Light Mesons in e^+e^- Annihilation

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 quantitites
   - $(g_\mu - 2)/2$
   - $\alpha(M_Z^2)$
   - QCD sum rules (α_s, quark and gluon condensates)

Muon Anomalous Magnetic Moment

$$\vec{\mu} = g\frac{e}{2m}\vec{s}, \qquad a = (g-2)/2.$$

a_μ is measured with a $5 \cdot 10^{-7}$ relative accuracy:

G.W. Bennett et al., 2004, 2006 $\quad a_\mu = (116592089 \pm 63) \cdot 10^{-11}$.

a_{e} is measured with a $2.4 \cdot 10^{-10}$ accuracy, but a_μ is much more sensitive to new physics effects: the gain is usually

$$\sim (m_\mu/m_{\mathrm{e}})^2 \approx 4.3 \cdot 10^4.$$

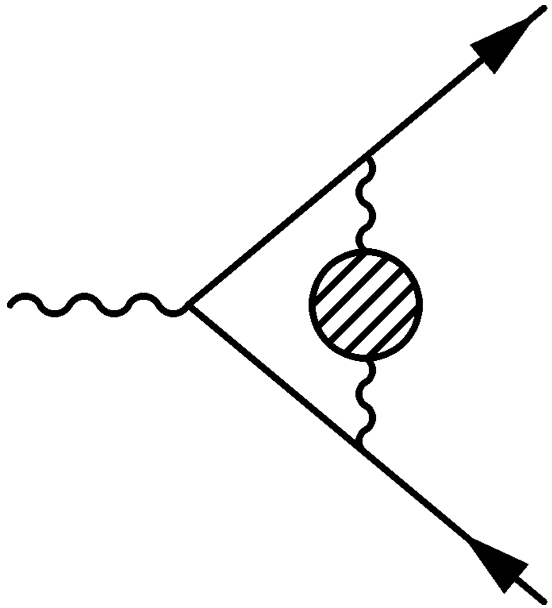
Any significant difference of a_μ^{exp} from a_μ^{th} indicates new physics beyond the Standard Model.

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{had}}.$$

The experimental value is higher than the SM prediction by 3.6σ, the accuracy of the prediction is dominated by that of a_μ^{had}

Hadronic contribution $a_\mu^{\rm had}$

$$a_\mu^{\rm had} = a_\mu^{\rm had,LO} + a_\mu^{\rm had,HO} + a_\mu^{\rm had,LBL}$$



$$a_\mu^{\rm had,LO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \, \frac{R(s)\, \hat{K}(s)}{s^2},$$

C. Bouchiat, L. Michel, Bouchiat, 1961; M. Gourdin, E. de Rafael, 1969

$$R(s) = \frac{\sigma(e^+e^- \to {\rm hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)},$$

$\hat{K}(s)$ grows from 0.63 at $s = 4m_\pi^2$ to 1 at $s \to \infty$,

$1/s^2$ emphasizes low energies, particularly $e^+e^- \to \pi^+\pi^-$ (72%)

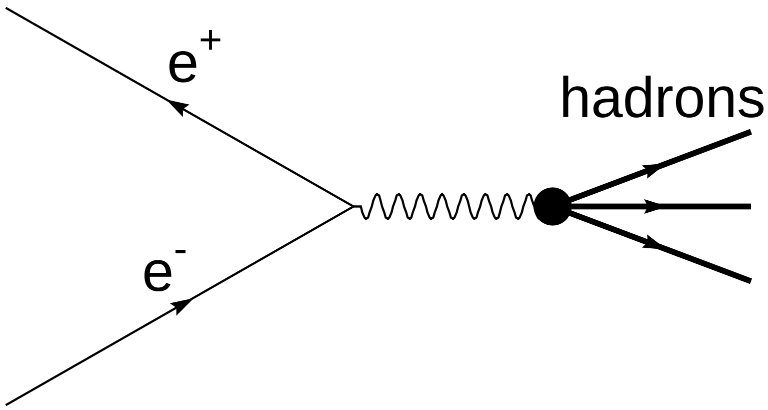
The $\sqrt{s}$ range from threshold to 2 GeV – about 93%

$a_\mu^{\rm had,LO} \sim 700 \cdot 10^{-10}$ $\Rightarrow$ accuracy better than 1% needed

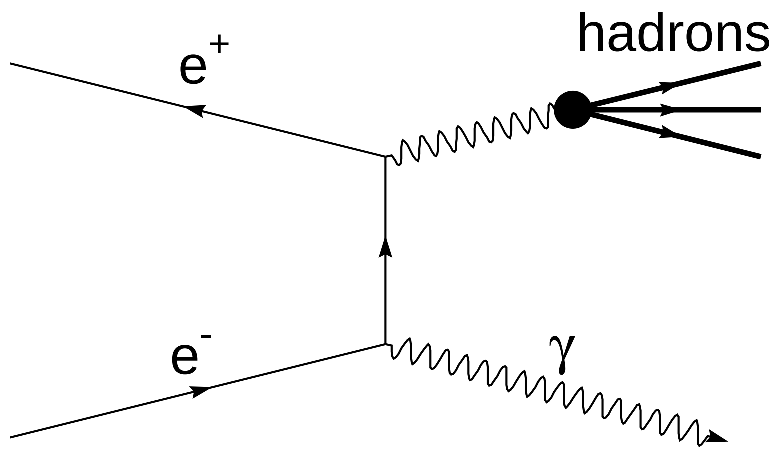
Contribution of Various Energy Ranges

$\sqrt{s}$, GeV	$\Delta a_\mu^{\rm had,LO}$
$\pi^+\pi^-$	507.80 ± 2.84
$\pi^+\pi^-\pi^0$	46.00 ± 1.73
K^+K^-	21.63 ± 0.73
$K^0_S K^0_L$	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



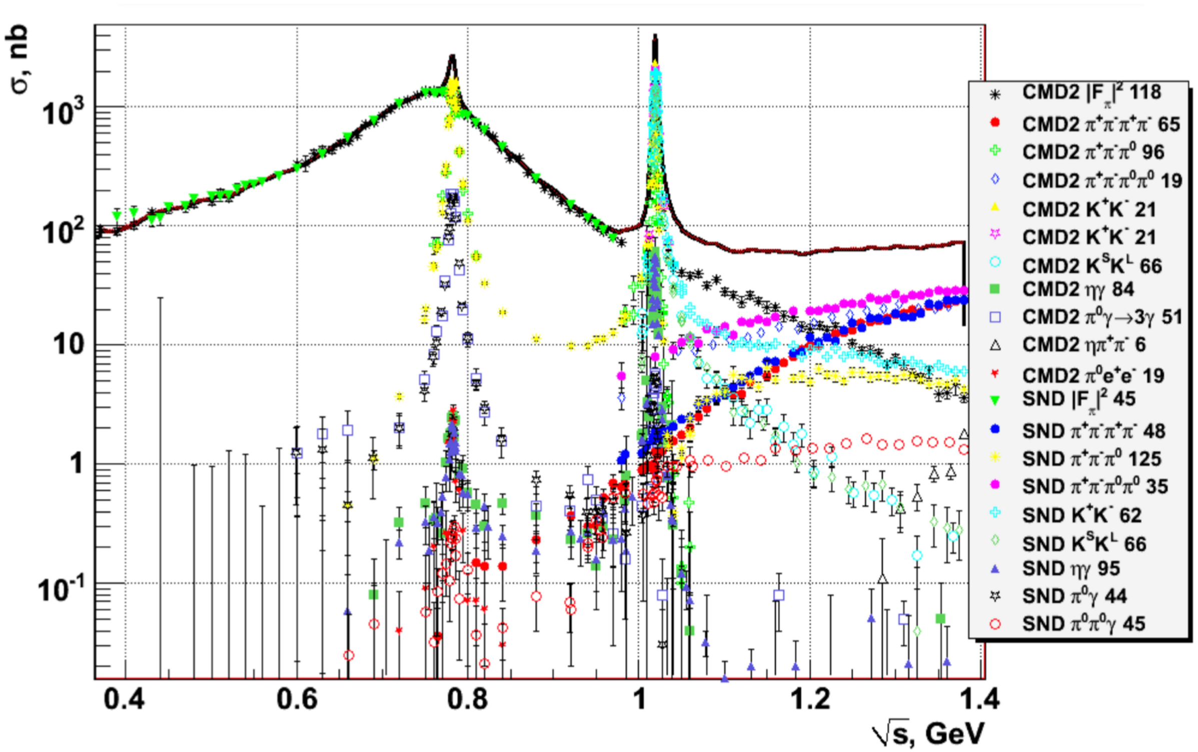
Scan



ISR

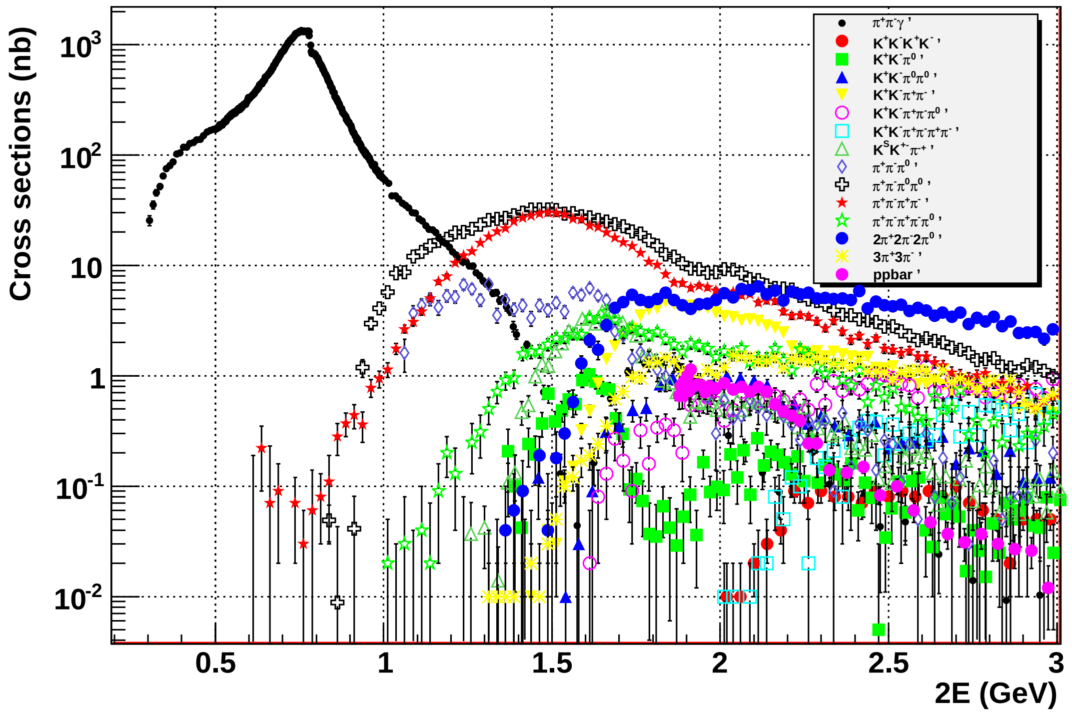
Scan can provide larger data samples, covers all final states,
VEPP-2000 and VEPP-4M can perform scans with a small $\sqrt{s}$ step
ISR benefits from the same systematics and flat acceptance,
may suffer from more complicated radiative effects, all neutrals hardly possible

Current Status of Exclusive Measurements – I



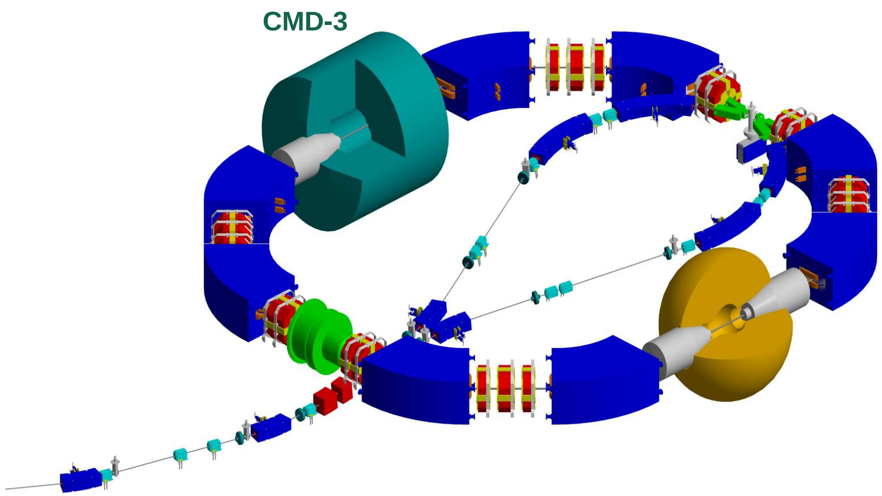
Impressive achievements of CMD-2, SND (scan at $\sqrt{s} < 1.4$ GeV)
and KLOE (ISR at $\sqrt{s} < 1.0$ GeV)

