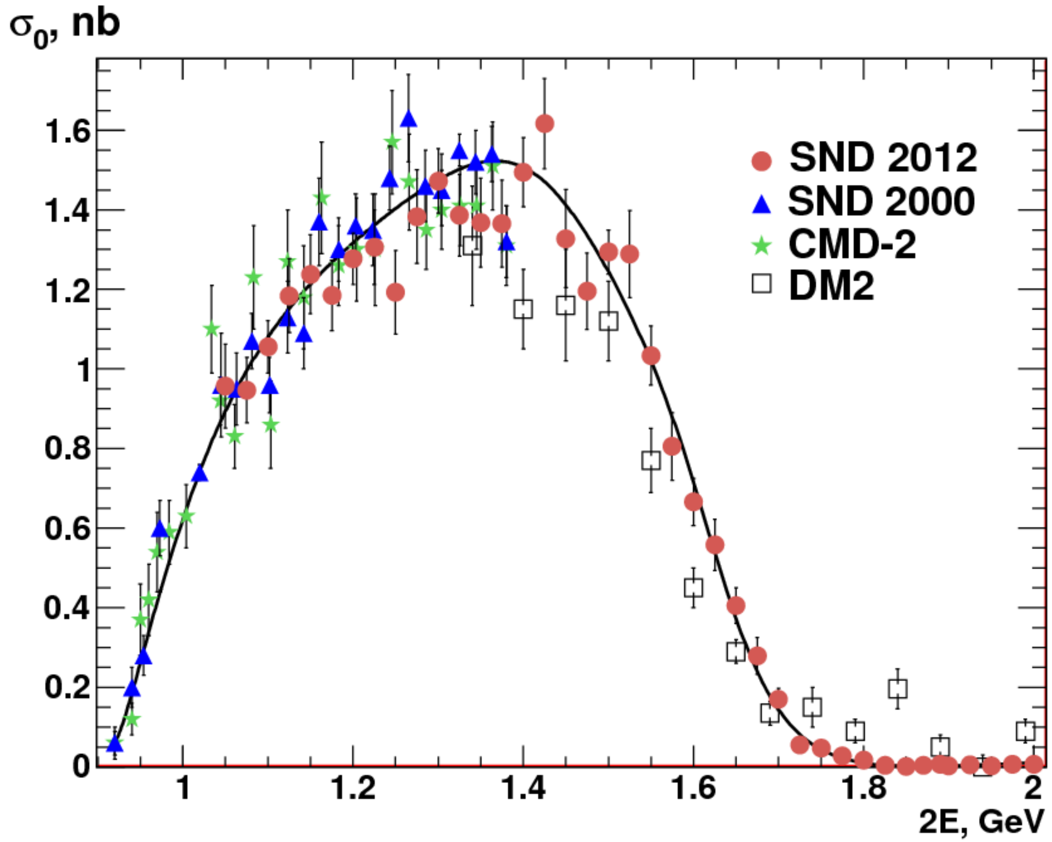
A ρ^0 is always present, $a_1^\pm(1260)\pi^\mp(a_2^\pm(1320)\pi^\mp)$ significant,
at higher $\sqrt{s}$ other mechanisms like $\rho^0 f_0$, $\rho^0 f_2(1270)$ appear

$e^+e^- \to 2\pi^+2\pi^-$ at SND



There are data from different detectors, agreement not yet perfect

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



Phys. Rev. D 88 (2013) 054013

First observation above 1.4 GeV

$e^+e^- \to 3\pi^+3\pi^-$ 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:
   - $\rho(1450)(\pi^+\pi^-)_{\rm S-wave} \to a_1(1260)^{\pm}\pi^{\mp}\pi^+\pi^- \to \rho^0 2(\pi^+\pi^-) \to 3(\pi^+\pi^-)$
   - $\rho(770)(2\pi^+2\pi^-)_{\rm S-wave} \to 3(\pi^+\pi^-)$
     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 $3\pi^+3\pi^-$, $2\pi^+2\pi^-2\pi^0$, $\pi^+\pi^-4\pi^0$

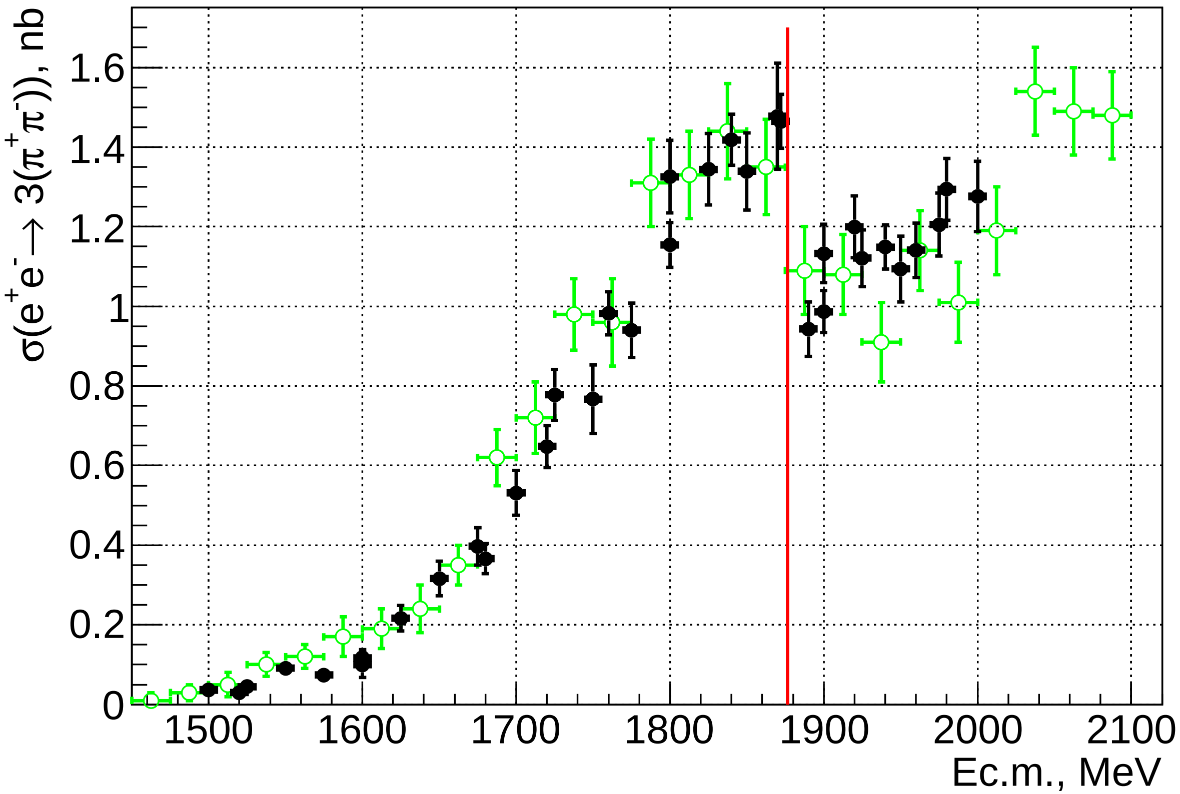
$e^+e^- \to 3\pi^+3\pi^-$ at CMD-3 – II

Systematic uncertainties for $\sigma(e^+e^- \to 3\pi^+3\pi^-)$

Source	$\text{Error}_{\text{CMD}}$, %	$\text{Error}_{\text{BABAR}}$, %
Model	4	3
Selection	3	$2 \bigoplus 3$
Lumi	2	3
Background (6 tr.)	1	3
Background (5 tr.)	3	-
$\Delta\sqrt{s}/\sqrt{s}(\sim 5 \cdot 10^{-3})$	1	-
Rad. corr.	1	1
Total	6	6

