Hadronic Vacuum Polarization (Experiment)

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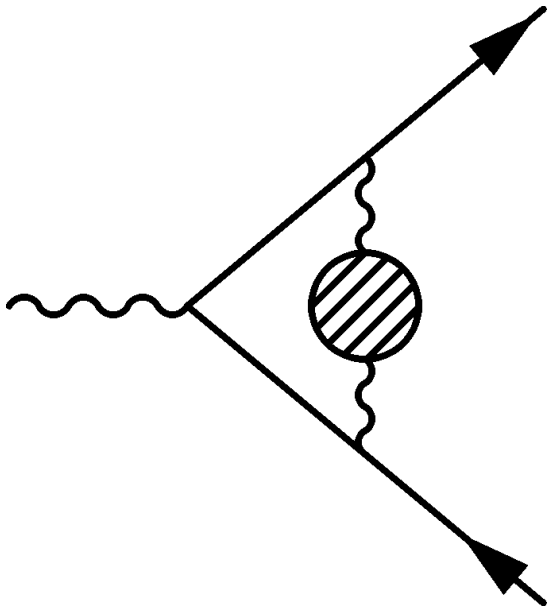
Outline

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

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

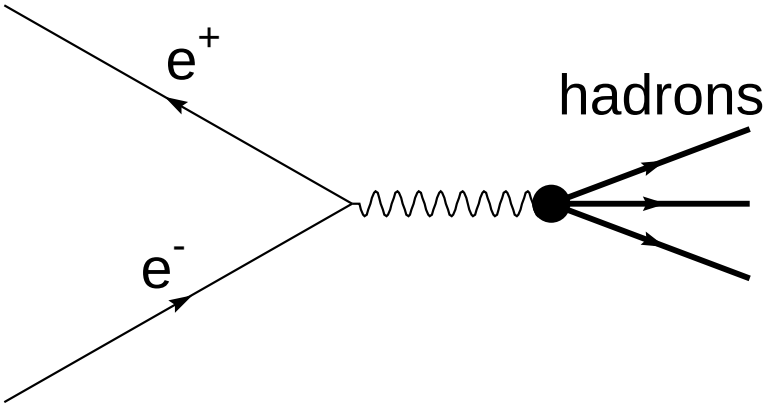
$$R(s) = \frac{\sigma(e^+e^-\to\text{hadrons})}{\sigma(e^+e^-\to\mu^+\mu^-)},$$