Current Status of Exclusive Measurements – II



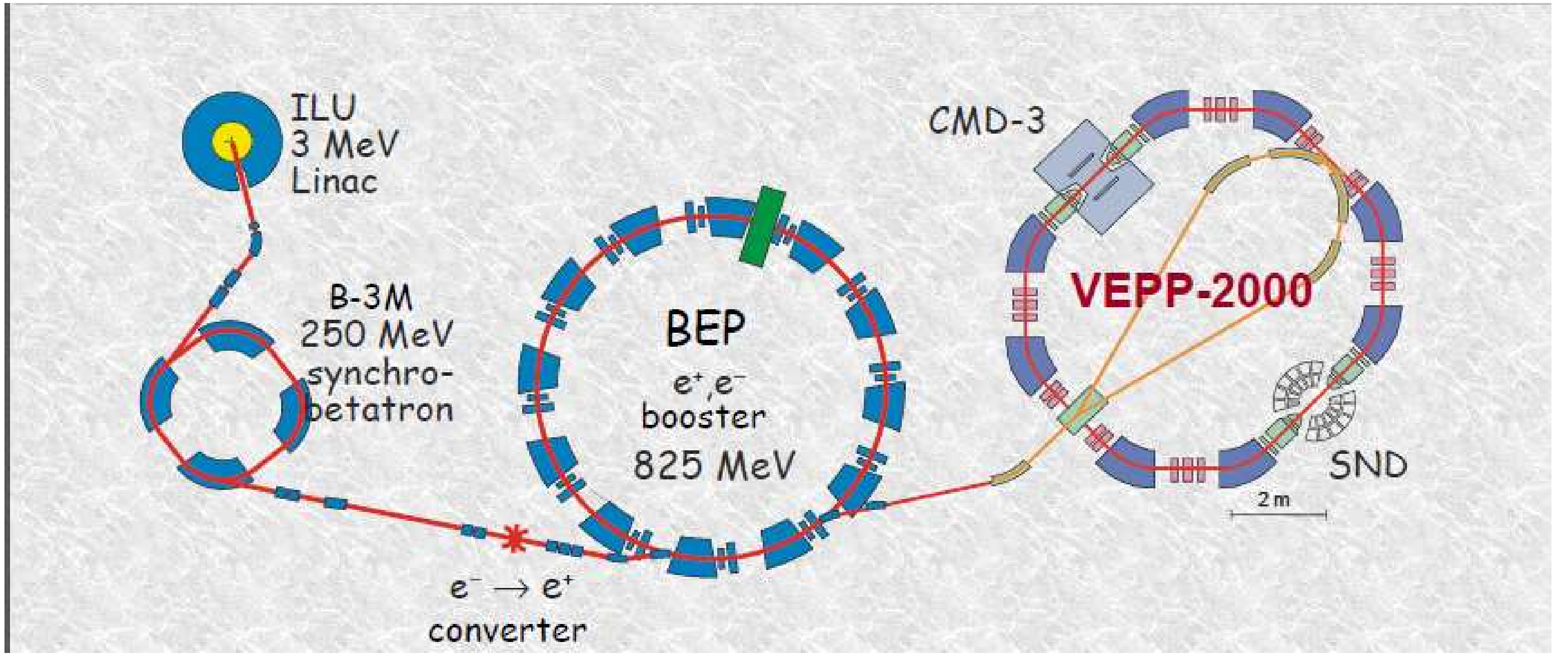
BaBar used ISR to study the energy range $\sqrt{s} < 3.0$ GeV,
Belle and BESIII may contribute as well to ISR measurements

VEPP-2000 – I



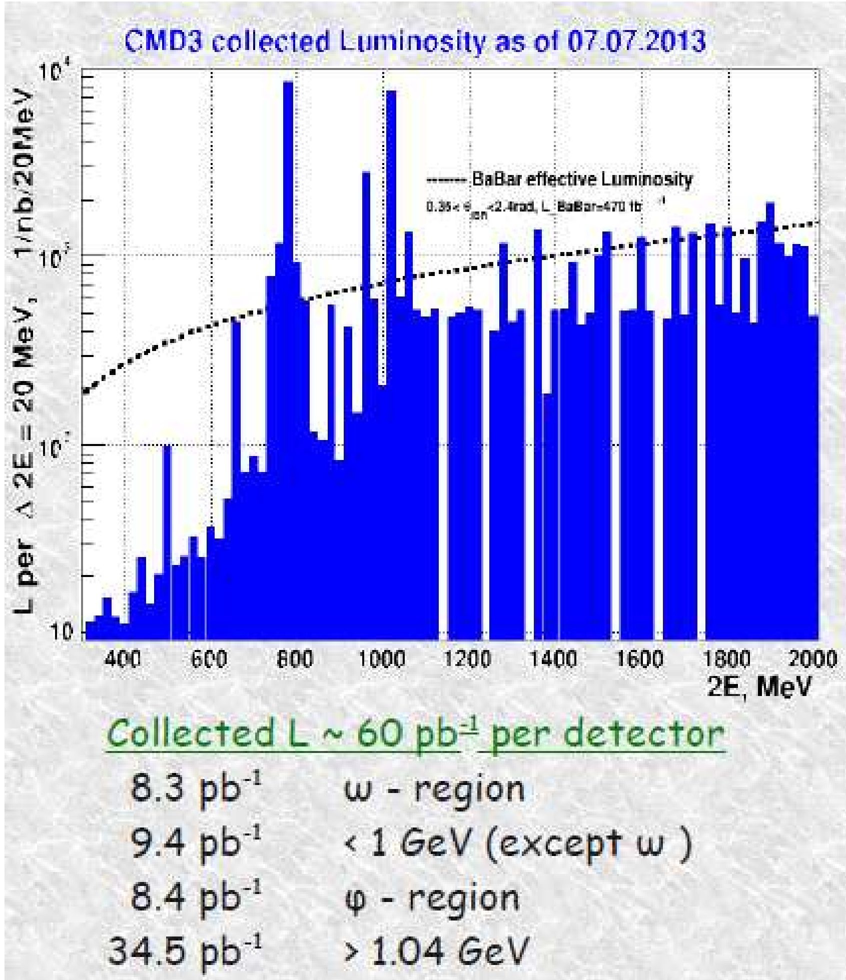
Collider	Operation	$\sqrt{s}$, MeV	$\mathcal{L}, 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
VEPP-2M	1975-2000	[360,1400]	3
VEPP-2000	2010-	$[2m_\pi, 2000]$	100

VEPP-2000 – II

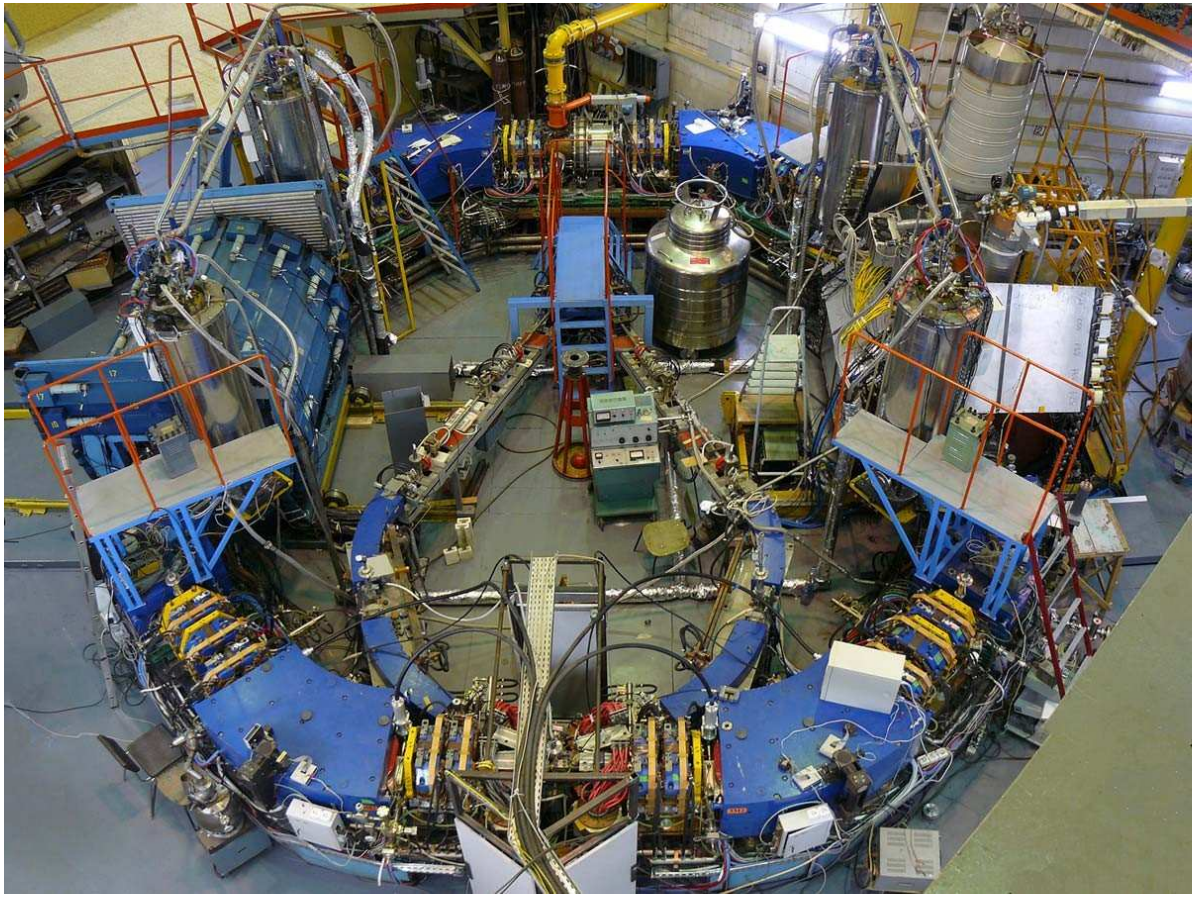


New optics with round beams ⇒ higher luminosity,
precise beam energy measurement using LCBS