Hope to decrease it to $\sim 3\%$

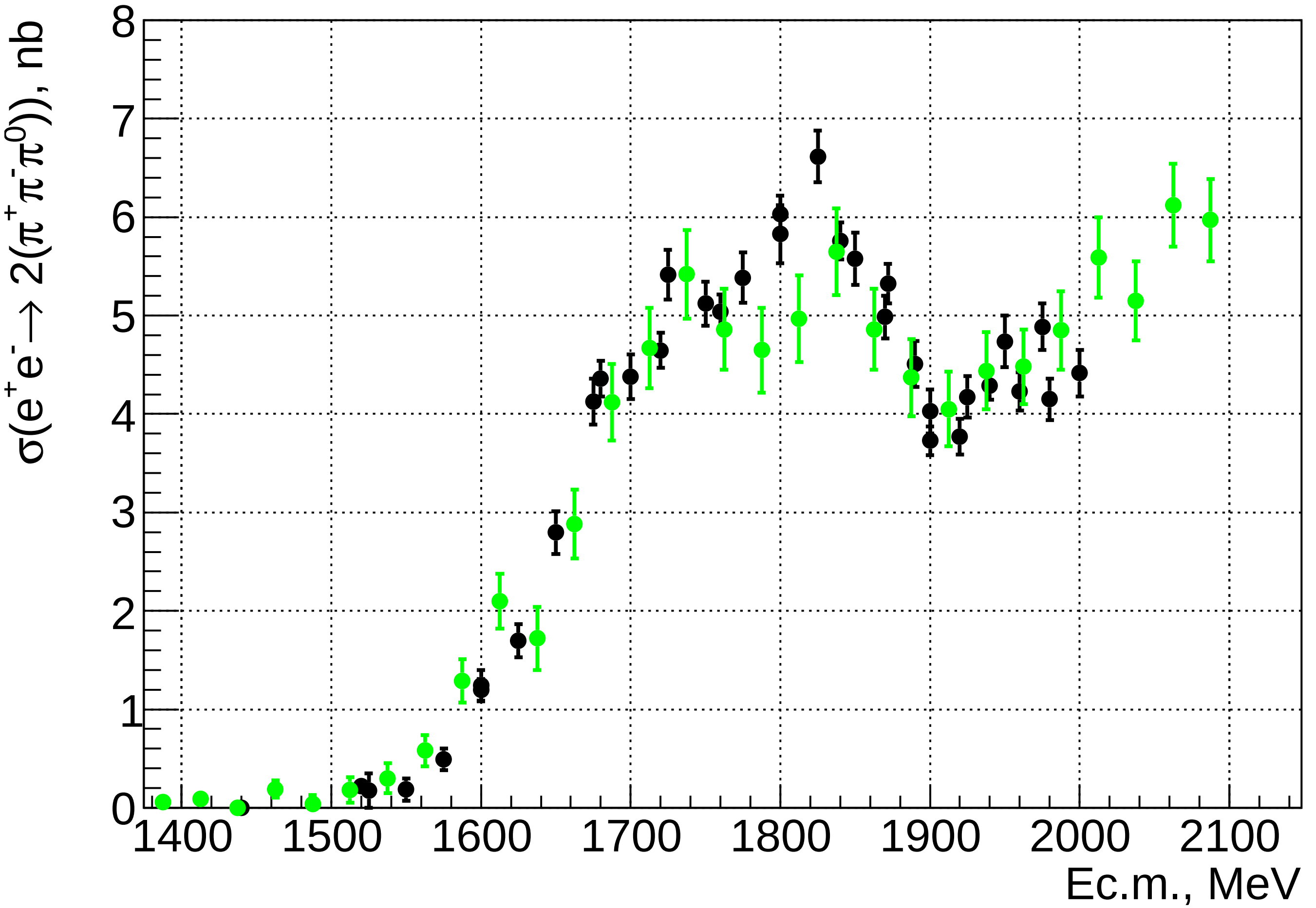
$e^+e^- \to 3\pi^+3\pi^-$ at CMD-3– III



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

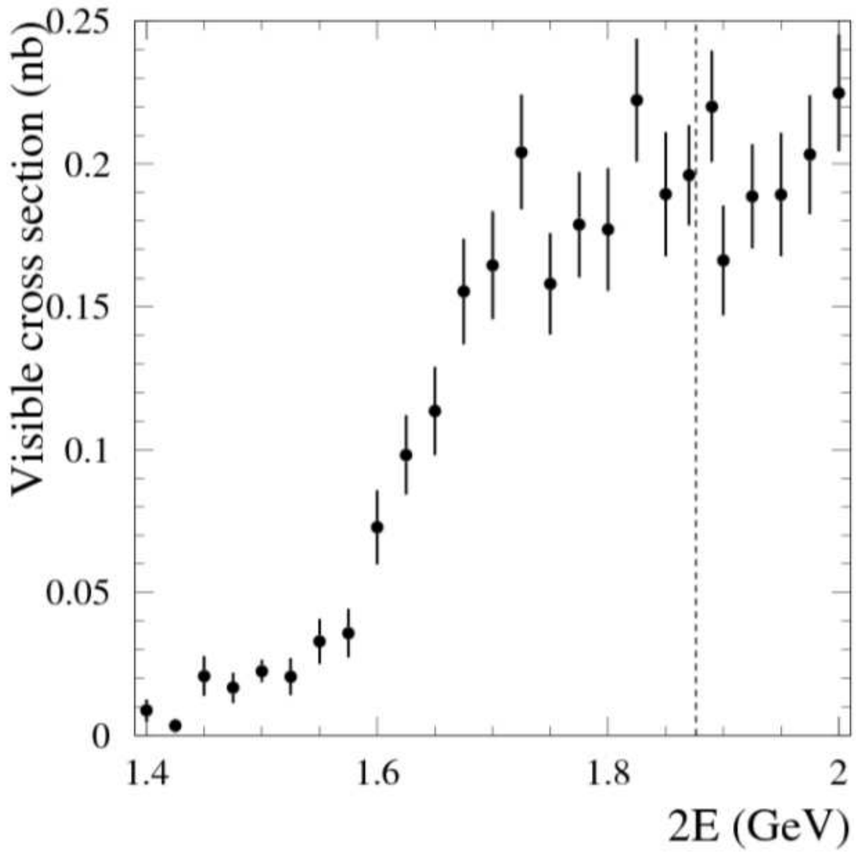
Phys. Lett. B 723 (2013) 82

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



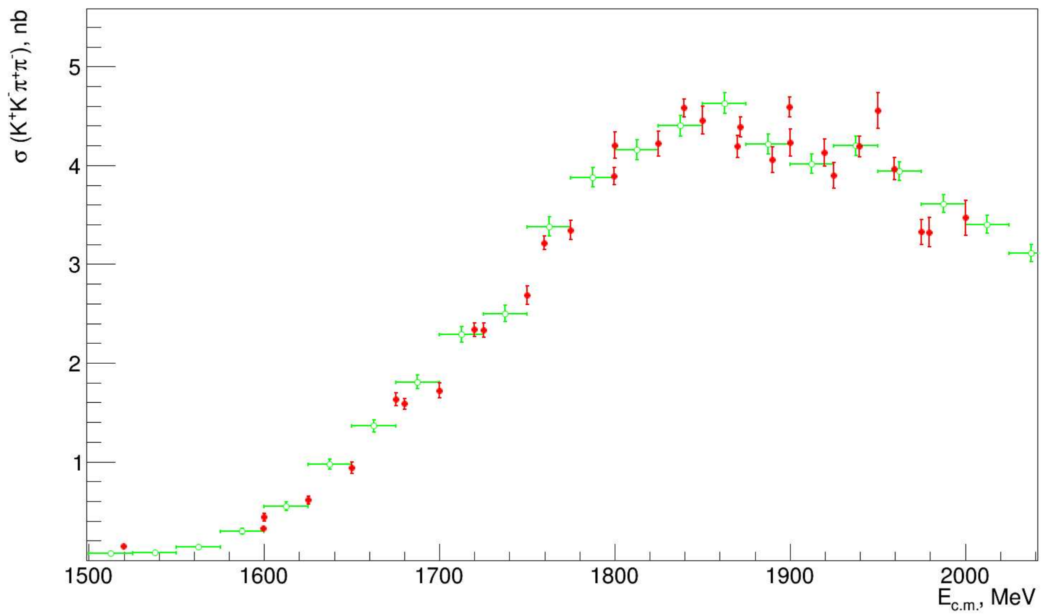
The dip structure near $N\bar{N}$ threshold also seen

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



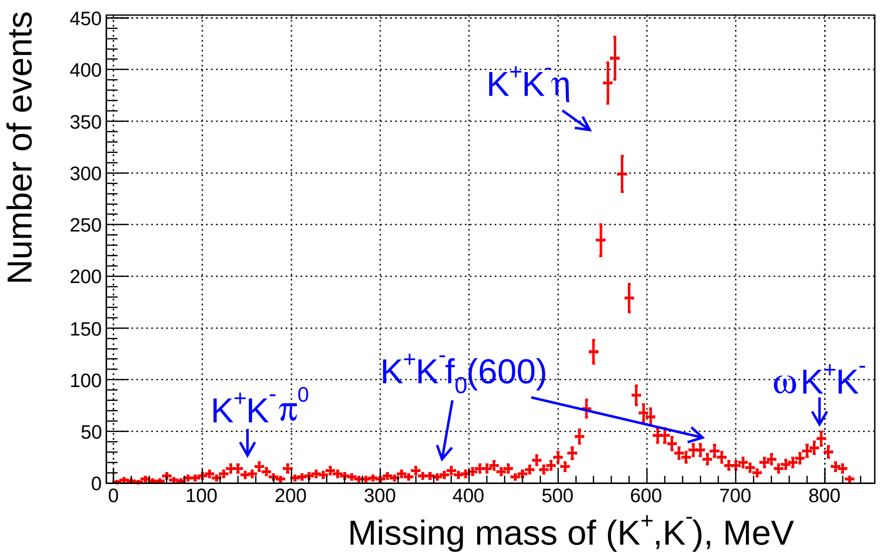
First ever measurement of this final state, very important for dynamics studies together with $e^+e^- \to 3\pi^+3\pi^-,\ 2\pi^+2\pi^-2\pi^0$