$\hat{K}(s)$ 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

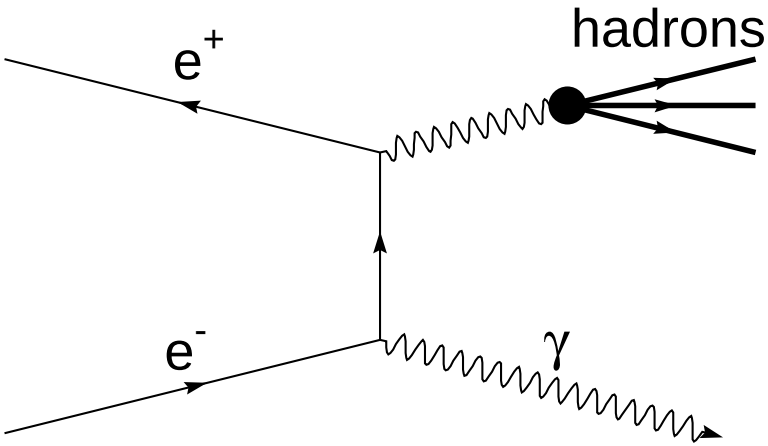
Contribution of Various Energy Ranges

$\sqrt{s}$, 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



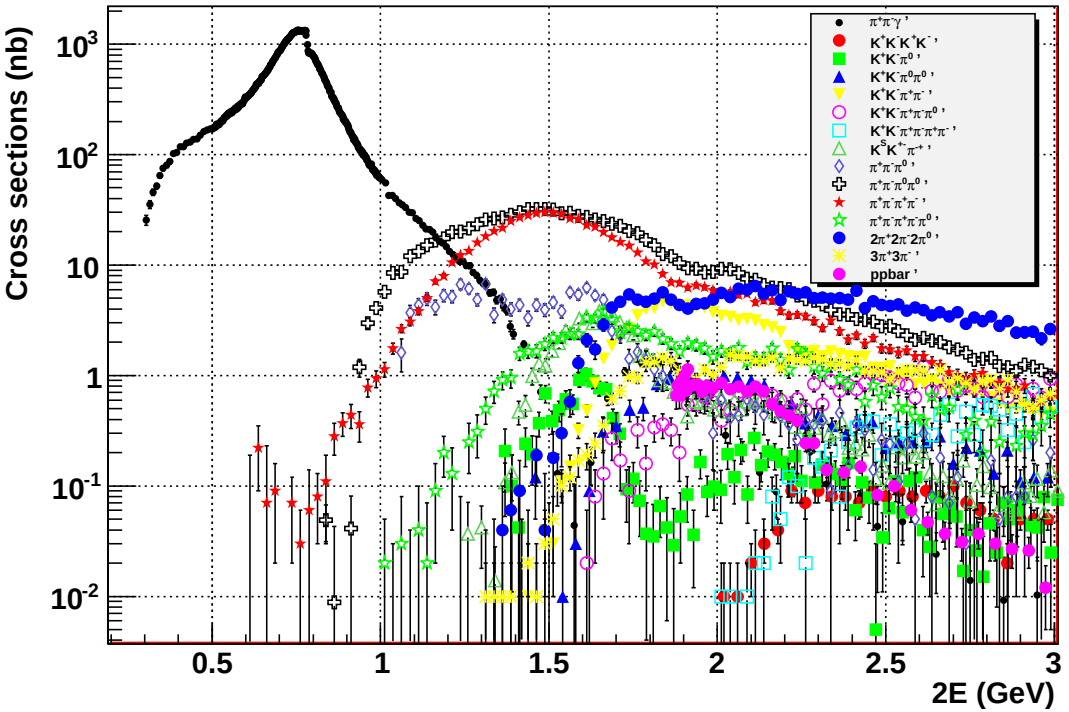
Scan



ISR

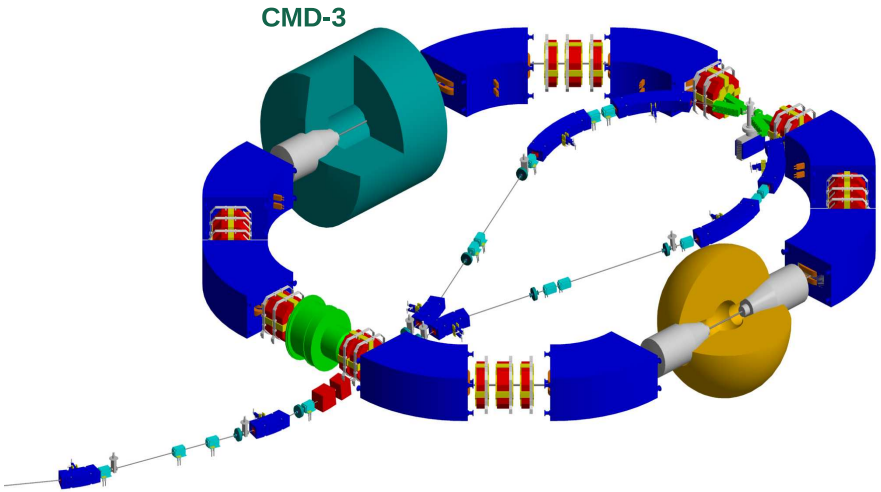
Scan can provide larger data samples, covers all final states,
VEPP-2000 and VEPP-4M can perform scans with a small $\sqrt{s}$ step
ISR benefits from the same systematics and flat acceptance,
may suffer from more complicated radiative effects, all neutrals hardly possible