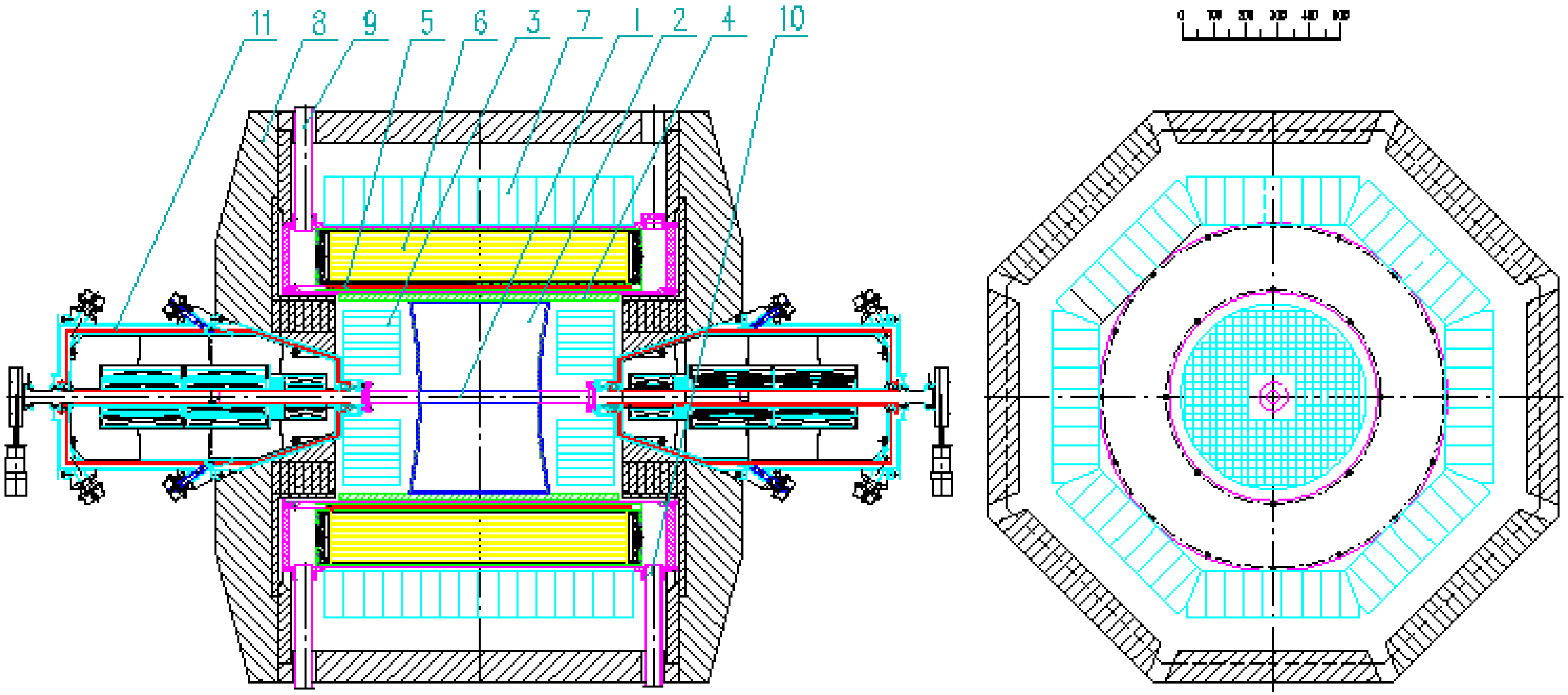
Data Taking at VEPP-2000



VEPP-2000 and Detectors

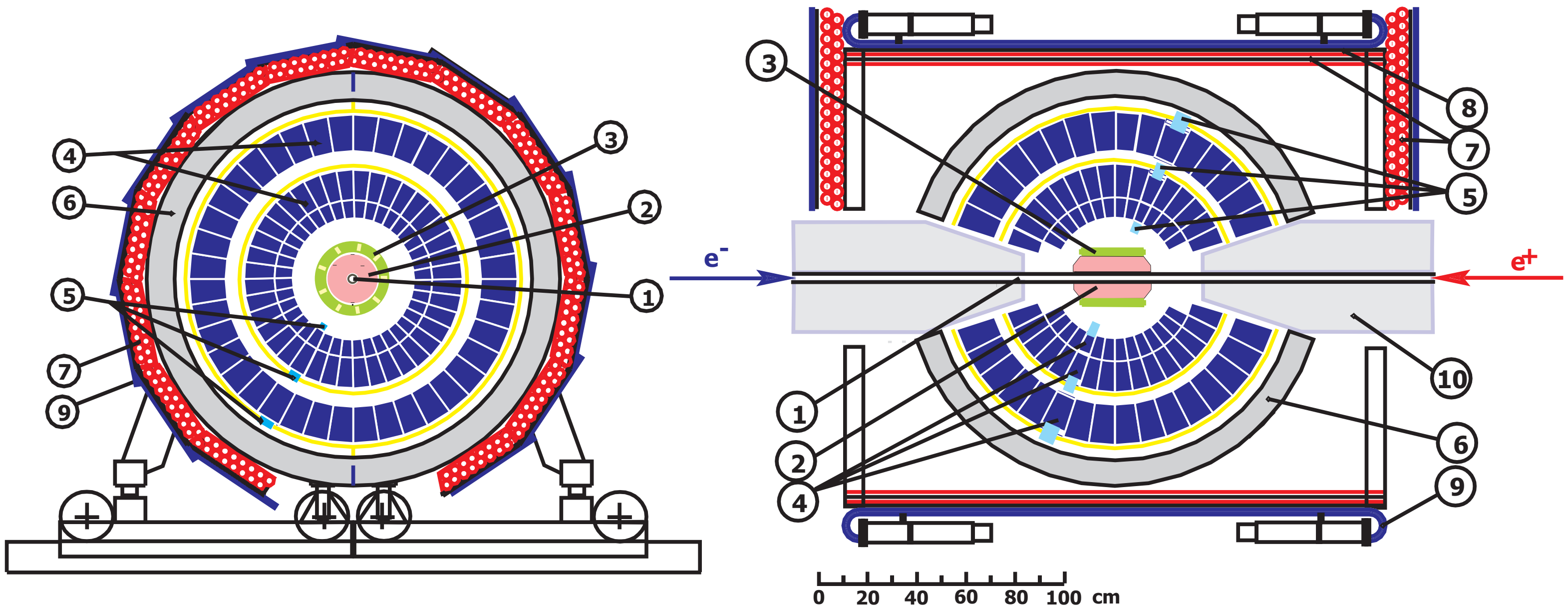


CMD-3



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

SND

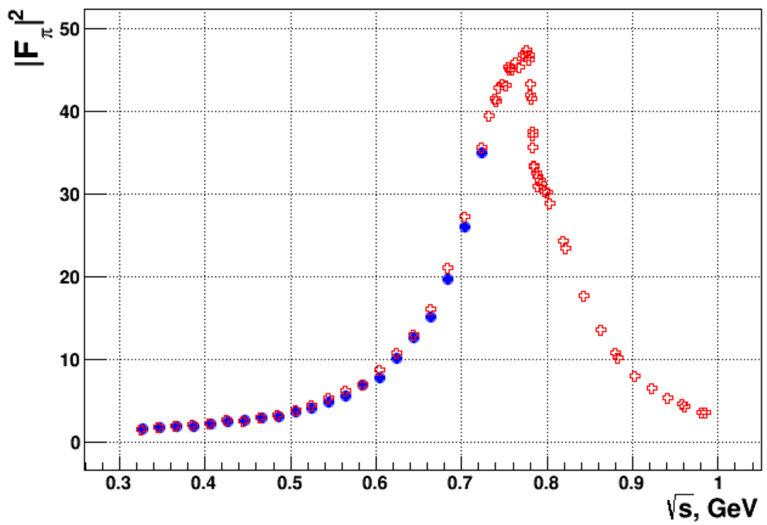


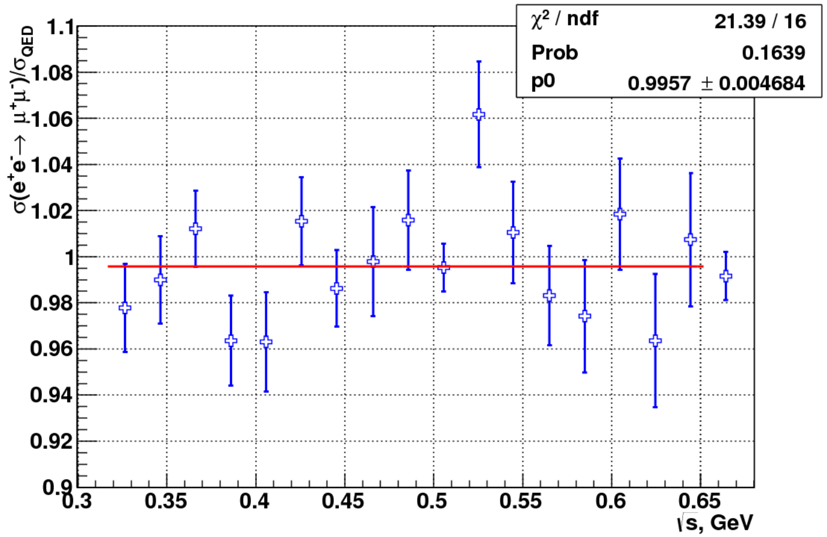
High-resolution NaI calorimeter with excellent tracking and PID

Performance of VEPP-2000 and Detectors

- The maximum luminosity is $2 \cdot 10^{31}$ 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 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} 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