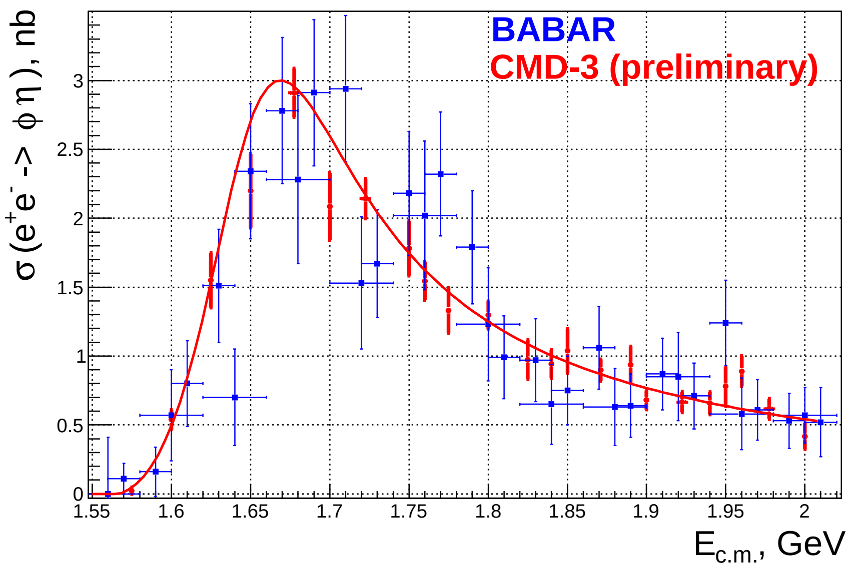
$e^+e^- \to K^+K^-\pi^+\pi^-$ at CMD-3



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

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

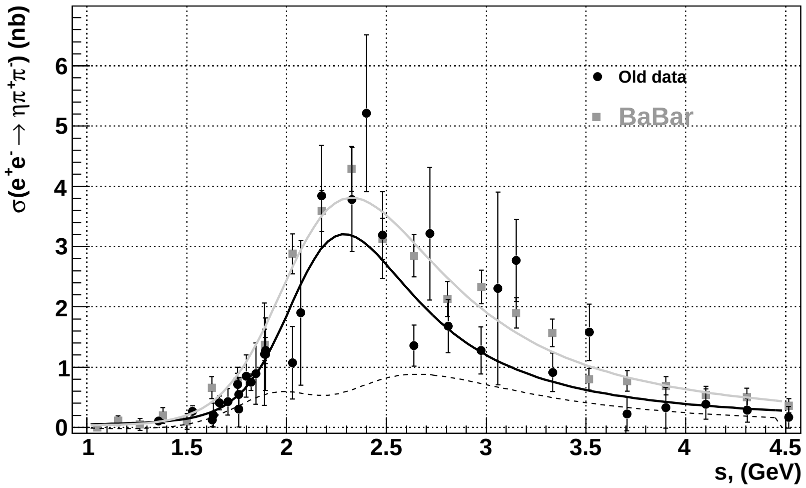


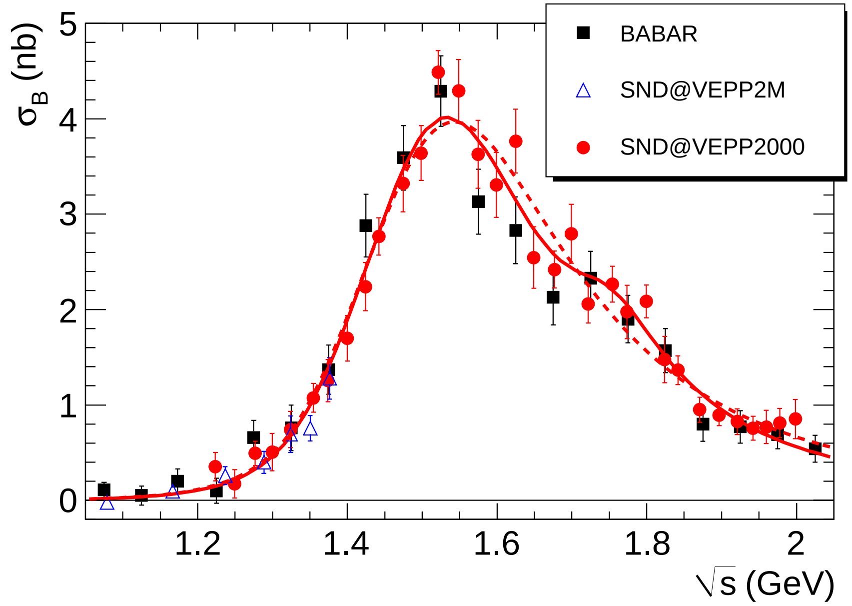


Dynamics is dominated by $\phi\eta$

The $\phi(1680)$ meson is clearly seen

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

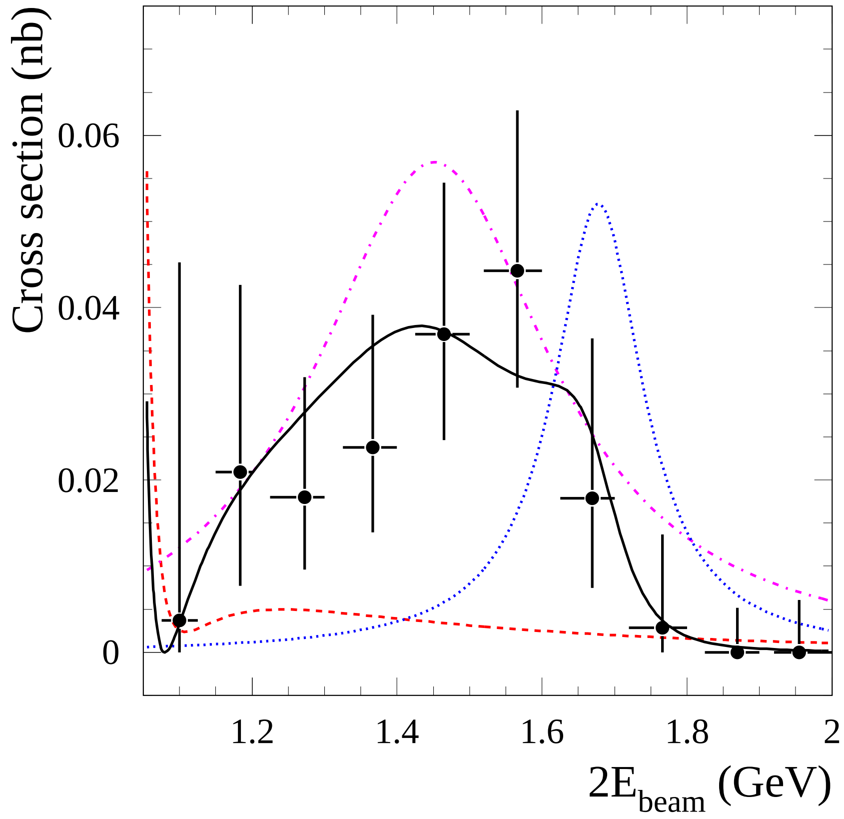




BaBar data higher than old data by $\sim 15\%$, not confirmed by new SND data?

M.N. Achasov et al., arXiv:1412.1971

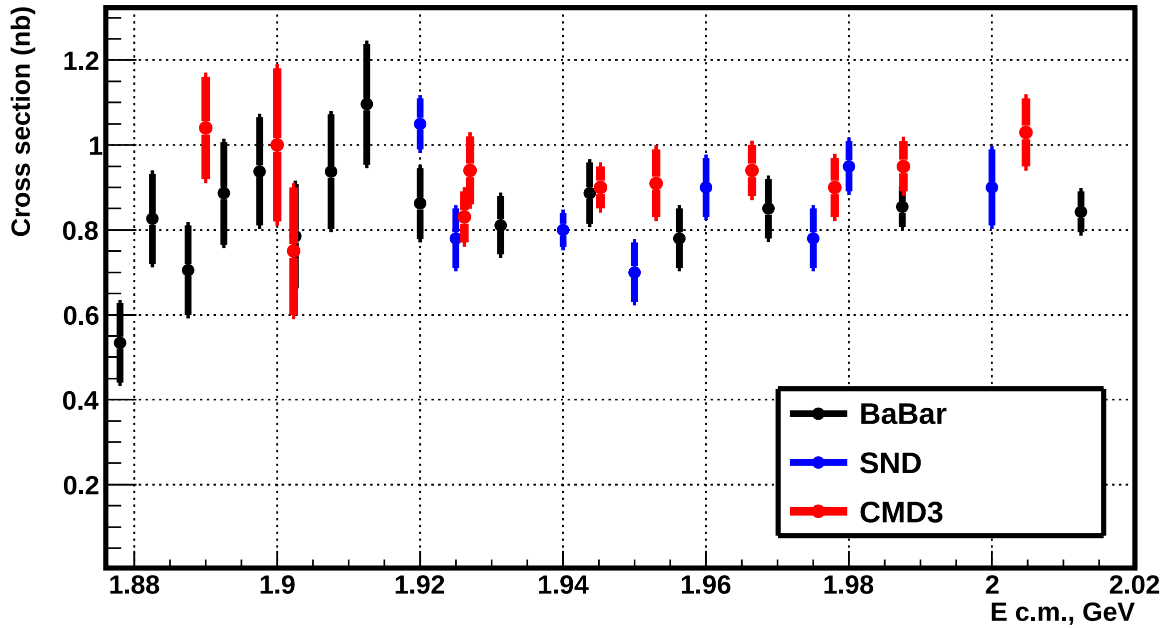
$e^+e^- \to \eta\gamma$ at SND



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

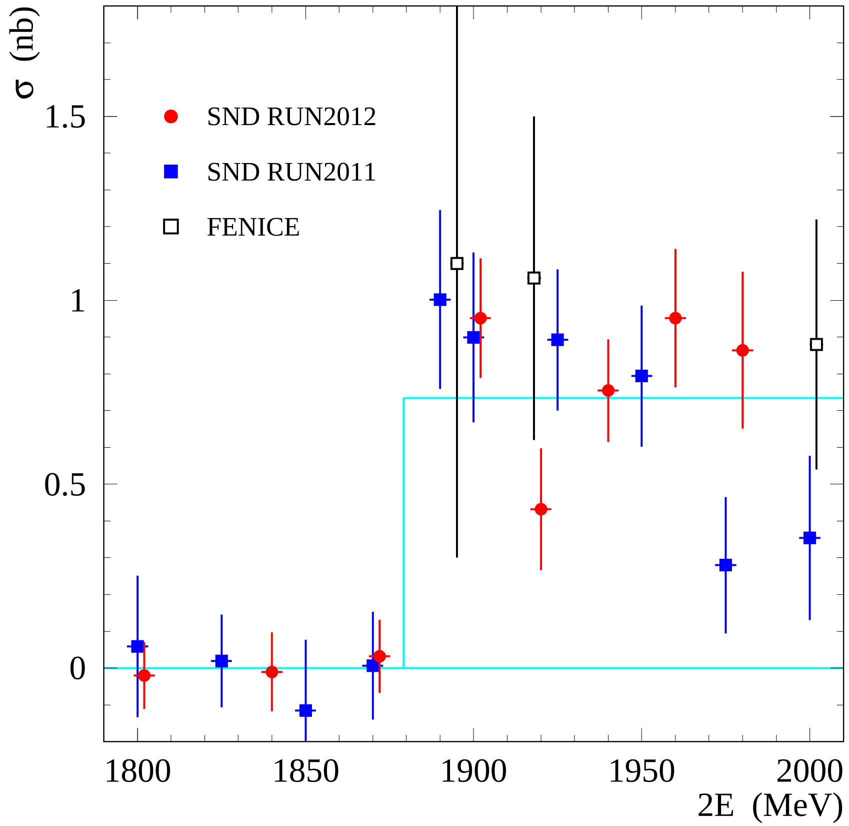
Dominated by the $\rho(1450)$ and $\phi(1680)$ mesons