Current Status of Exclusive Measurements



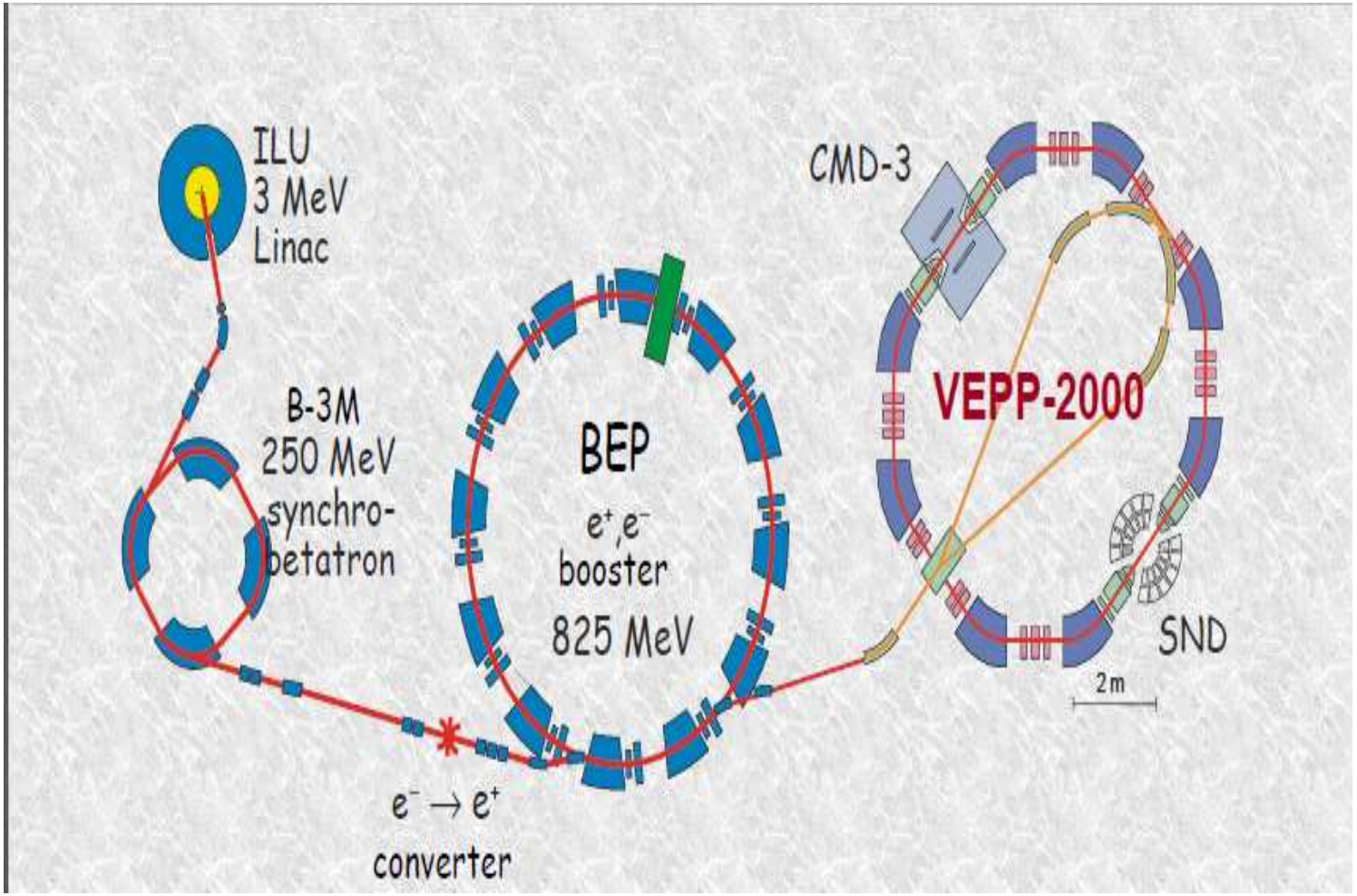
Impressive achievements of CMD-2, SND (scan at $\sqrt{s} < 1.4$ GeV) and KLOE (ISR at $\sqrt{s} < 1.0$ GeV) and BaBar (ISR at $\sqrt{s} < 3.0$ GeV), Belle and BESIII may contribute as well to ISR measurements