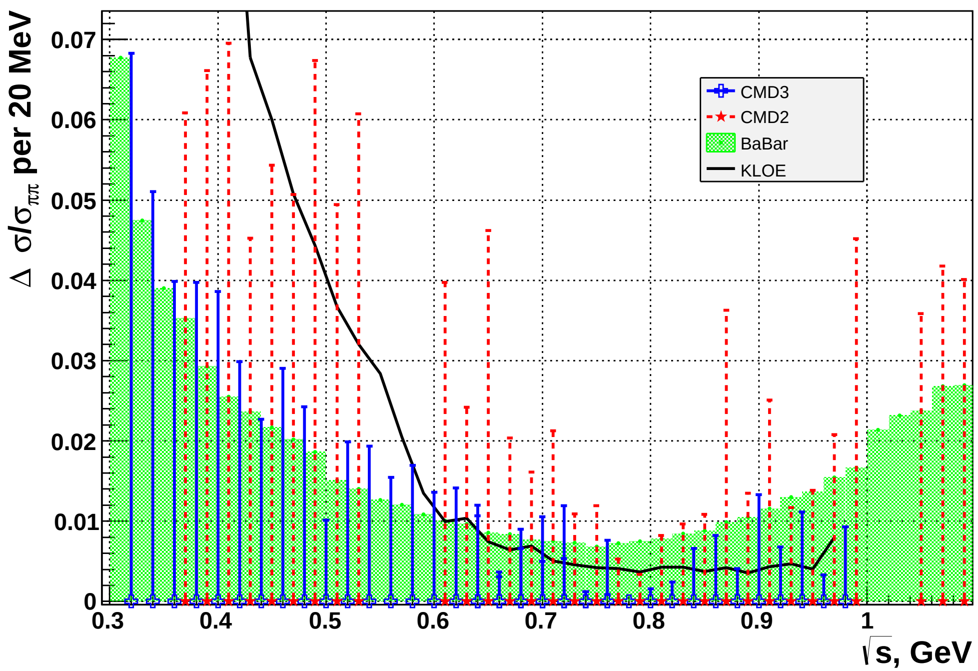




Identification at low energy - by DC with separation of $\mu^+\mu^-$

At high energy - by energy deposition in calorimeters

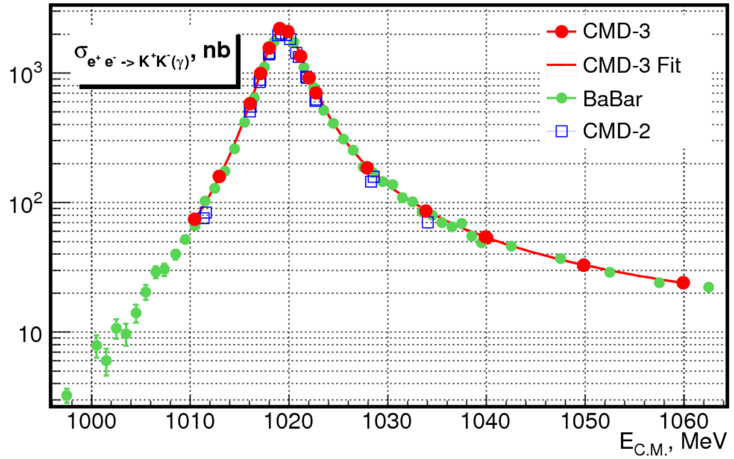
$e^+e^- \to \pi^+\pi^-$ at CMD-3 – II

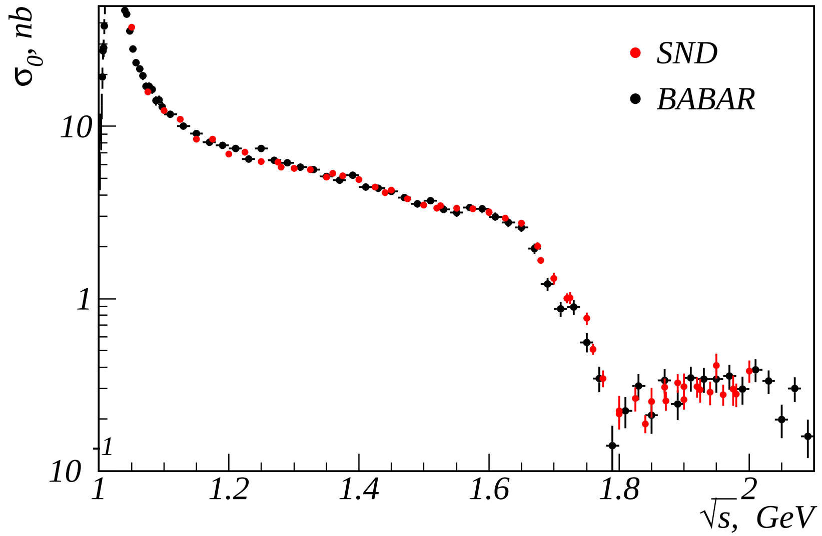


Statistical precision better than that of BaBar

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

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

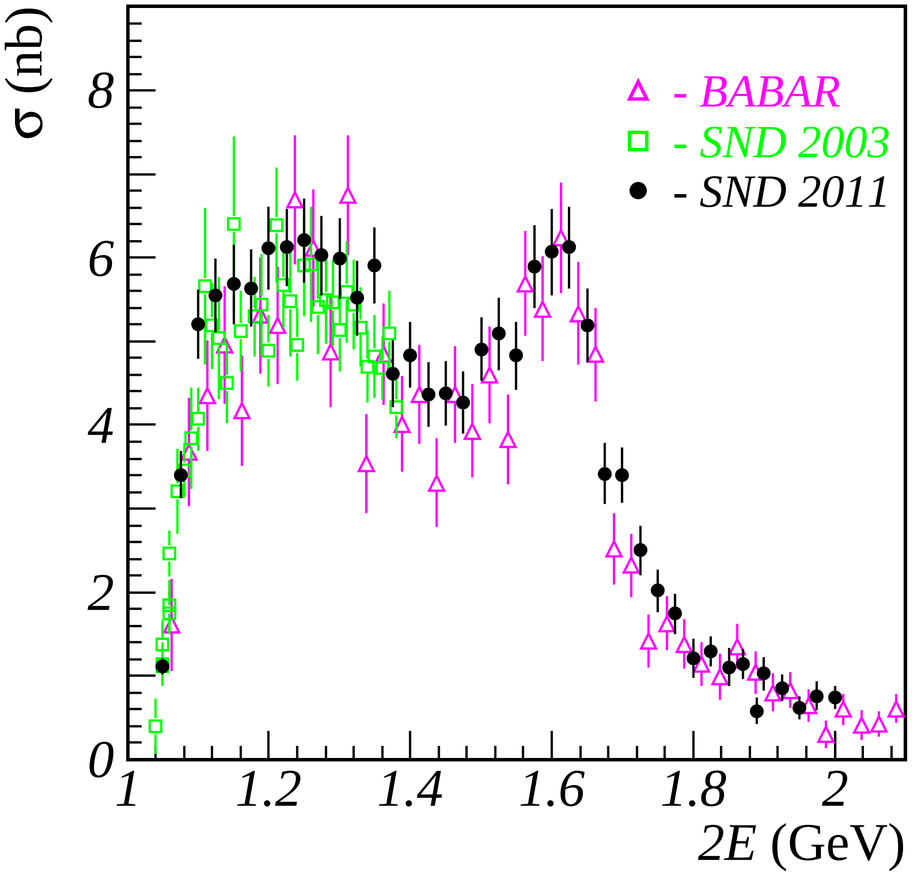




BaBar claims aggressive systematics of 0.72% at the ϕ, increasing to 7% at 2 GeV

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

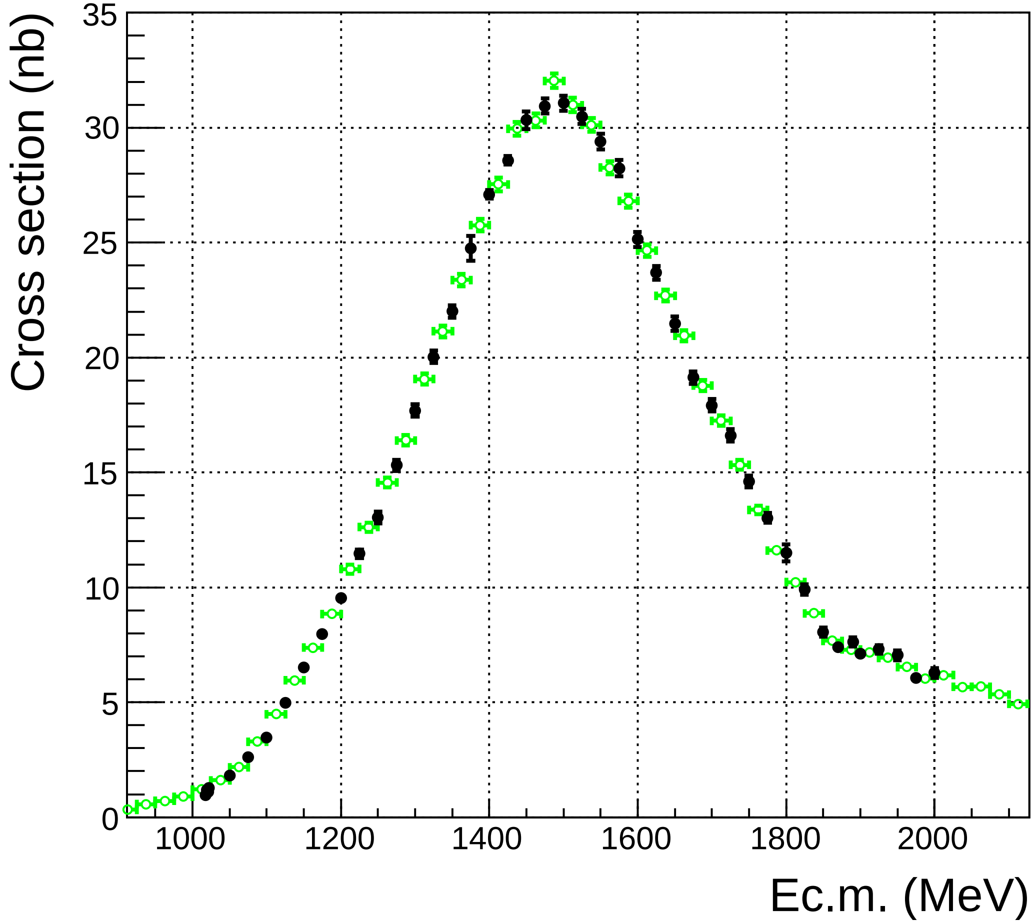
$e^+e^- \to \pi^+\pi^-\pi^0$ at SND



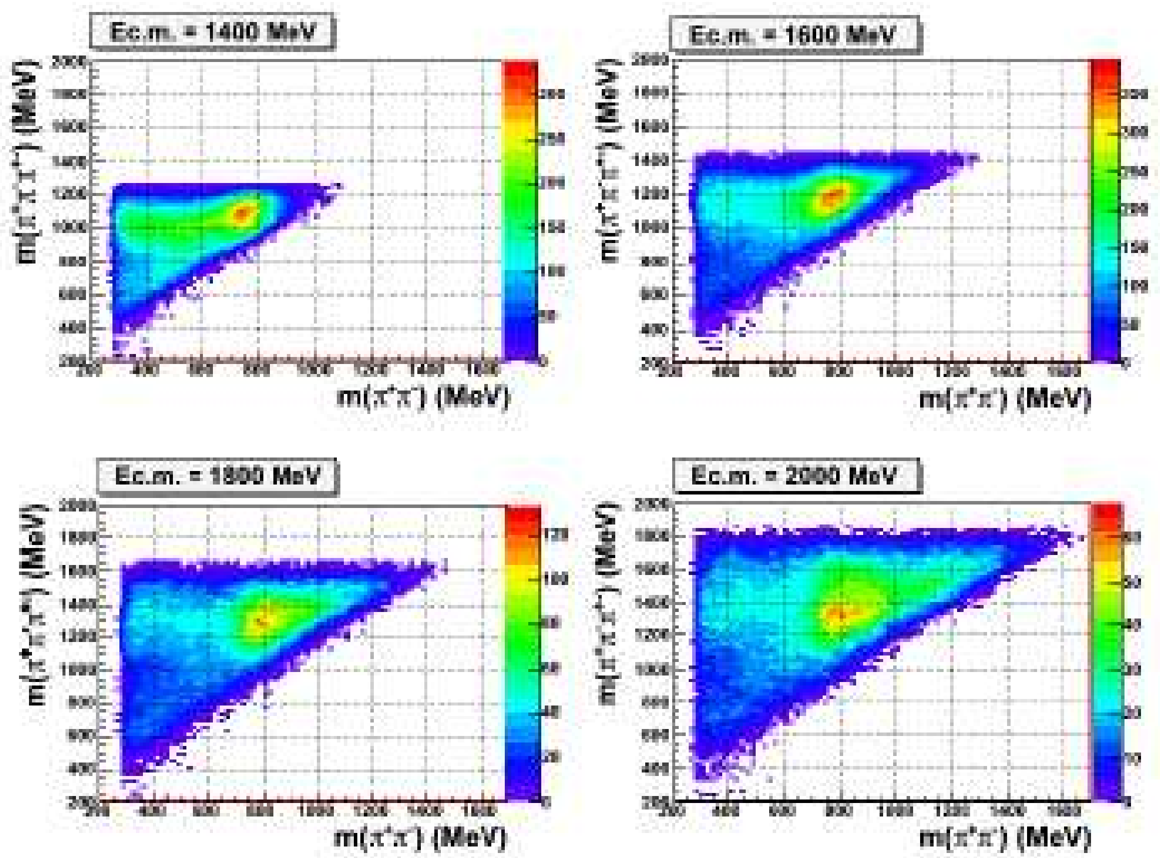
Two ω' clearly seen: $\omega(1420)$ and $\omega(1650)$

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

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

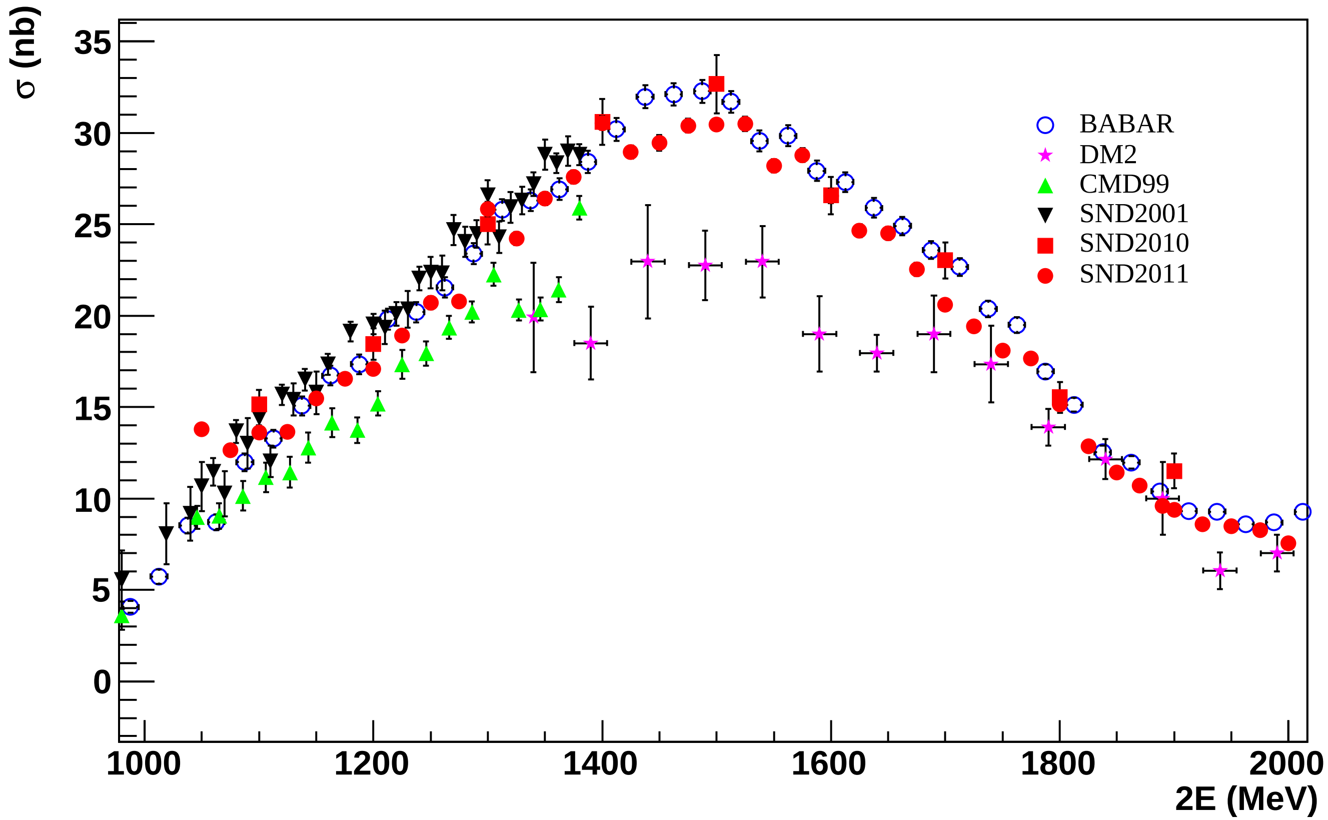


Dynamics of $e^+e^- \to 2\pi^+2\pi^-$ at CMD-3



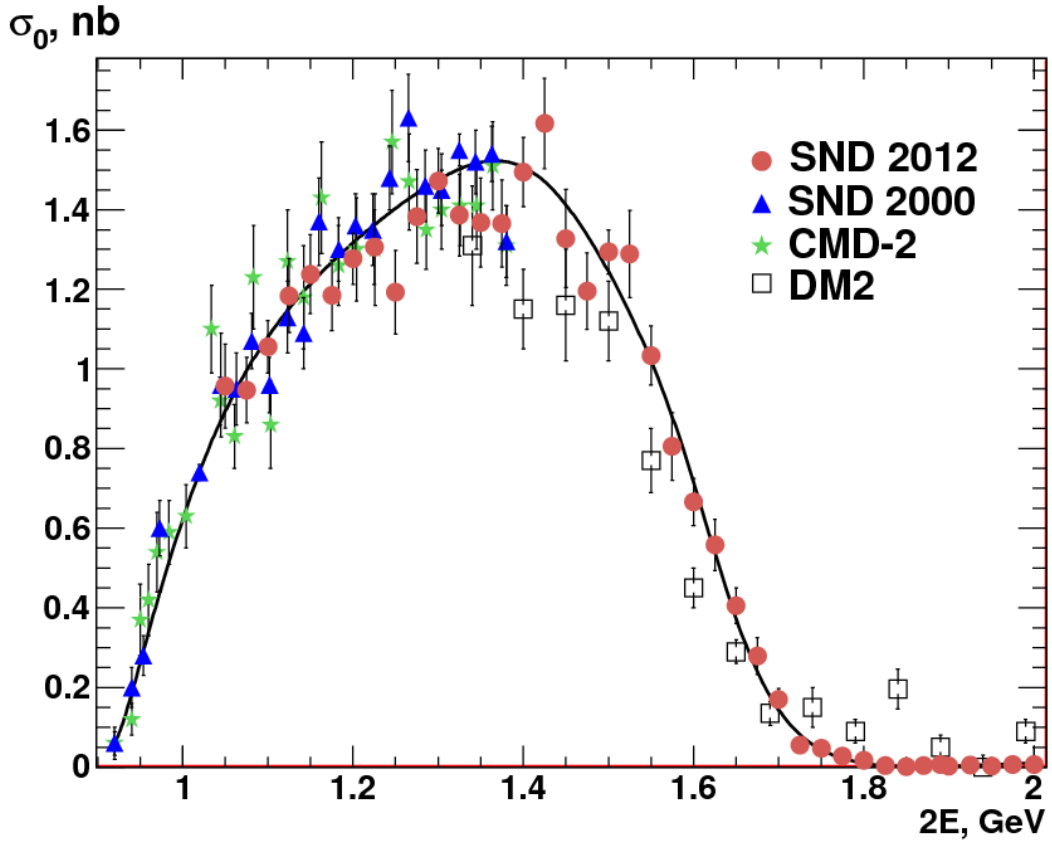
A ρ^0 is always present, $a_1^\pm(1260)\pi^\mp(a_2^\pm(1320)\pi^\mp)$ significant, at higher $\sqrt{s}$ other mechanisms like $\rho^0 f_0$, $\rho^0 f_2(1270)$ appear