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



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

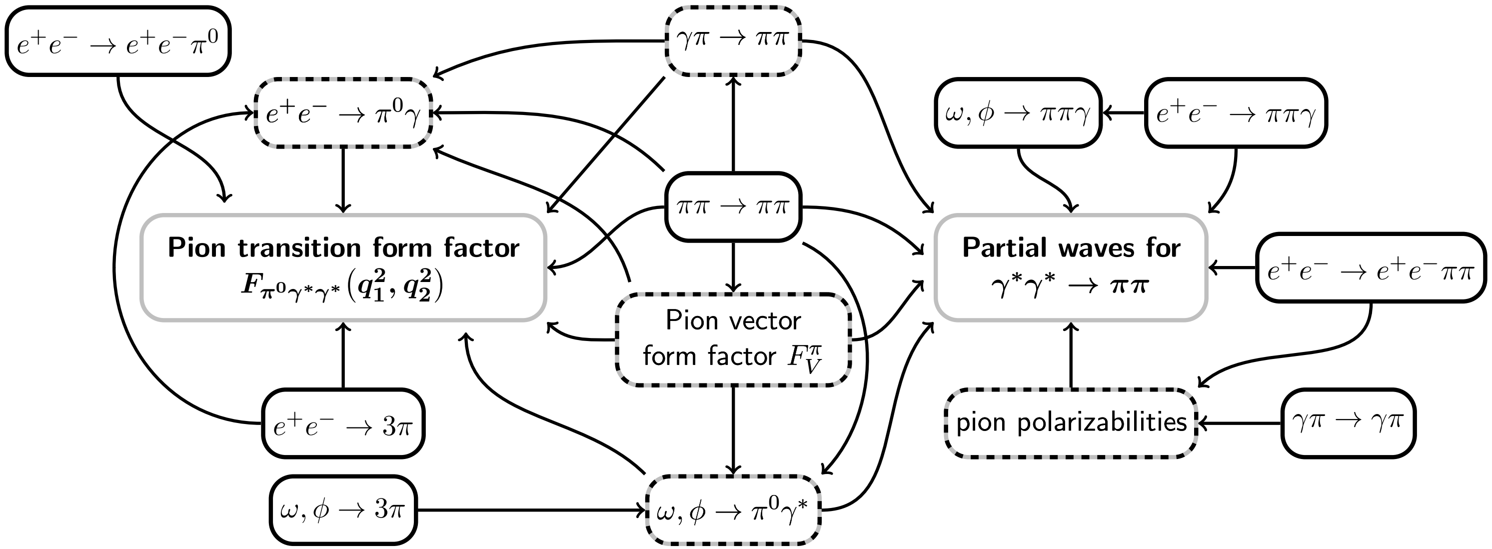
$e^+e^- \to n\bar{n}$ at SND



The first and more precise measurement after FENICE

M.N. Achasov et al., arXiv:1410.3188

Transition Form Factors and Hadronic LbL



The new dispersive approach relates $a_\mu^{\mathrm{had,LbL}}$ to data:

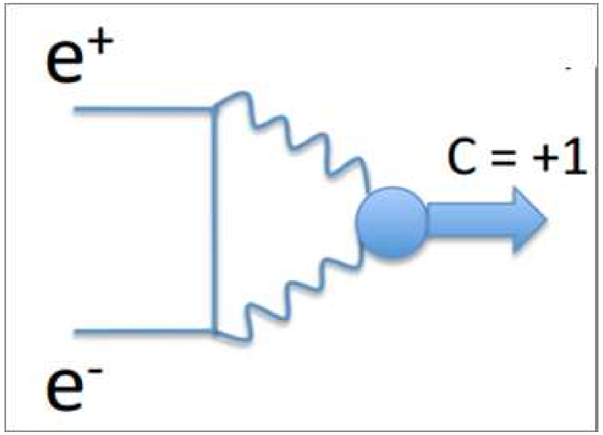
G. Colangelo et al., JHEP 1409 (2014) 091, Phys. Lett. B 738 (2014) 6

Measurements of various processes are in order: $\gamma^{(*)}\gamma^{(*)} \to \pi\pi$, $e^+e^- \to \pi^0\gamma, e^+e^-\pi^0, \pi^+\pi^-\pi^0$

Also important are $\gamma^{(*)}\gamma^{(*)} \to \pi^0, \eta, \eta'$; $\pi^0, \eta, \eta' \to l^+l^-$

Search for C-even resonances in e^+e^- – I

Direct production of C-even states in e^+e^- is possible via a $\gamma\gamma$:



The unitarity bound assuming 2 real photons is

$$\mathcal{B}_{P\to l^+l^-} = \mathcal{B}_{P\to\gamma\gamma}\frac{\alpha^2}{2\beta}\left(\frac{m_e}{m_P}\right)^2\left[\ln\left(\frac{1+\beta}{1-\beta}\right)\right]^2, \beta = \sqrt{1-4\left(\frac{m_e}{m_P}\right)^2}.$$

For η' the unitarity bound is $\mathcal{B} = 3.75\cdot 10^{-11}$,

but can be enhanced by photon virtuality and transition f/f

"Standard" mechanism via $e^+e^- \to e^+e^-P$ involves two almost real photons

and provides $\Gamma(P\to\gamma\gamma)$ only

Search for C-even resonances in e^+e^- – II

$\eta'(958)$, $f_0(980)$, $a_0(980)$, $f_2(1270)$, $a_2(1320)$ and $f_0(1370)$ mesons were studied with the ND (1988) and SND (2000) detectors at the VEPP-2M collider.

State	Mode	$\Gamma(e^+e^-)_{\rm exp}$, eV	Group	$\Gamma(e^+e^-)_{\rm unit.bound}$, eV
$\eta'(958)$	$\eta\pi^+\pi^-$	< 0.06	ND	$7.5 \cdot 10^{-6}$
$f_0(980)$	$\pi^0\pi^0$	< 8.4	ND	
$a_0(980)$	$\eta\pi^0$	< 1.5	ND	
$f_2(1270)$	$\pi^0\pi^0$	< 0.11	SND	0.03
$a_2(1320)$	$\eta\pi^0$	< 0.56	SND	0.01
$f_0(1370)$	$\pi^0\pi^0$	< 20	ND	

ND, P.V. Vorobyev et al., Sov. J. Nucl. Phys. 48 (1988) 273

SND, M.N. Achasov et al., Phys. Lett. 492 (2000) 8

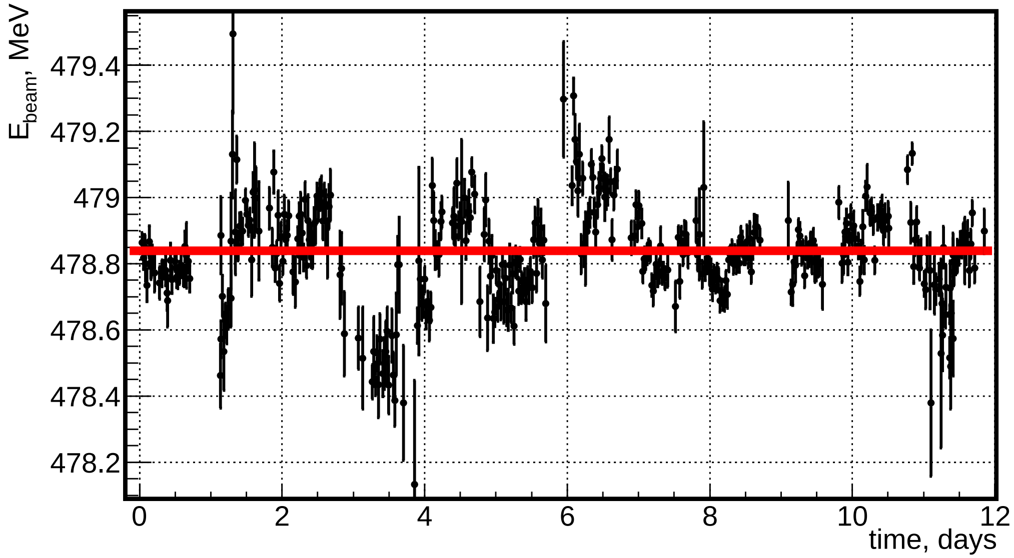
Search for $e^+e^- \to \eta'$ with CMD-3 – I