VEPP-2000 – I

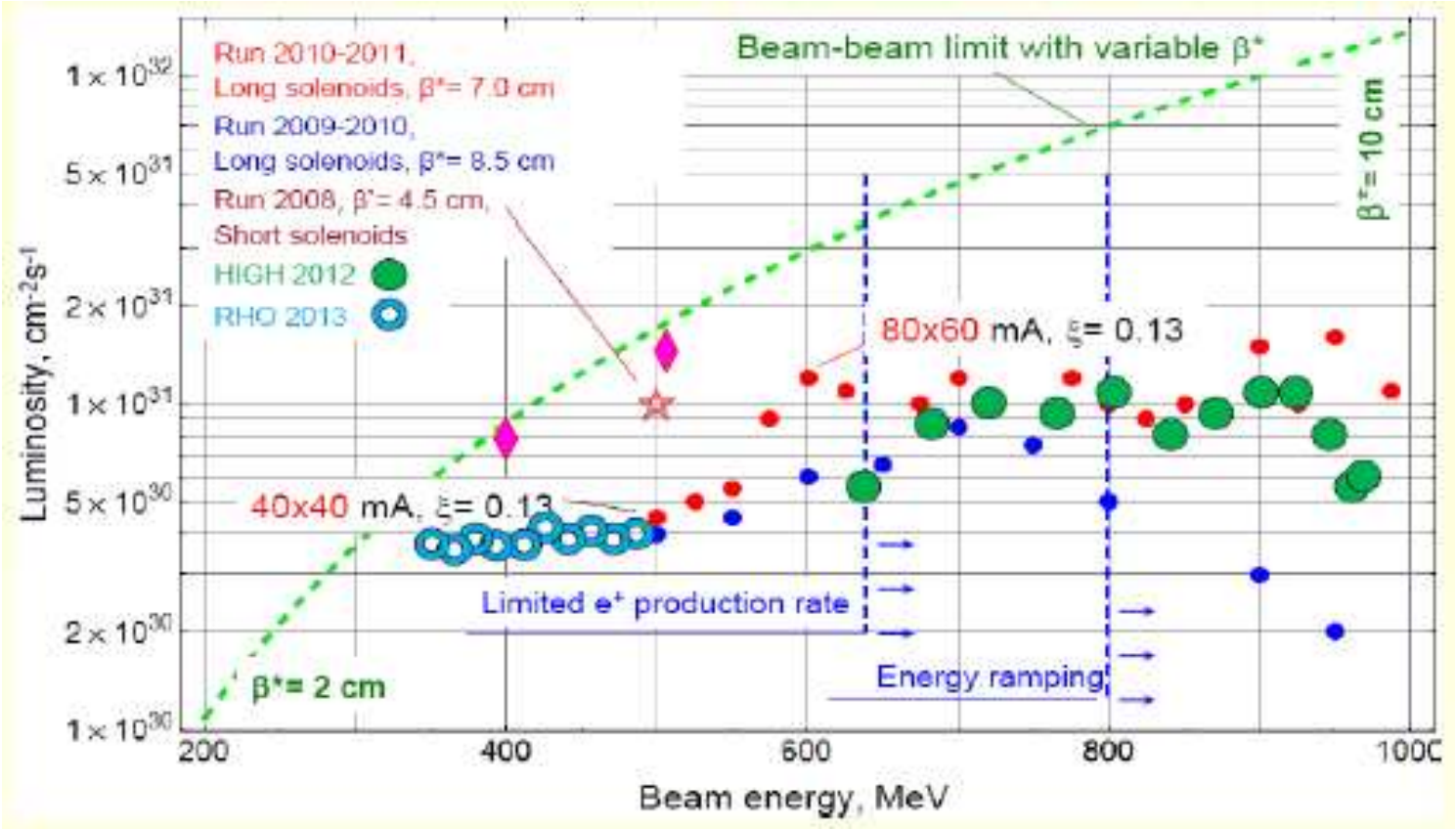


Collider	Operation	$\sqrt{s}$, MeV	$\mathcal{L}, 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
VEPP-2M	1975-2000	[360,1400]	3