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

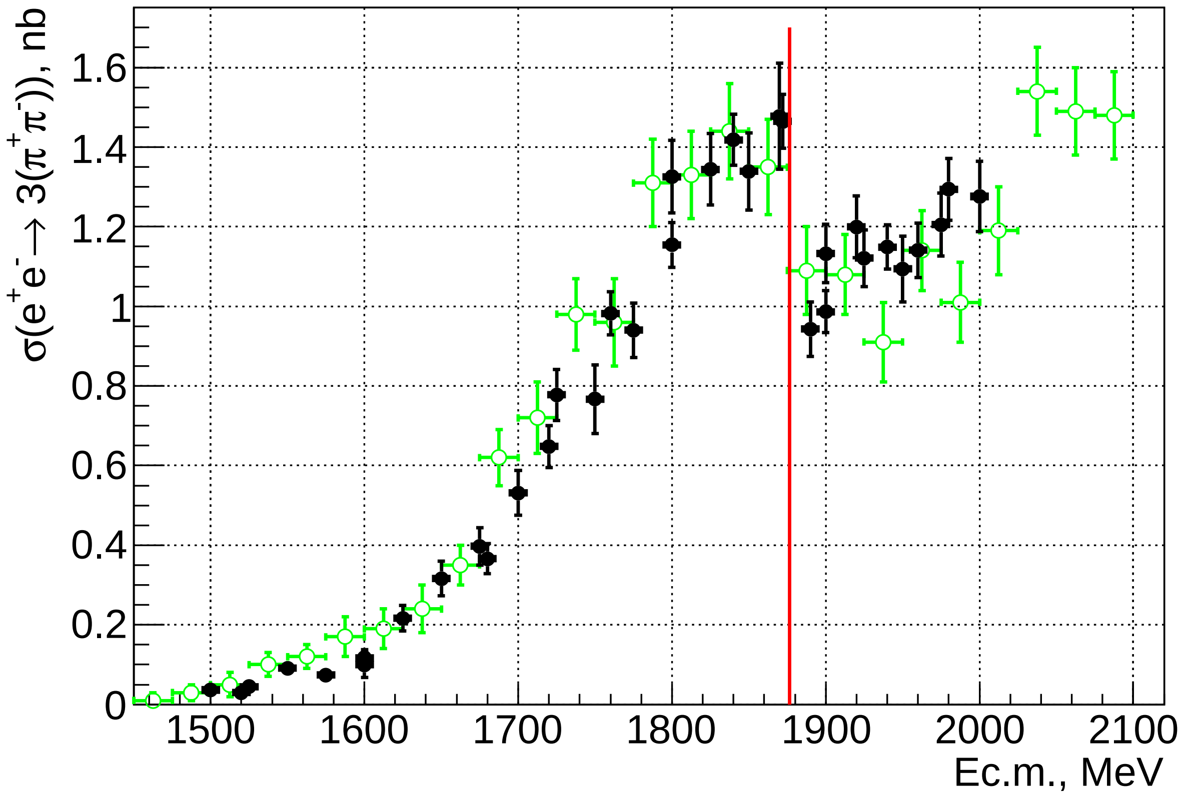
$e^+e^- \to 3\pi^+3\pi^-$ at CMD-3 – II

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

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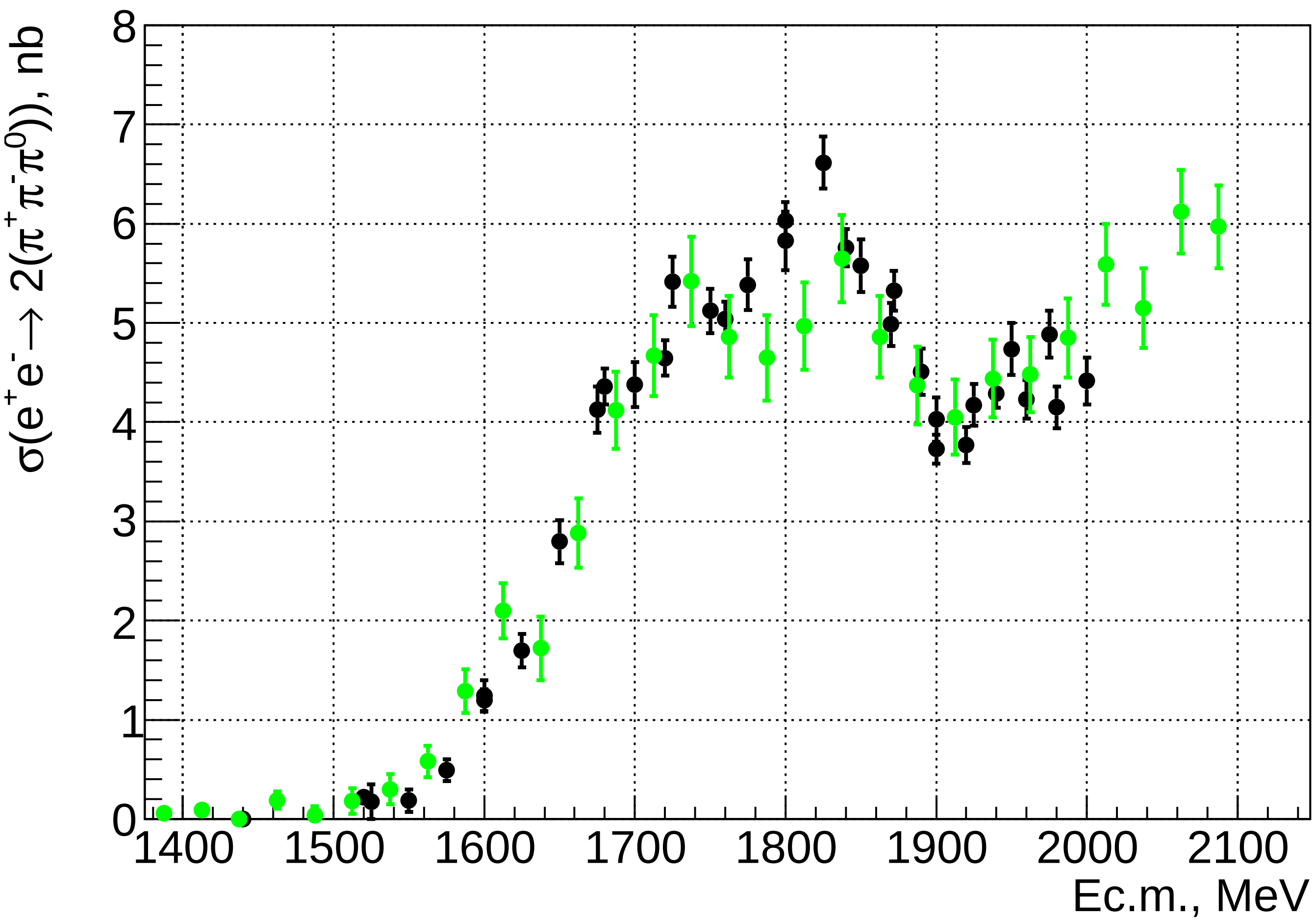
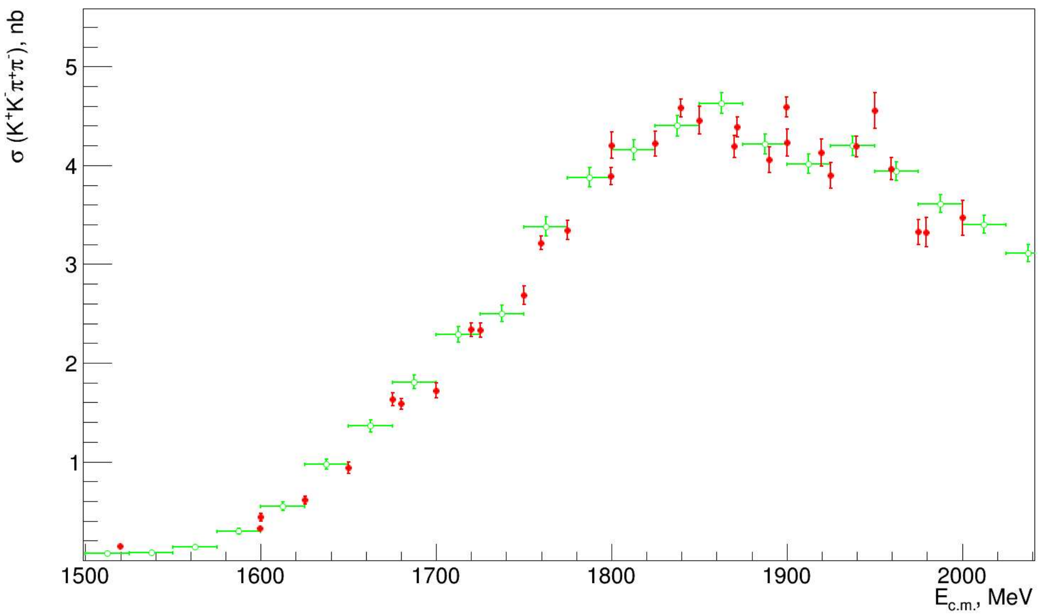
$e^+e^- \to 2\pi^+2\pi^-2\pi^0$ at CMD-3



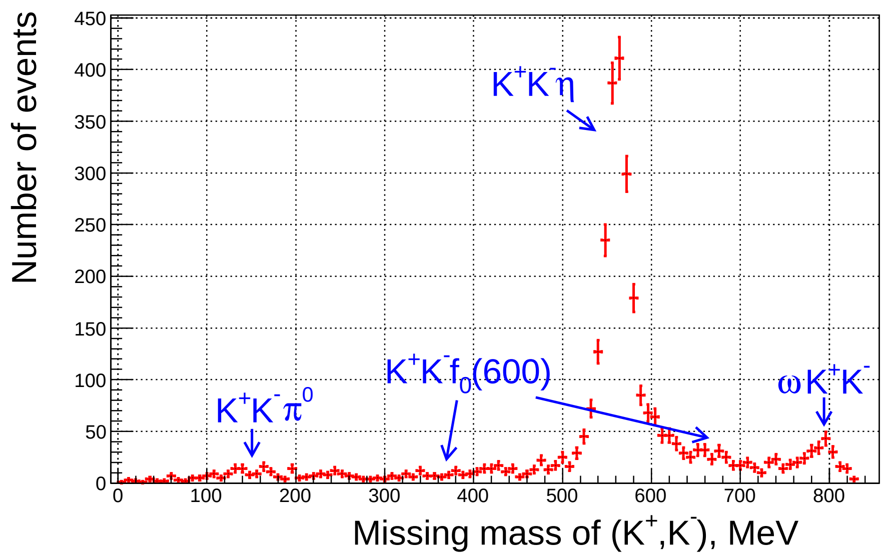
The dip structure near $N\bar{N}$ threshold also seen