CMD-3 repeated a search for the process $e^+e^- \to \eta'(958) \to \eta\pi^+\pi^-,\ \eta \to 2\gamma$ using $\int L dt = 2.69$ pb^{-1} collected with the CMD-3 detector at the VEPP-2000 c.m. energy $E_{\rm c.m.} \approx m_{\eta'} = 957.78 \pm 0.06$ MeV$/c^2$

The total width of the η' is rather small, (198 ± 9) keV,
it is very important to have c.m. energy close to this value.
The collider beam energy was continuously monitored during
the whole period of data taking (12 days) using
the Back-Scattering-Laser-Light system providing the accuracy of $6 \cdot 10^{-5}$

R.R. Akhmetshin et al., arXiv:1409.1664, accepted by Phys. Lett. B

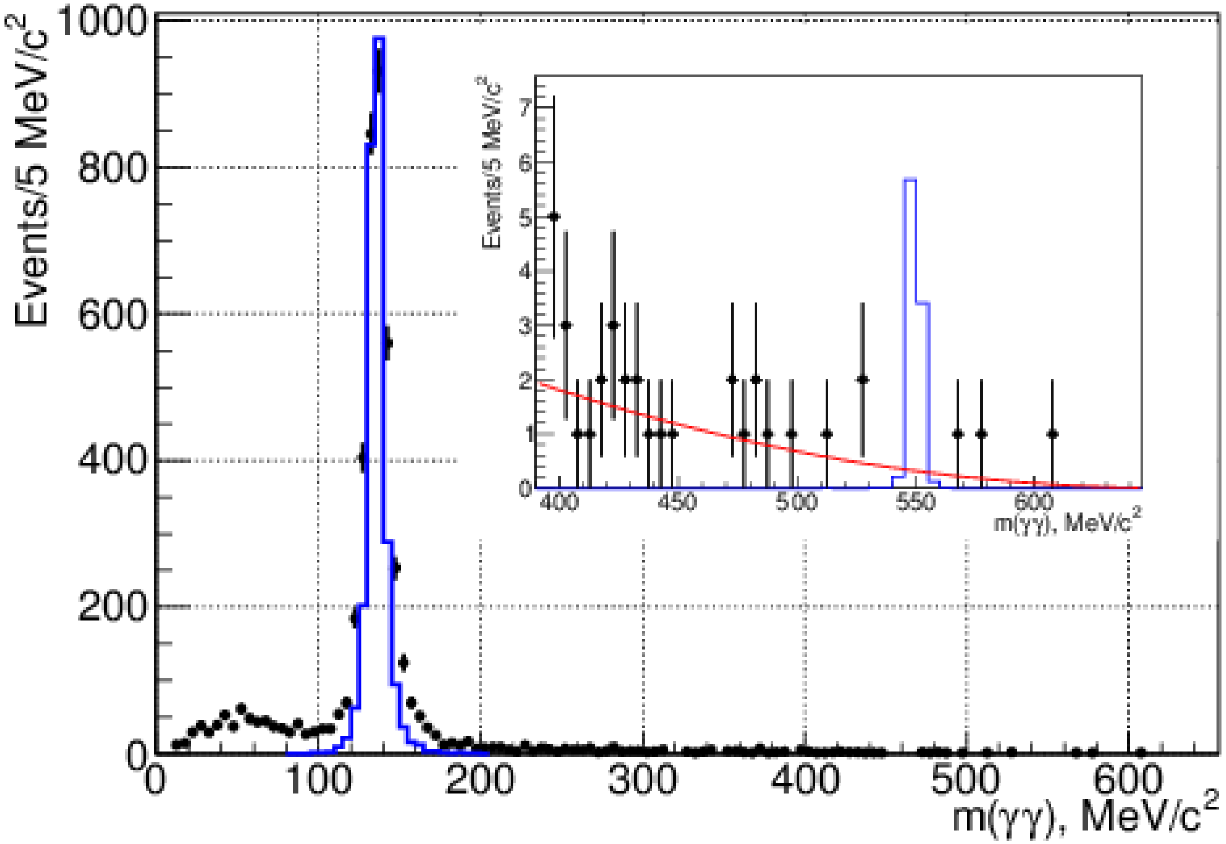
Search for $e^+e^- \to \eta'$ with CMD-3 – II



Measurements of the beam energy show good stability of the collider energy. The average value of the c.m. energy is $E^{av.}_{c.m.} = 957.678 \pm 0.014$ MeV with a few deviations of up to 0.2 MeV, corresponding to less than 5% of the integrated luminosity, which are still within an energy spread of the collider

The collider beams have an energy spread mainly due to the quantum effects. For VEPP-2000 the c.m. energy spread $\sigma_{E_{c.m.}} = (0.246 \pm 0.030)$ MeV

Search for $e^+e^- \to \eta'$ with CMD-3 – III



Search for $e^+e^- \to \eta'$ with CMD-3 – IV

From the absence of the signal

$$\Gamma_{\eta' \to e^+e^-}\mathcal{B}_{\eta' \to \pi\pi\eta}\mathcal{B}_{\eta \to \gamma\gamma} < 0.00041 \text{ eV at } 90\% \text{ C.L.}.$$

and with $\mathcal{B}_{\eta' \to \pi\pi\eta}$ and $\mathcal{B}_{\eta \to \gamma\gamma}$ from PDG:

$$\Gamma_{\eta' \to e^+e^-} < 0.0024 \text{ eV}$$

Group	ND, 1988	CMD-3, 2014
$\Gamma_{\eta' \to e^+e^-}$, eV	< 0.06	< 0.0024
$\Gamma_{\eta'}$, keV	~ 300	198 ± 9
$\mathcal{B}_{\eta' \to e^+e^-}, 10^{-8}$	< 21	< 1.2

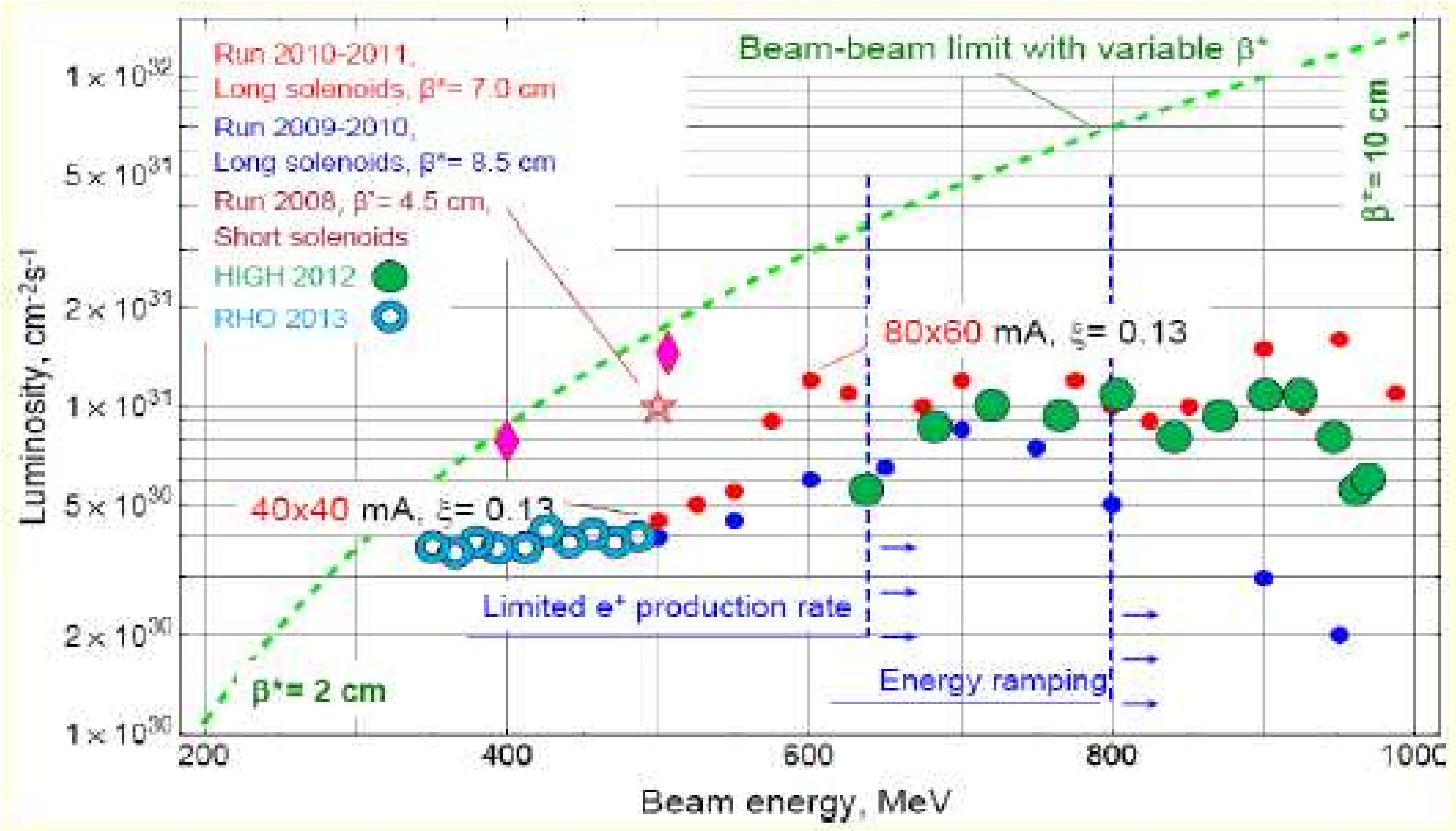
Much more stringent than that of ND, but
still 300 times higher than the unitarity bound