VEPP-2000	2010-	$[2m_\pi, 2000]$	100

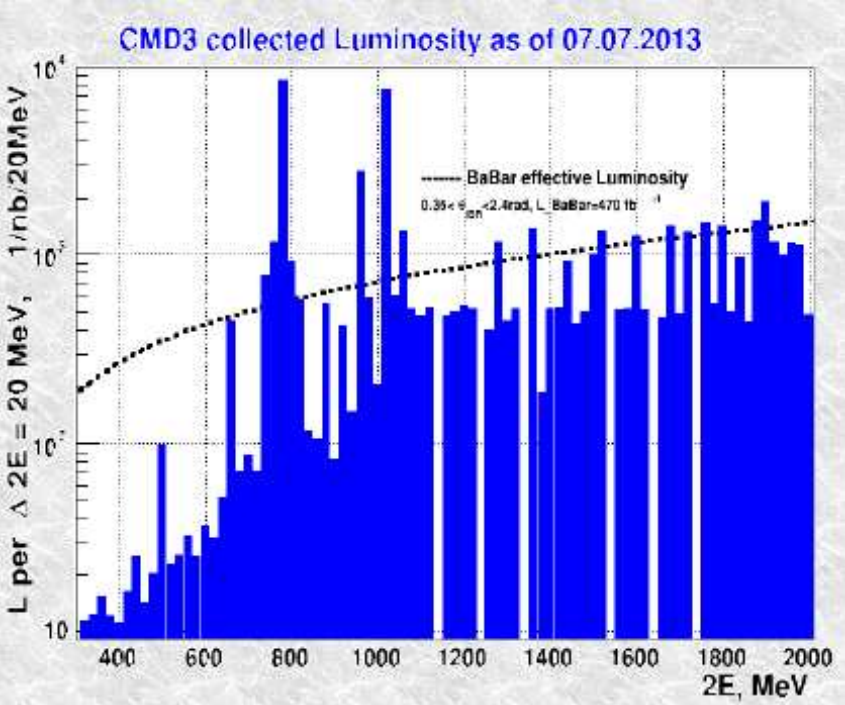
VEPP-2000 – II


ILU
3 MeV
Linac
B-3M
250 MeV
synchro-
betatron
BEP
e+,e-
booster
825 MeV
e- → e+
converter
CMD-3
VEPP-2000
SND
2m