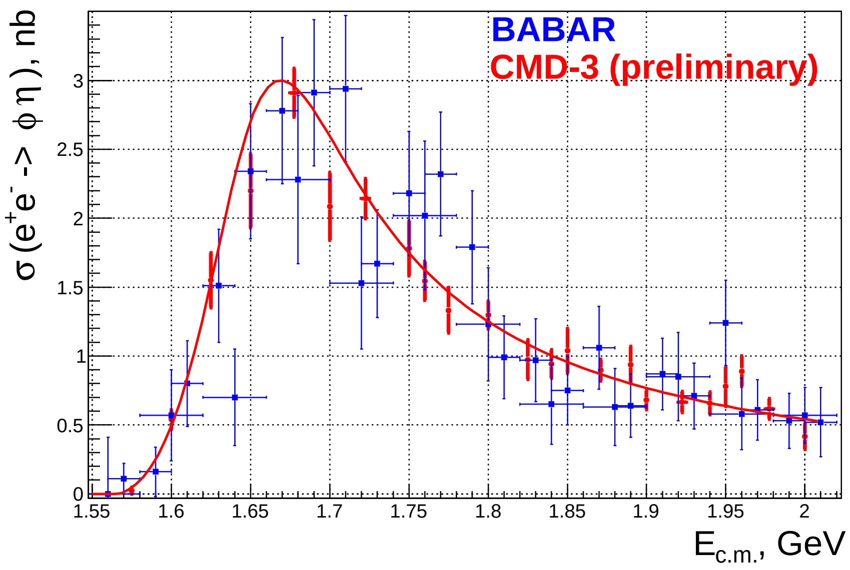
$e^+e^- \to K^+K^-\pi^+\pi^-$ at CMD-3



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

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

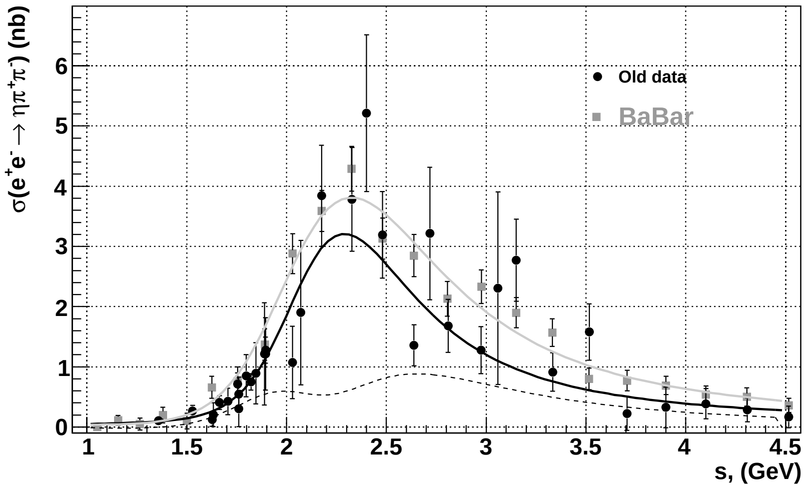


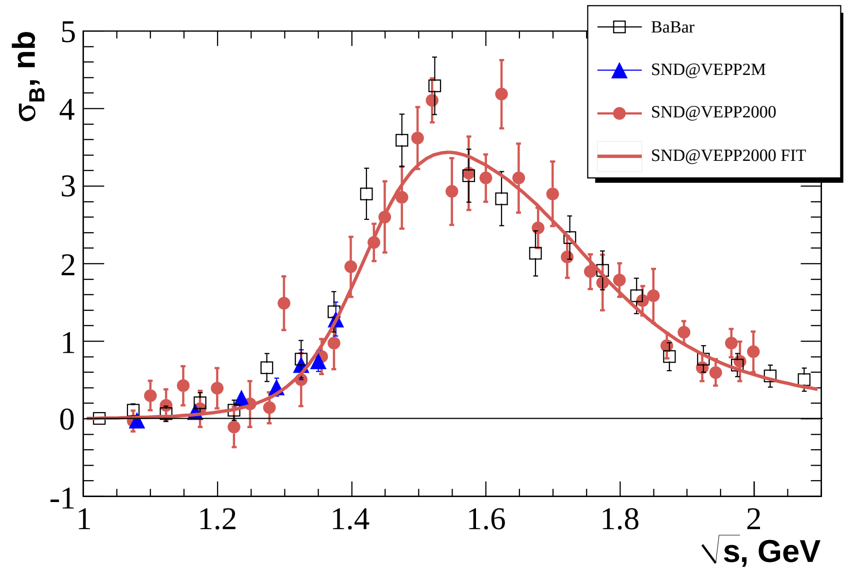


Dynamics is dominated by $\phi\eta$

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

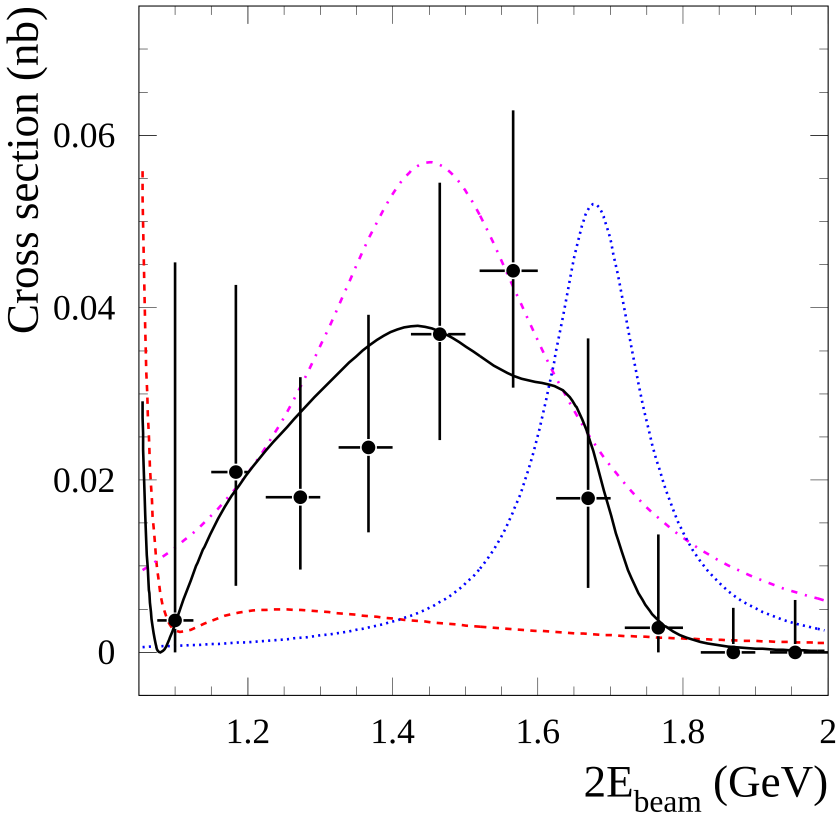
$e^+e^- \to \eta\pi^+\pi^-$ at SND





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

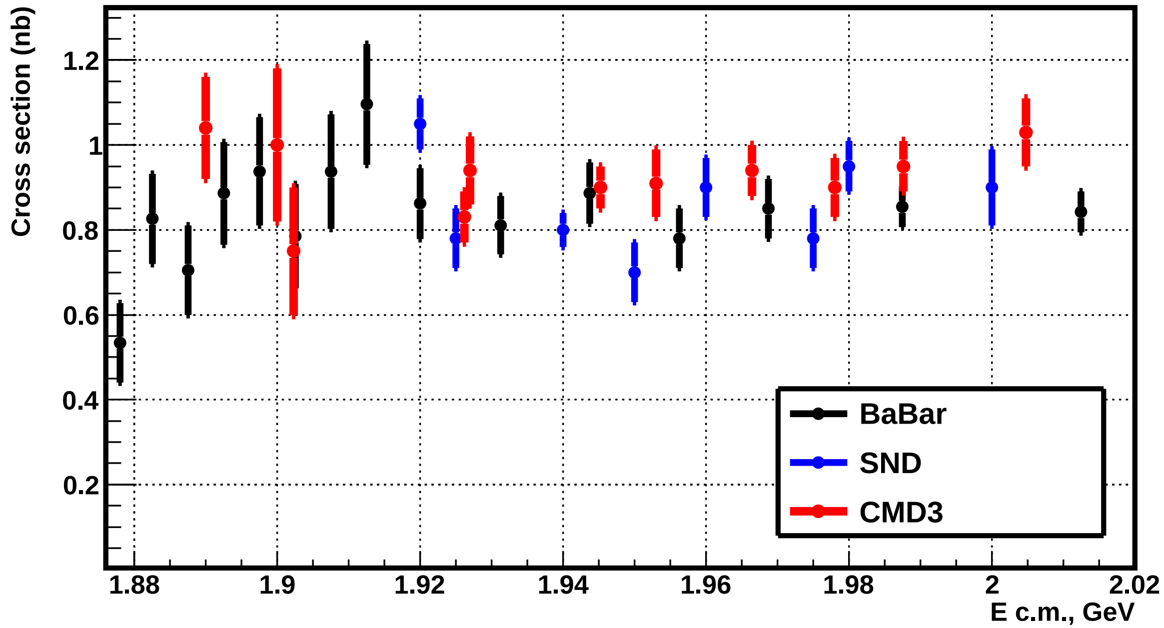
$e^+e^- \to \eta\gamma$ at SND



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

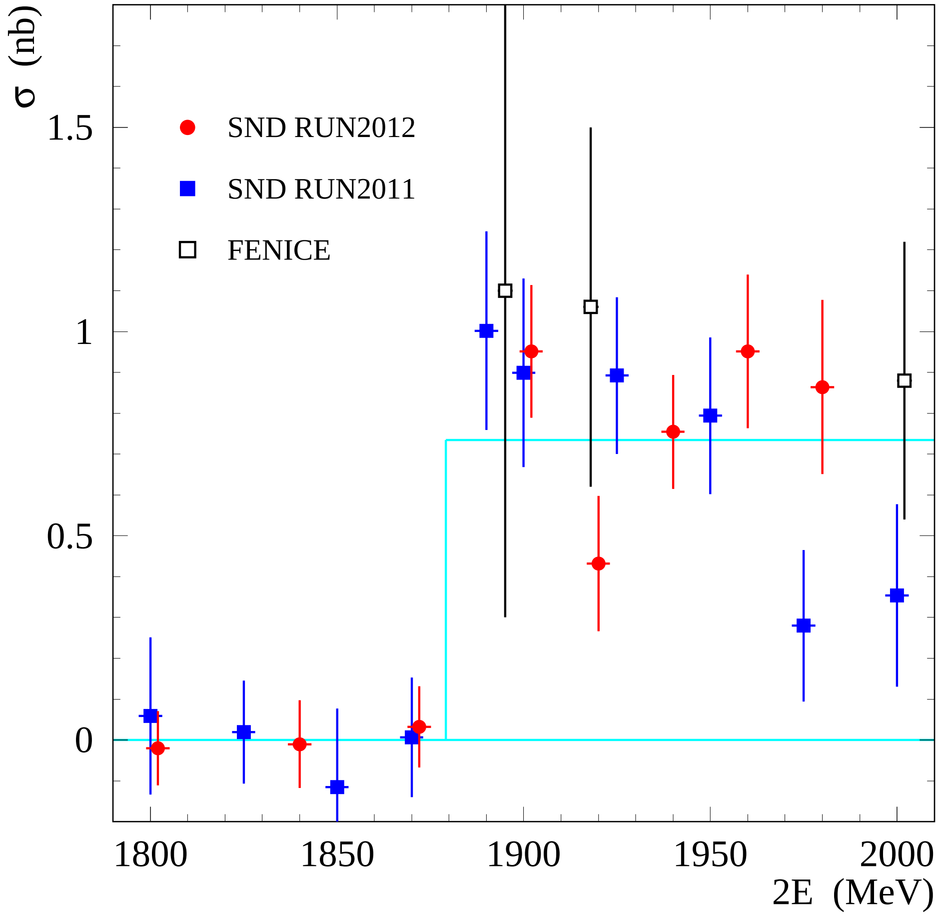
Dominated by the $\rho(1450)$ and $\phi(1680)$ mesons

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



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

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



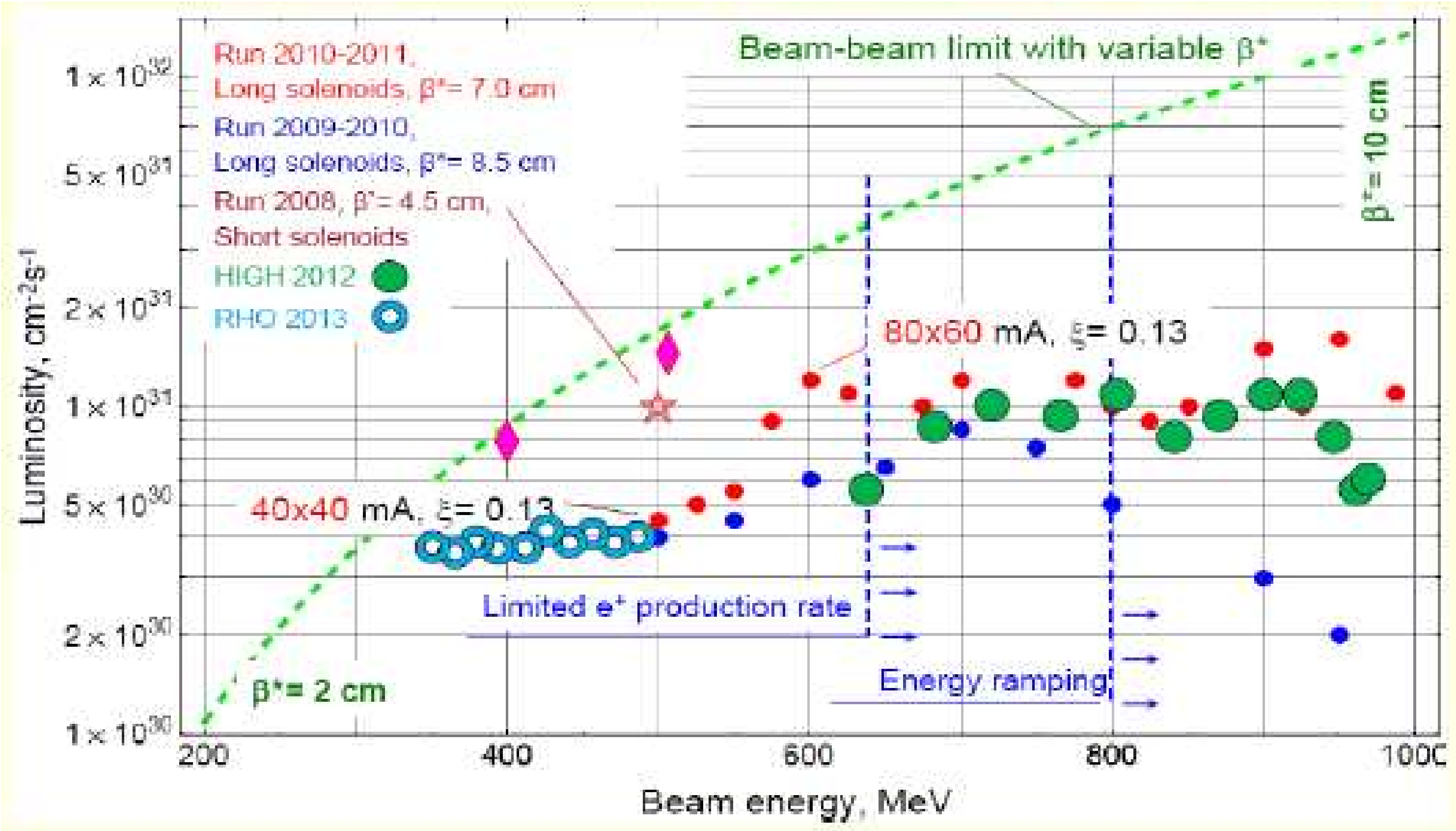
The first and more precise measurement after FENICE