Conclusions

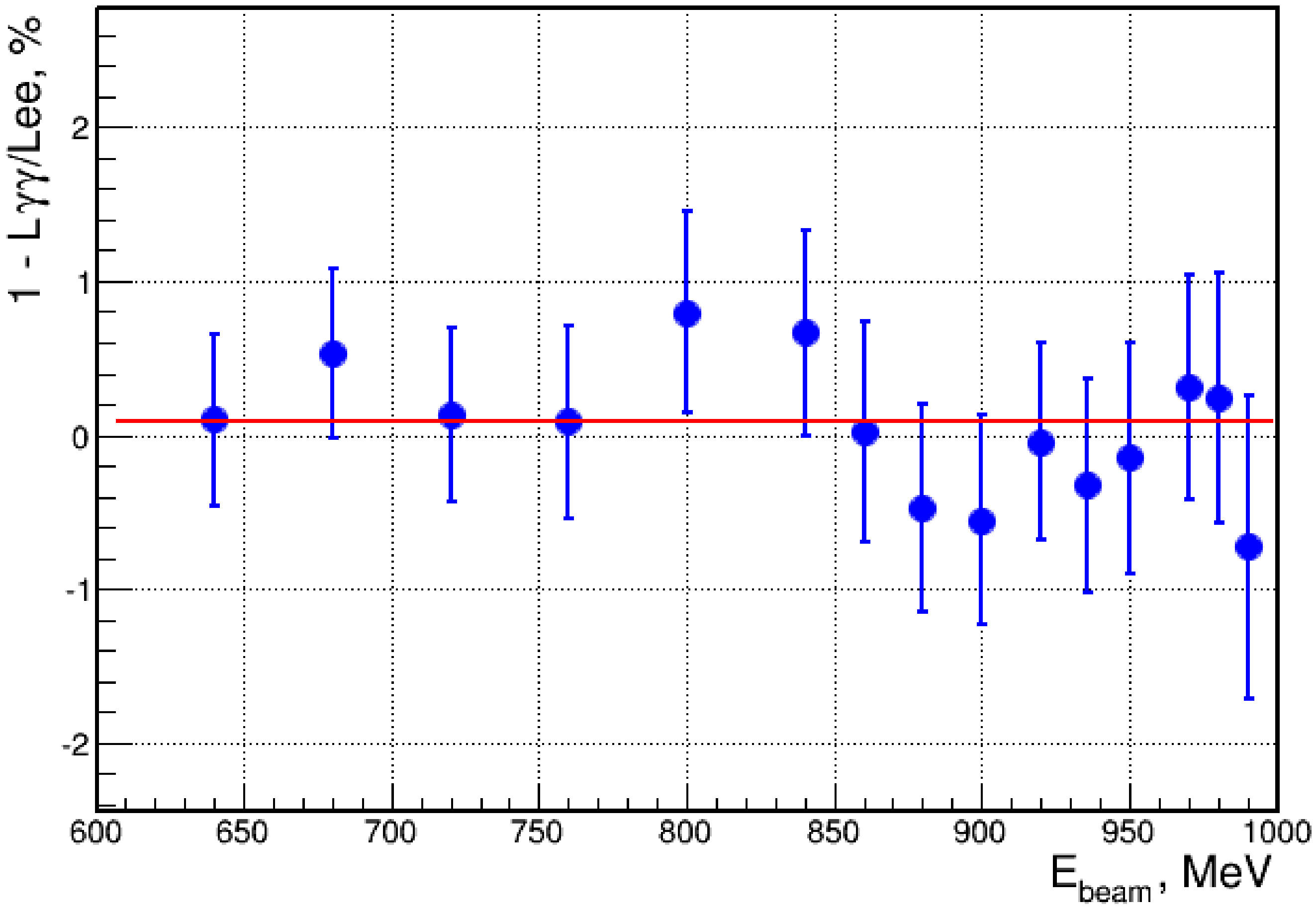
- VEPP-2000 is running smoothly with CMD-3 and SND, their accuracy is comparable or better than ISR measurements, $\times 20$ more to be collected in 2015-2020
- The goals are 0.35%(0.5%) for $\pi^+\pi^-$ and 3% for multibody modes
- Below 2 GeV progress (a factor of 2-3) expected in exclusive σ's due to scans in Novosibirsk and ISR from KLOE, 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 huge COMPASS data samples
- One should also measure various transition form factors in $\gamma^{(*)}\gamma^{(*)} \to$ hadrons to relate them to $a_\mu^{\text{had,LbL}}$: $\gamma^{(*)}\gamma^{(*)} \to P,\ \pi\pi;\ P \to l^+l^-,\ \ldots$