VEPP-2000 – III



Data Taking at VEPP-2000



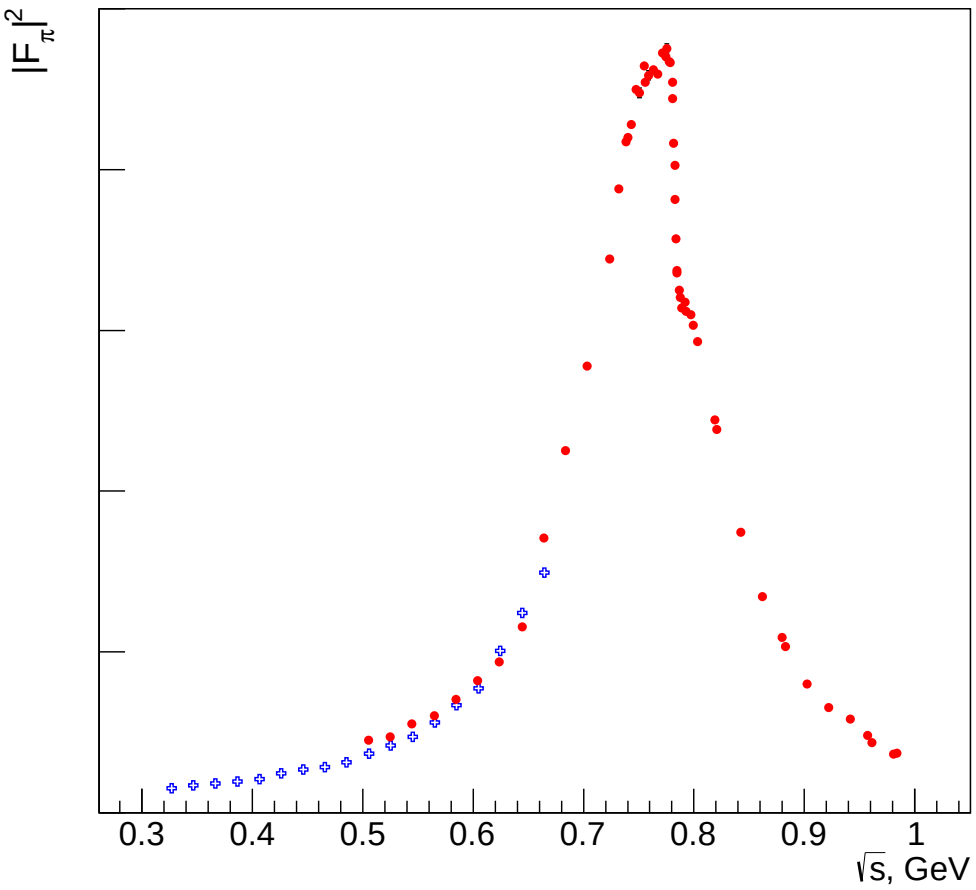
Collected L ~ 60 pb^{-1} per detector

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

Performance of VEPP-2000 and Detectors

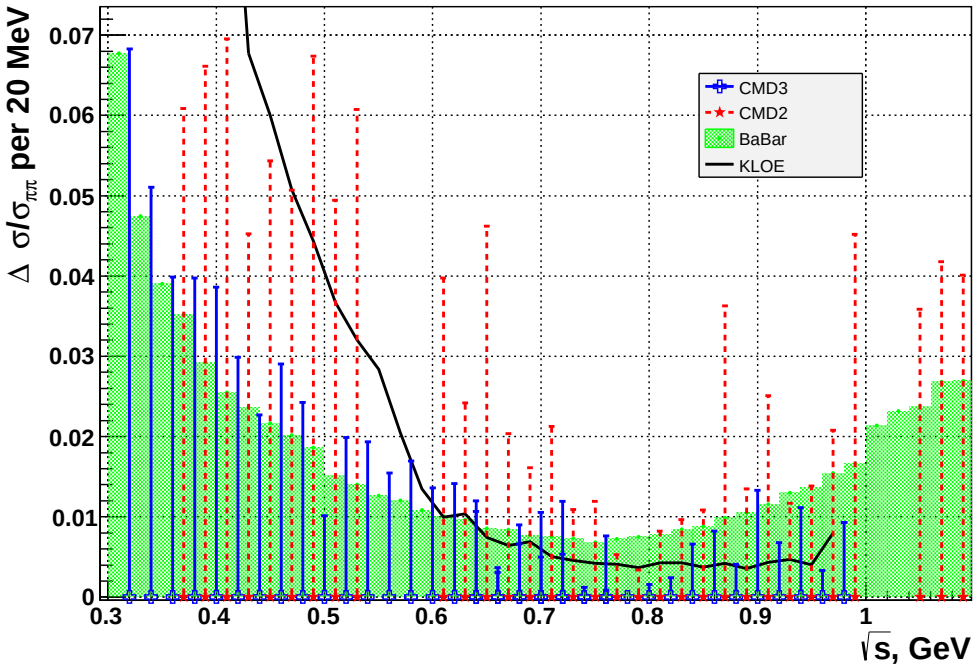
- The maximum luminosity is $2 \cdot 10^{31}$ cm^{-1}s^{-1} at 1.7-1.8 GeV, falling much slower with decreasing energy than before the round beams
- The integrated luminosity is about 60 pb^{-1} per detector, a factor of 6 higher than before from ϕ to 2 GeV, the number of multihadronic events per 1 pb^{-1} $\sim 50k$
- 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