Conclusions

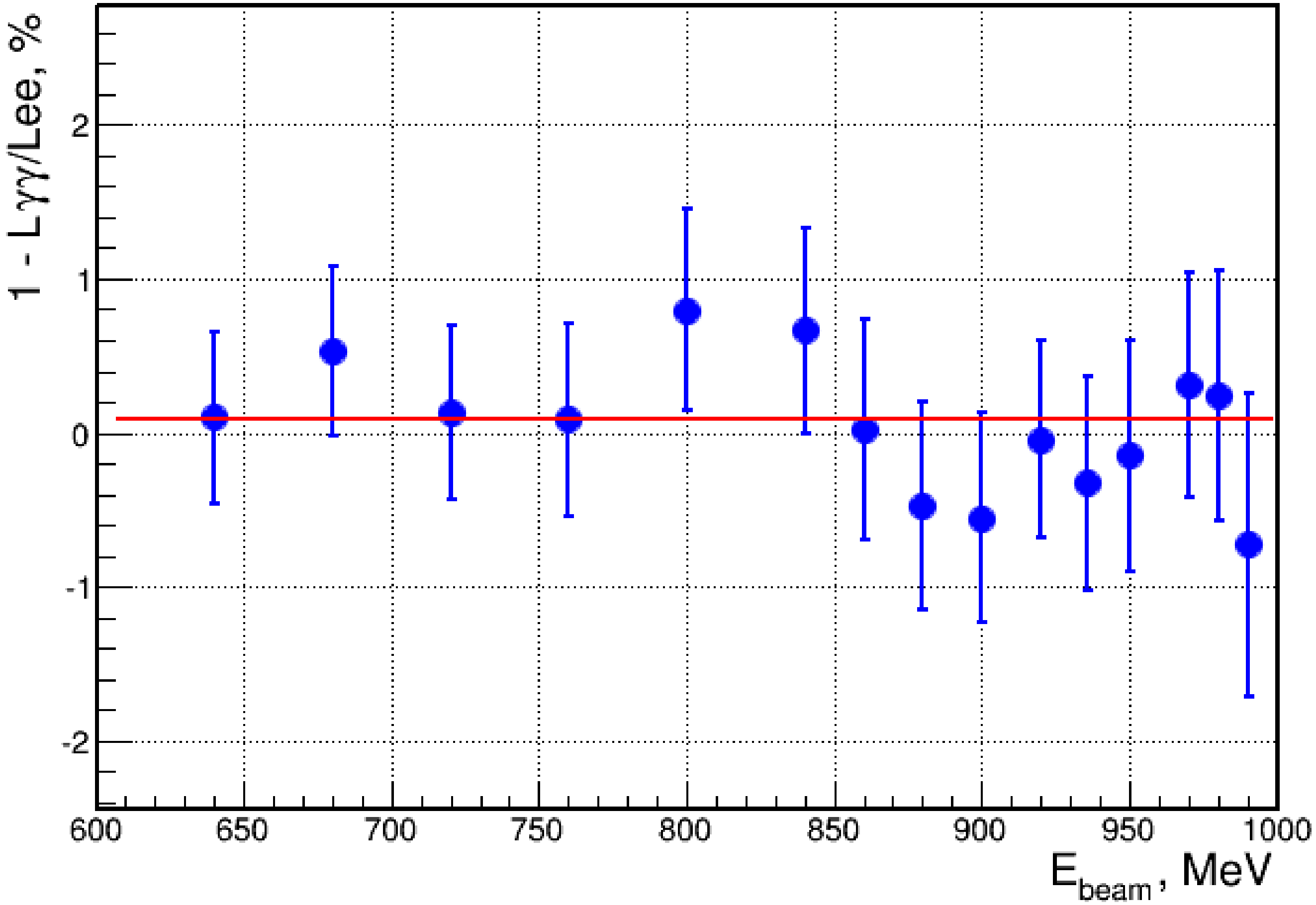
- VEPP-2000 is running smoothly with CMD-3 and SND, their accuracy is comparable or better than ISR measurements
- The goals are 0.35%(0.5%) for $\pi^+\pi^-$ and 3% for multibody modes
- Below 2 GeV progress (a factor of 2-3) expected in exclusive σ's due to scans in Novosibirsk and ISR from KLOE, BaBar, 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 unprecedented COMPASS data samples

Back-up

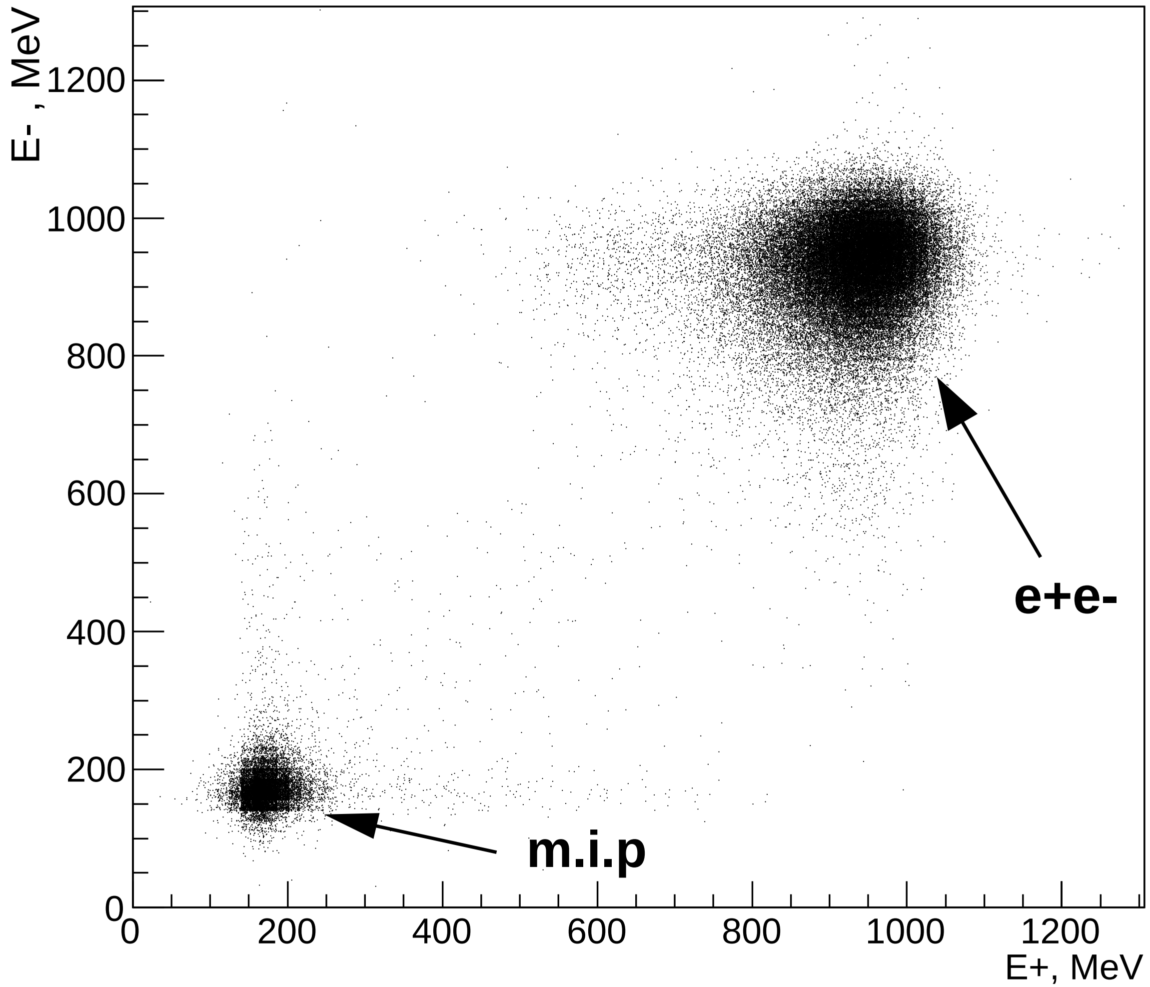
VEPP-2000 – III



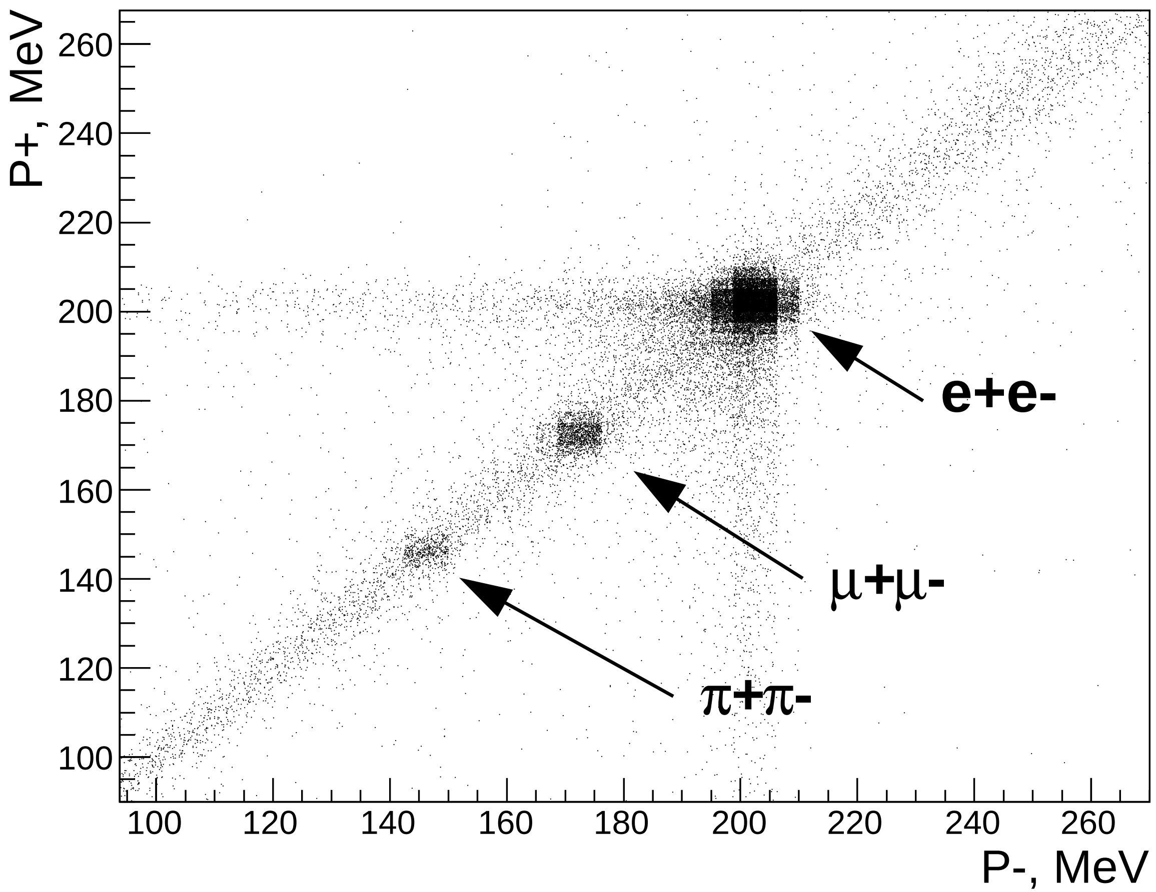
Luminosity Measurement at CMD-3



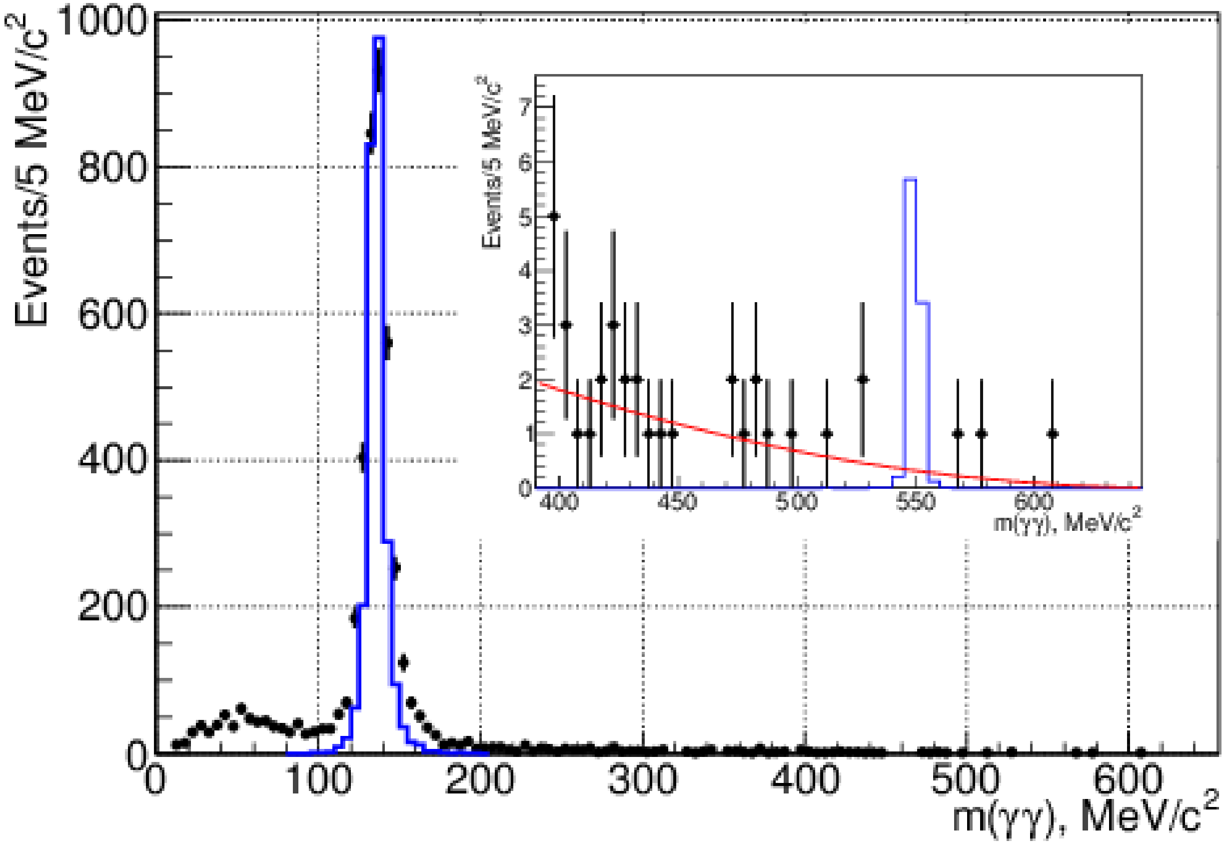
Particle Identification at CMD-3 – I



Particle Identification at CMD-3 – II



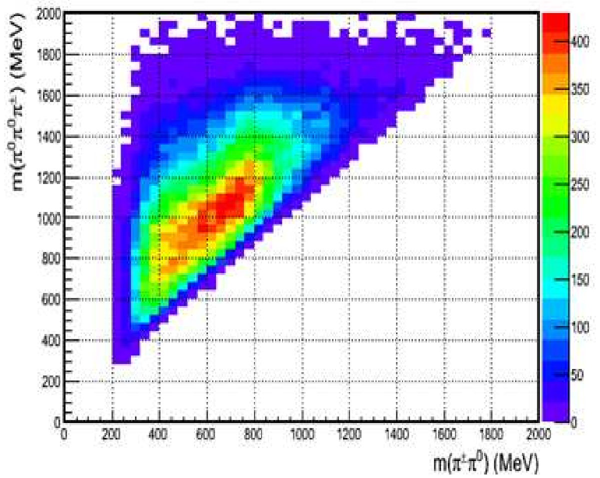
Search for $e^+e^- \to \eta' \to \eta\pi^+\pi^-$ at CMD-3