Back-up

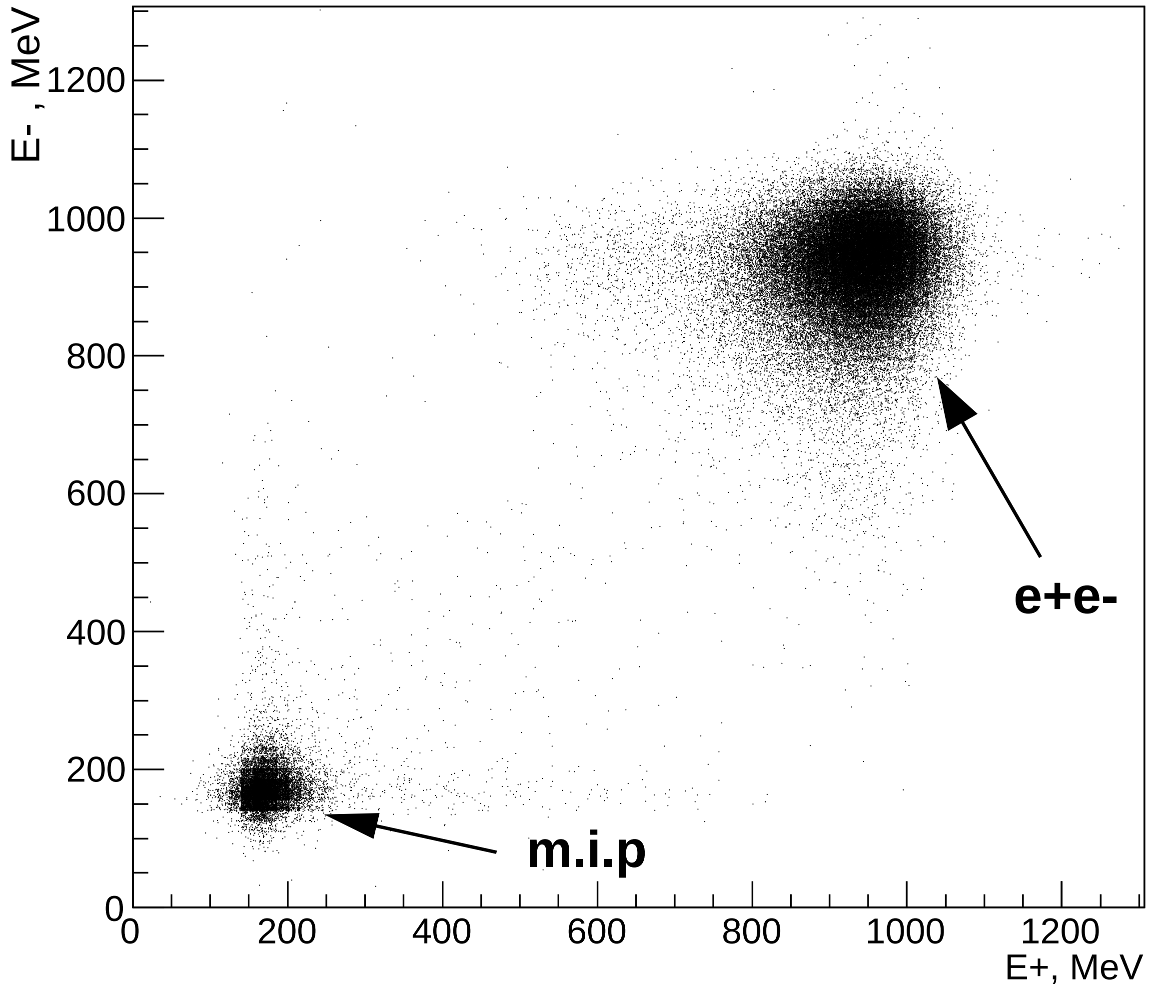
VEPP-2000 – III



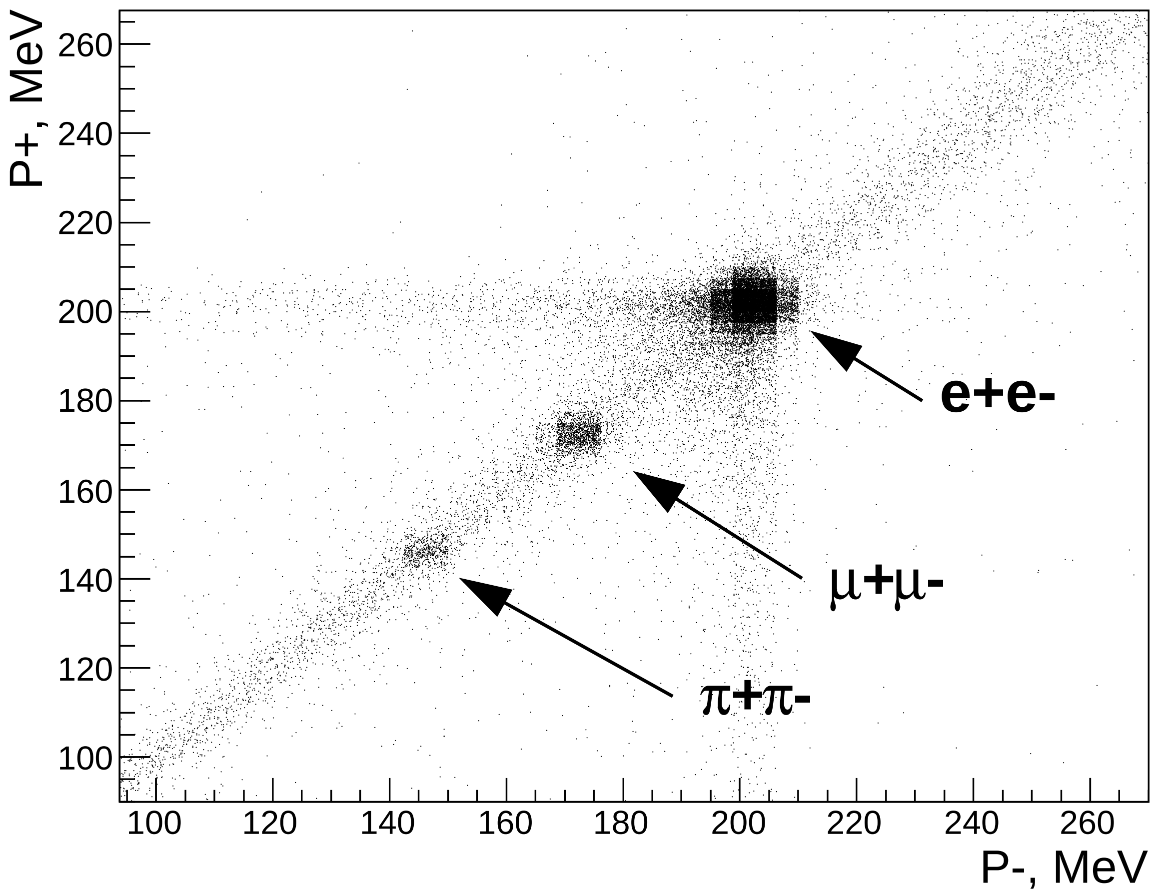
Luminosity Measurement at CMD-3



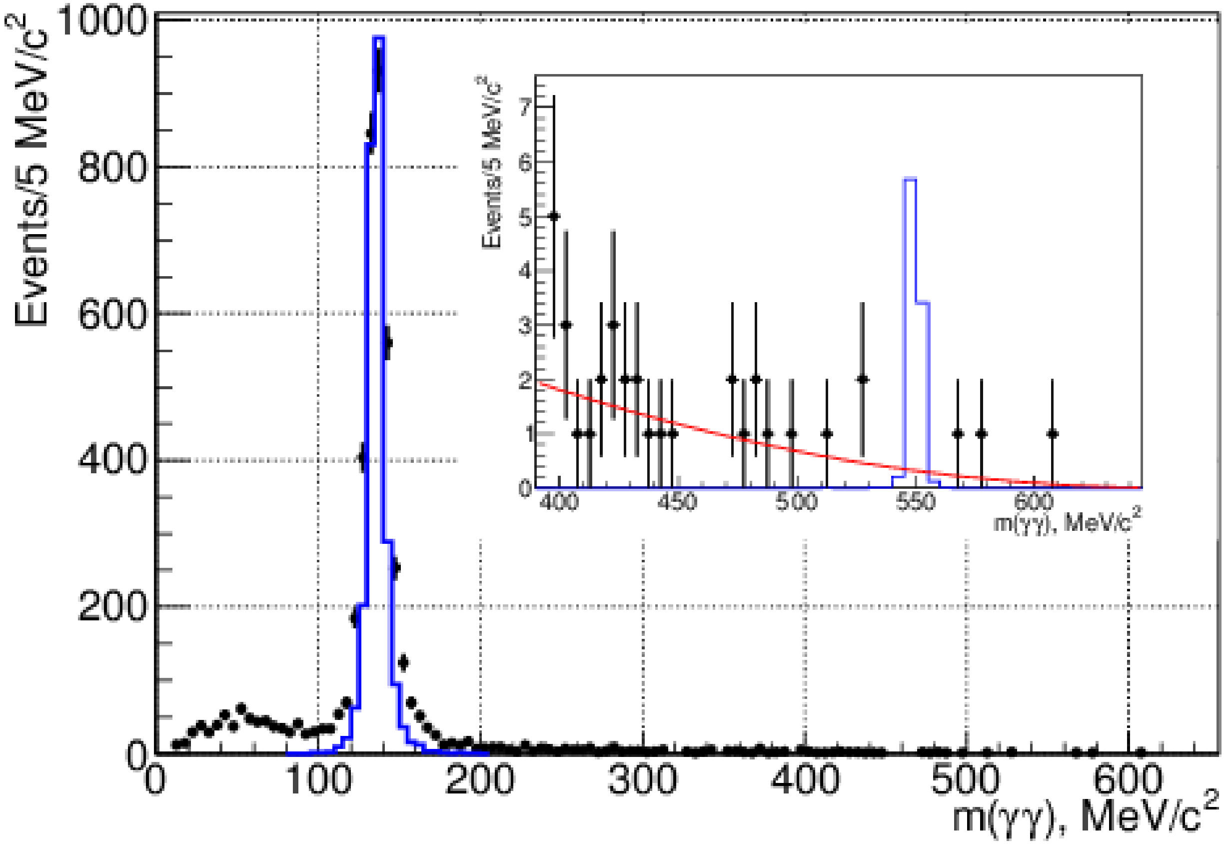
Particle Identification at CMD-3 – I



Particle Identification at CMD-3 – II



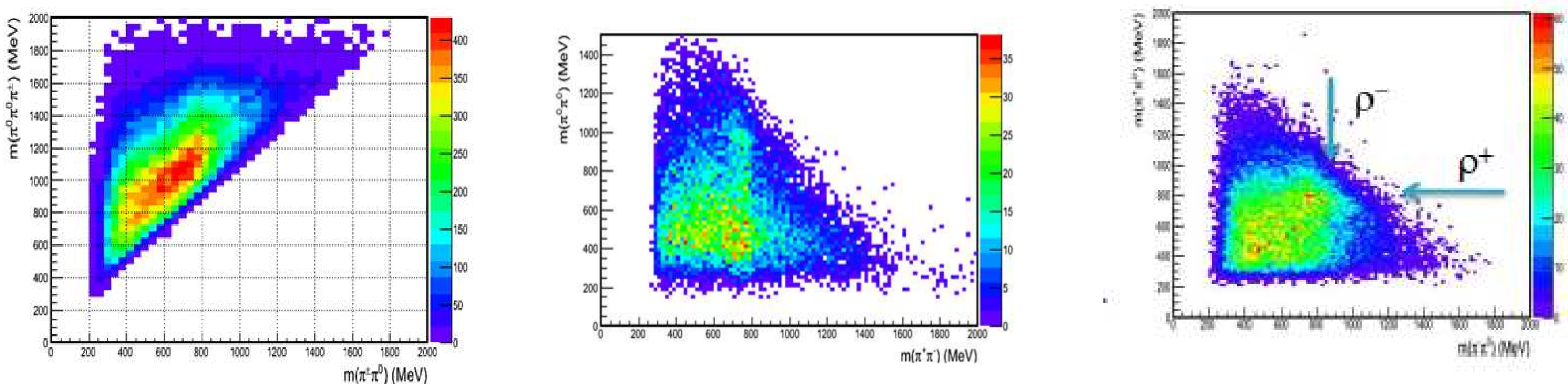
Search for $e^+e^- \to \eta' \to \eta\pi^+\pi^-$ at CMD-3



arXiv:1409.1664:

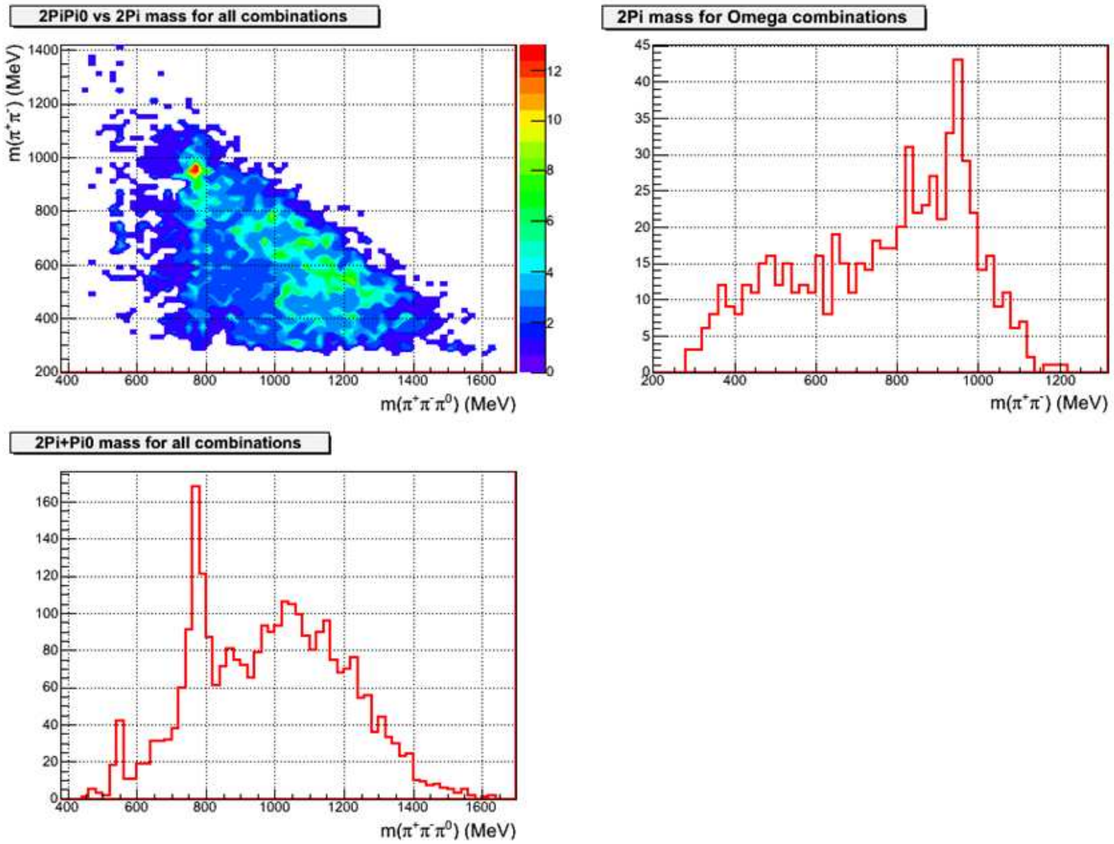
$\mathcal{B}(\eta' \to e^+e^-) < 1.2 \times 10^{-8}$