$e^+e^- \to \pi^+\pi^-$ at CMD-3 – I



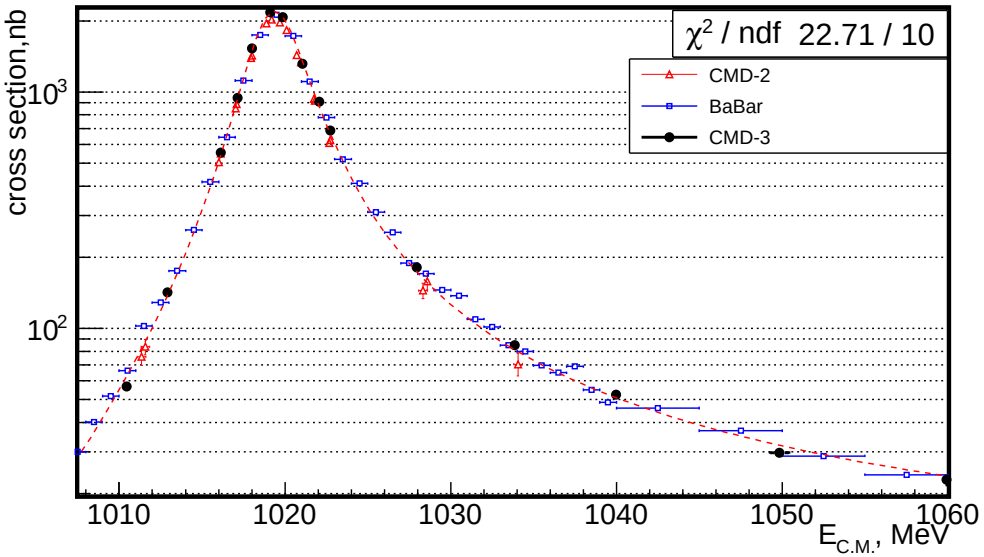
Overlap of μ/π separation by DC and calorimeters