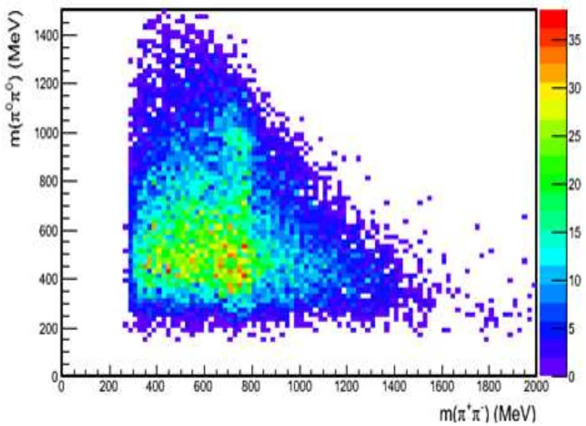


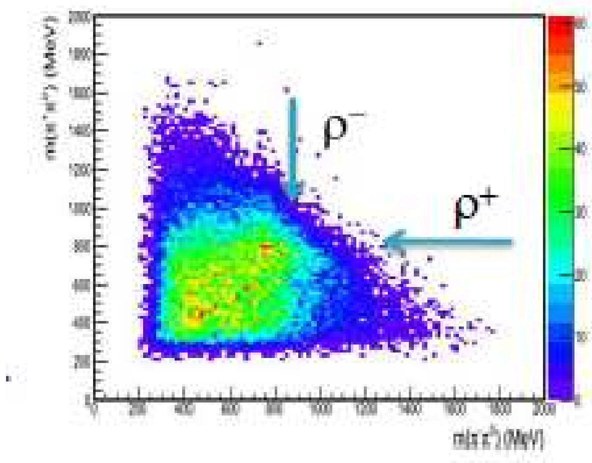
arXiv:1409.1664:

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

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

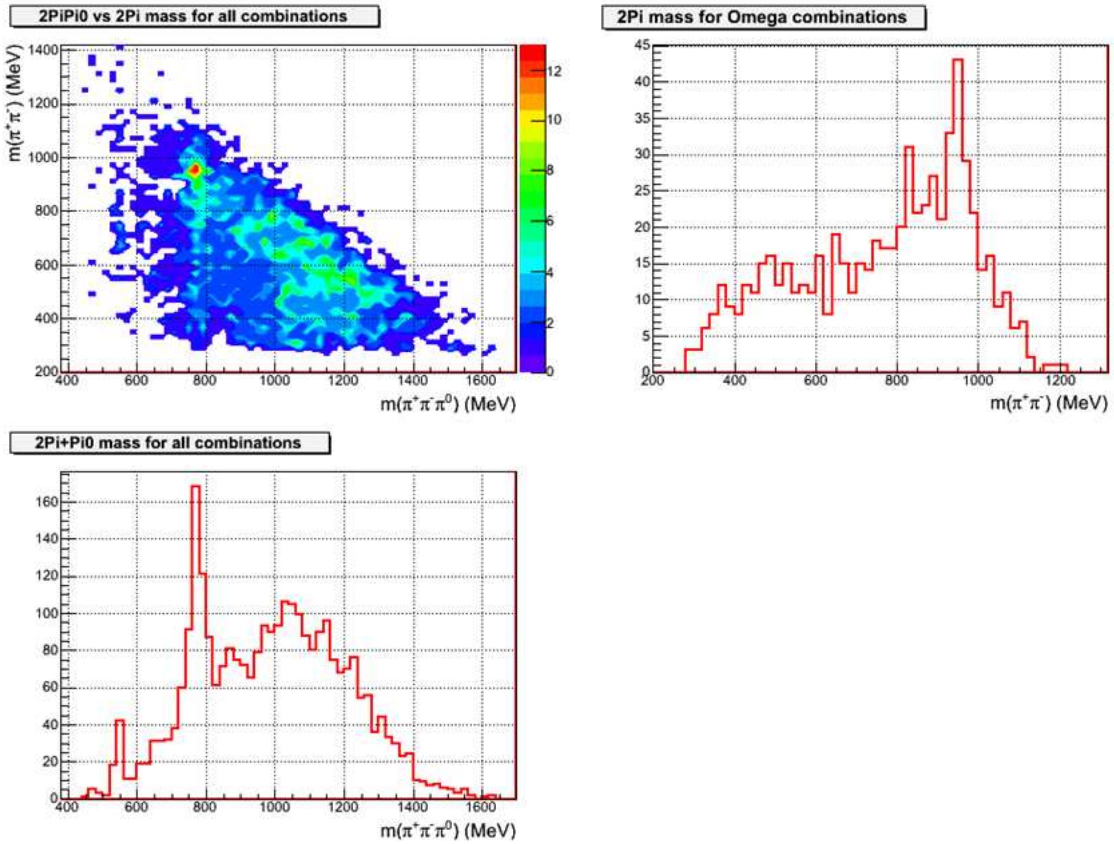






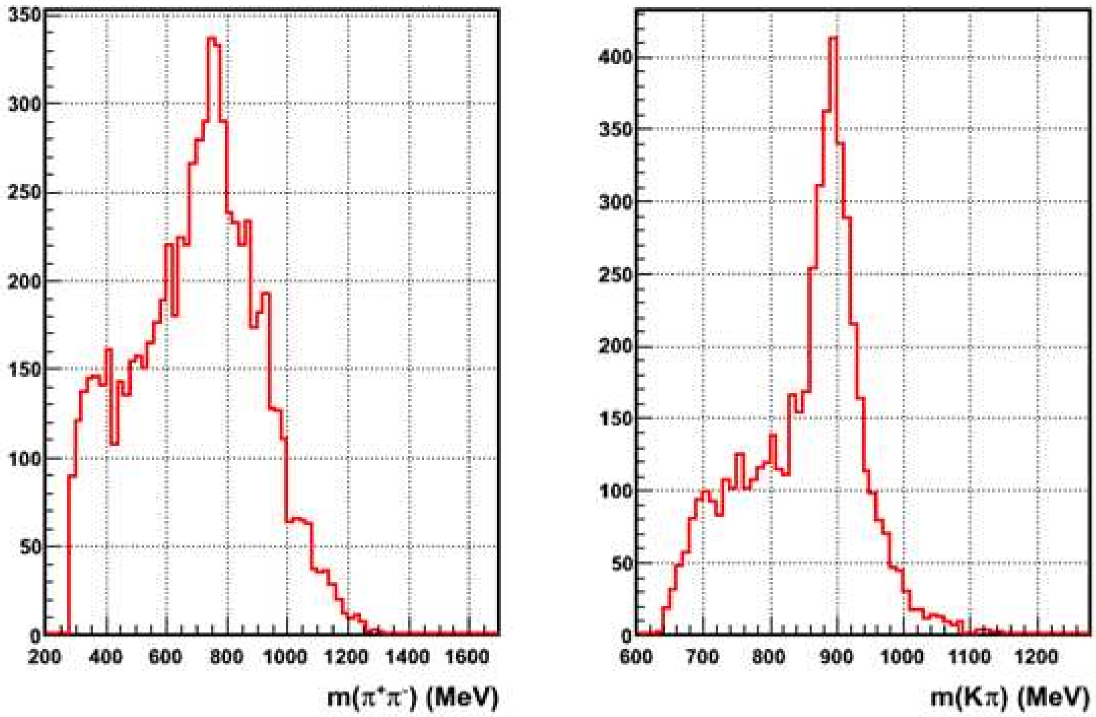
$a_1^{\pm}(1260)\pi^{\mp}$, $\rho^0 f_0$ and $\rho^+\rho^-$ intermediate states seen, other mechanisms possible: $a_2^{\pm}(1320)\pi^{\mp}$, $\pi^{\pm}(1300)\pi^{\mp}$, ...

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



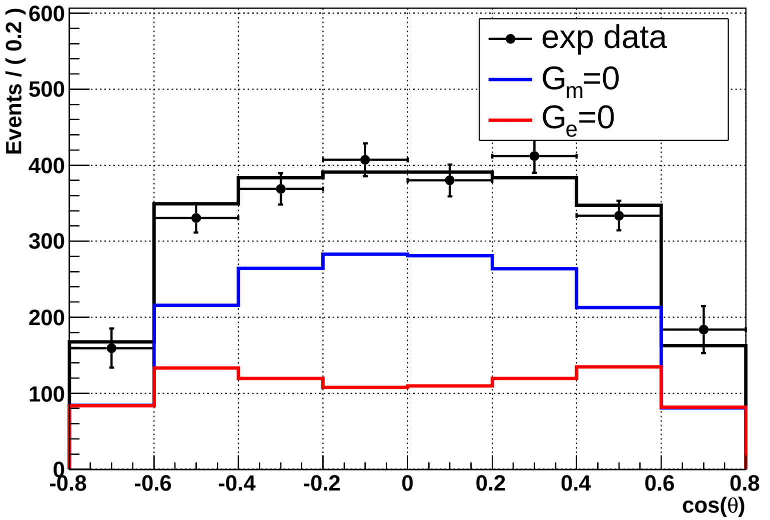
Various mechanisms seen: $\omega\pi^+\pi^-$, $\eta\pi^+\pi^-$, $\omega f_0(980)$

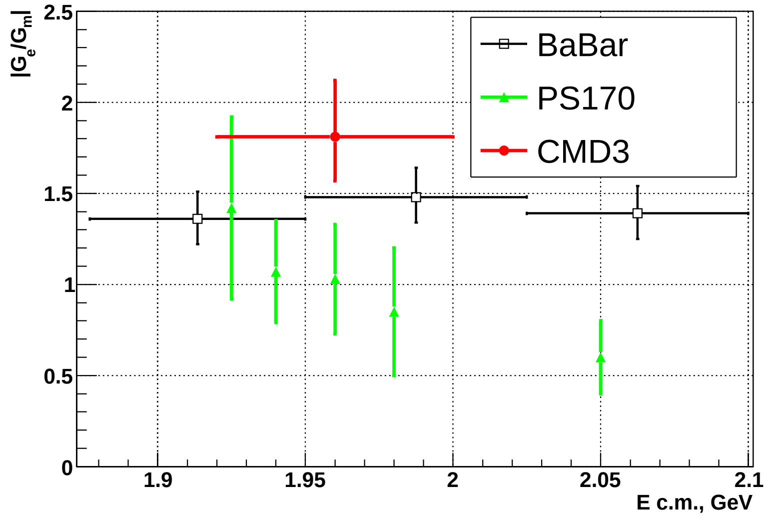
$e^+e^- \to K^+K^-\pi^+\pi^-$ at CMD-3 – I



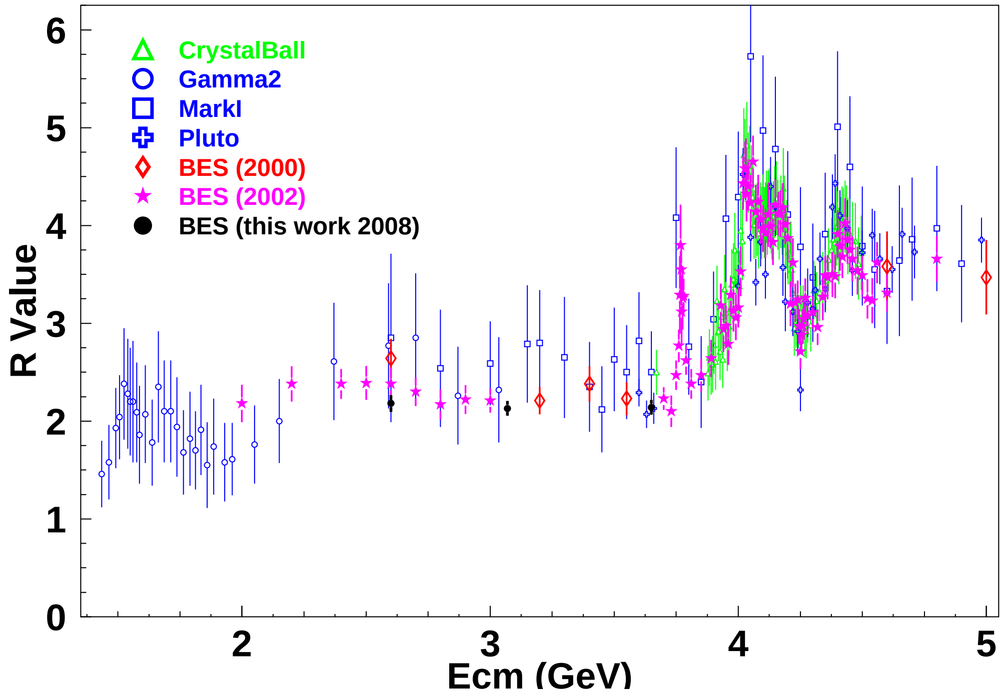
Many different mechanisms seen: $K_1(1270)\bar{K} \to K\bar{K}\rho$, $K^*(892)\bar{K}\pi$, $K_1(1400)\bar{K} \to K^*(892)\bar{K}\pi$, $\phi\pi^+\pi^-$

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;

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