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



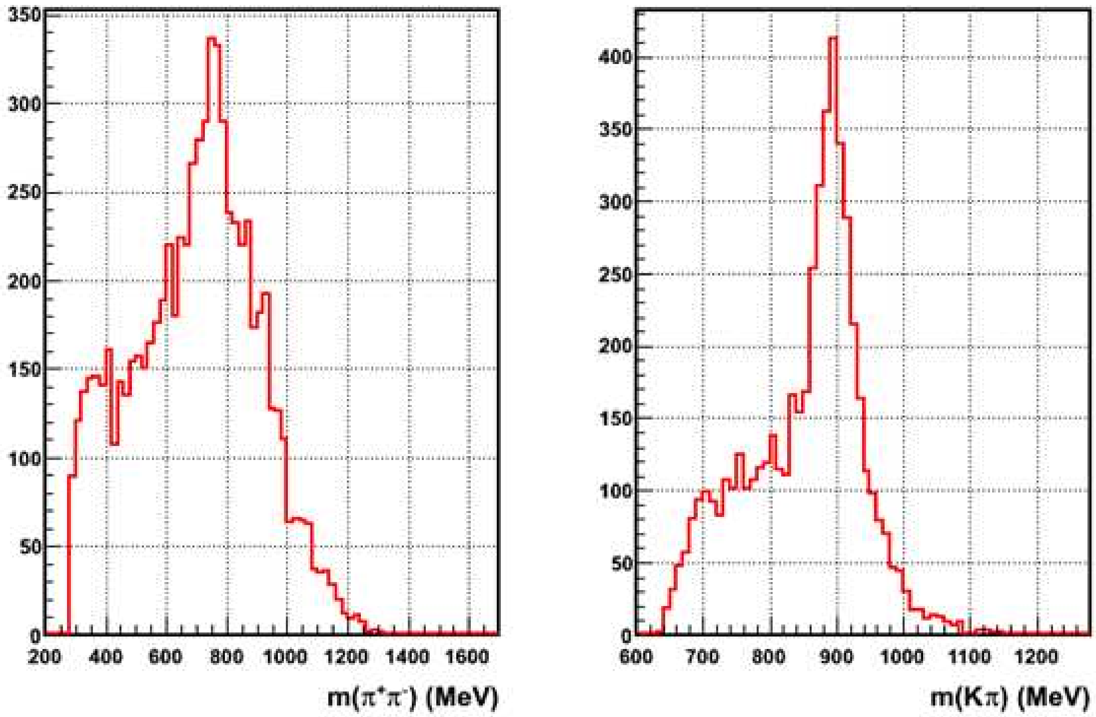
$a_1^{\pm}(1260)\pi^{\mp}$, $\rho^0 f_0$ and $\rho^+\rho^-$ intermediate states seen,
other mechanisms possible: $a_2^{\pm}(1320)\pi^{\mp}$, $\pi^{\pm}(1300)\pi^{\mp}$, ...

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



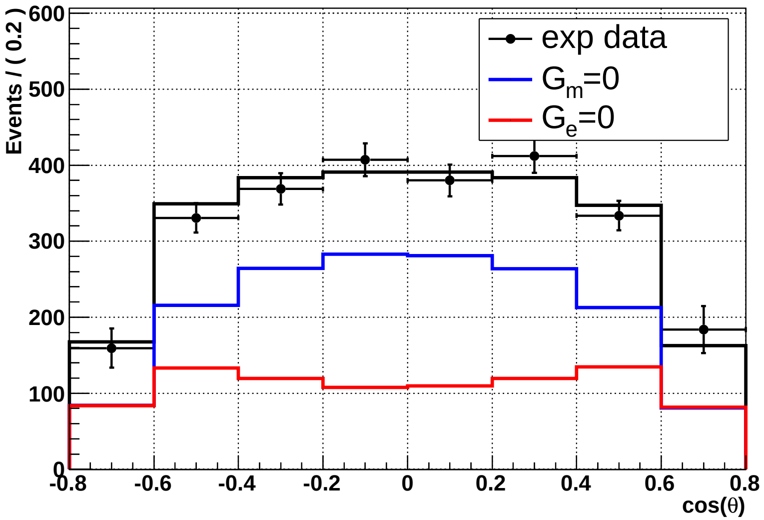
Various mechanisms seen: $\omega\pi^+\pi^-$, $\eta\pi^+\pi^-$, $\omega f_0(980)$

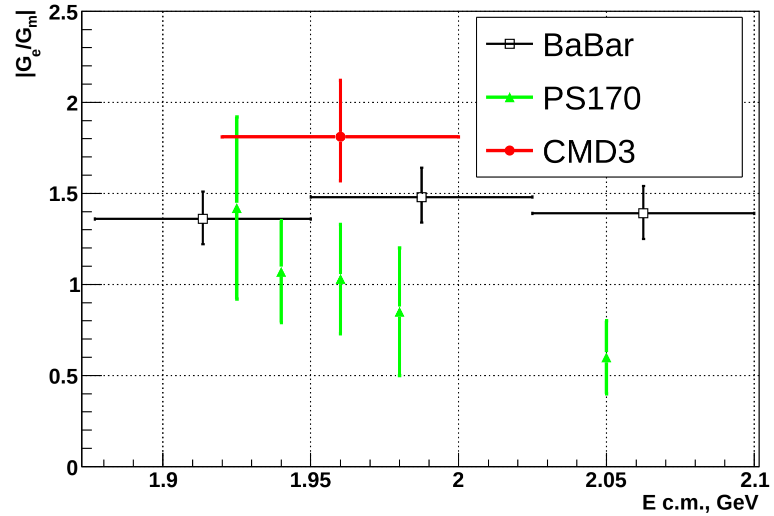
$e^+e^- \to K^+K^-\pi^+\pi^-$ at CMD-3 – I



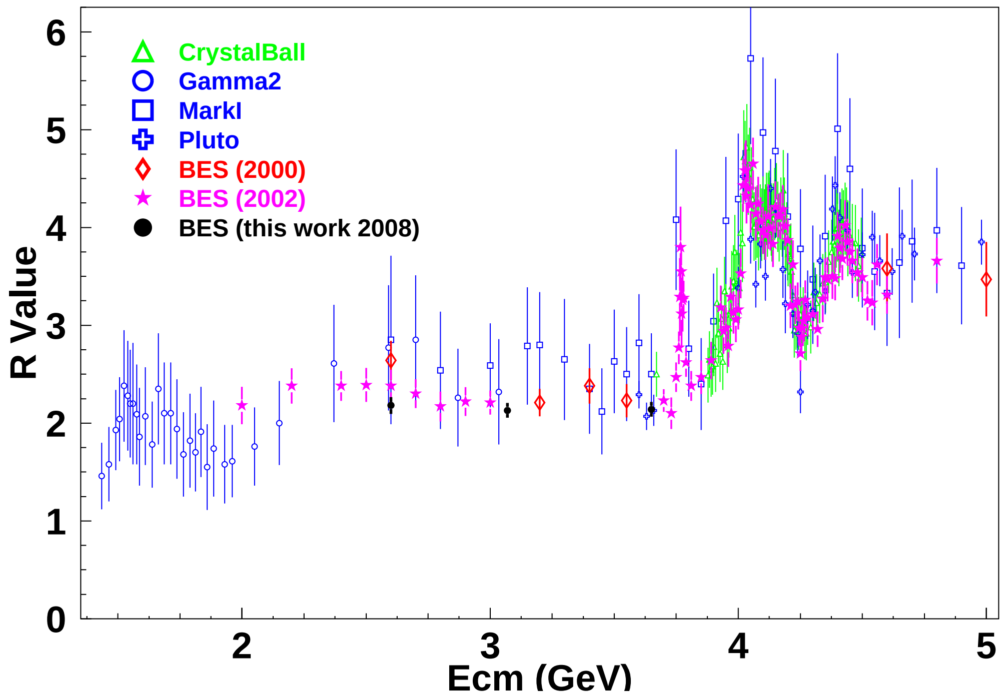
Many different mechanisms seen: $K_1(1270)\bar{K} \to K\bar{K}\rho$, $K^*(892)\bar{K}\pi$, $K_1(1400)\bar{K} \to K^*(892)\bar{K}\pi$, $\phi\pi^+\pi^-$

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