$e^+e^- \to \pi^+\pi^-$ at CMD-3 – II



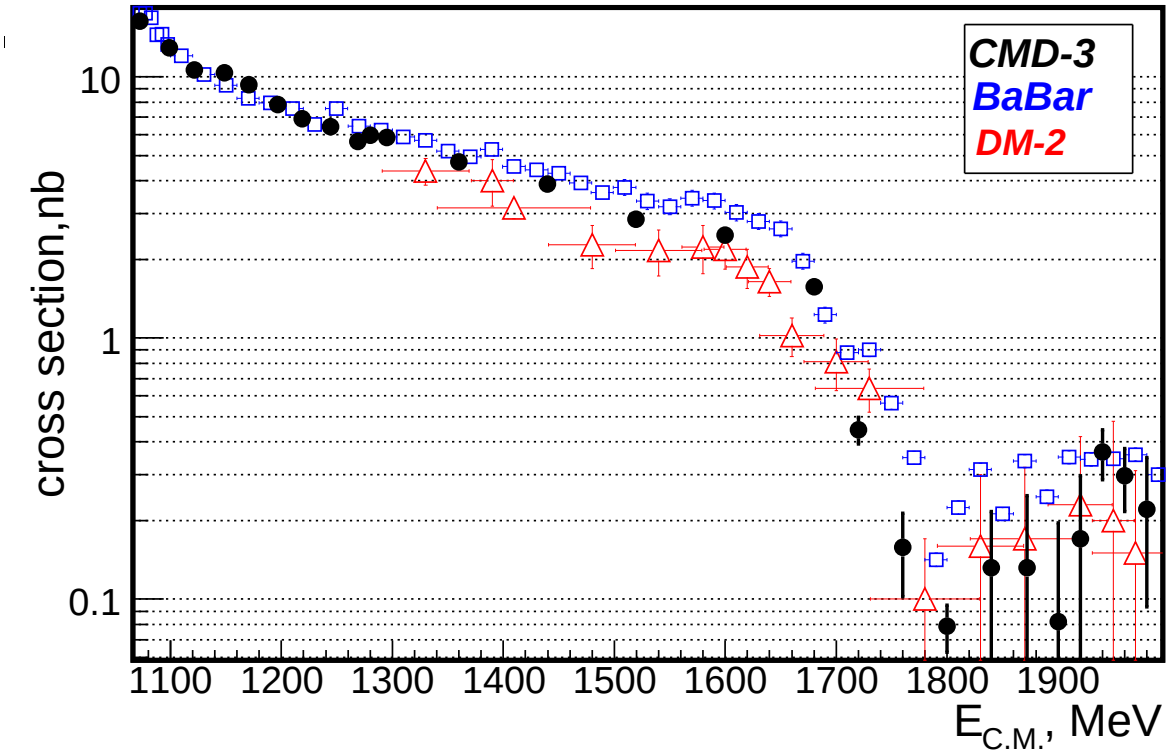
Statistical precision better than that of BaBar

$e^+e^- \to K^+K^-$ at CMD-3 – I



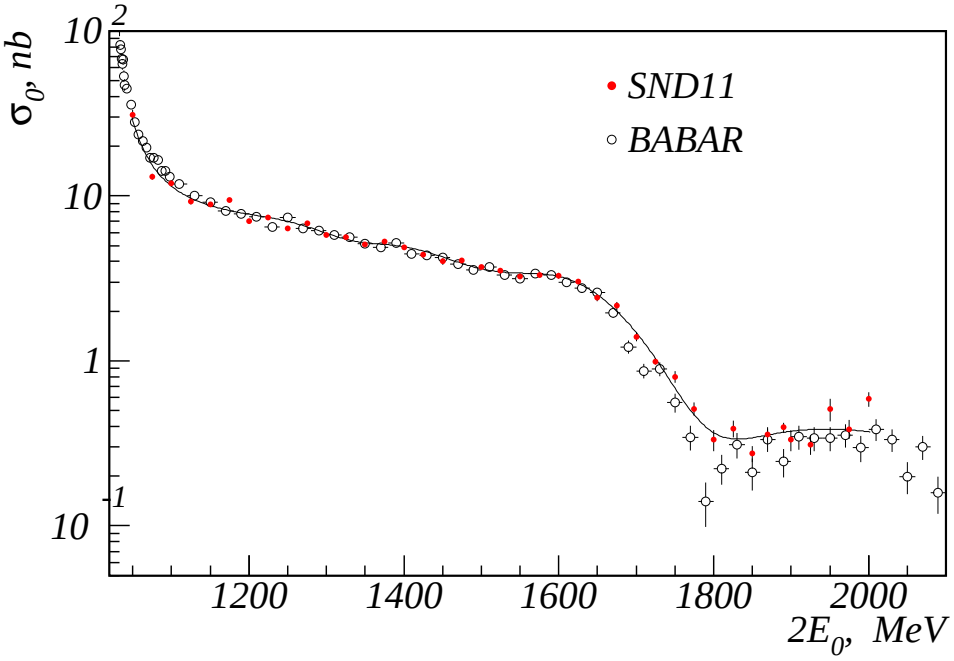
BaBar data higher than CMD-3, CMD-2 and CMD-3 agree

$e^+e^- \to K^+K^-$ at CMD-3 – II



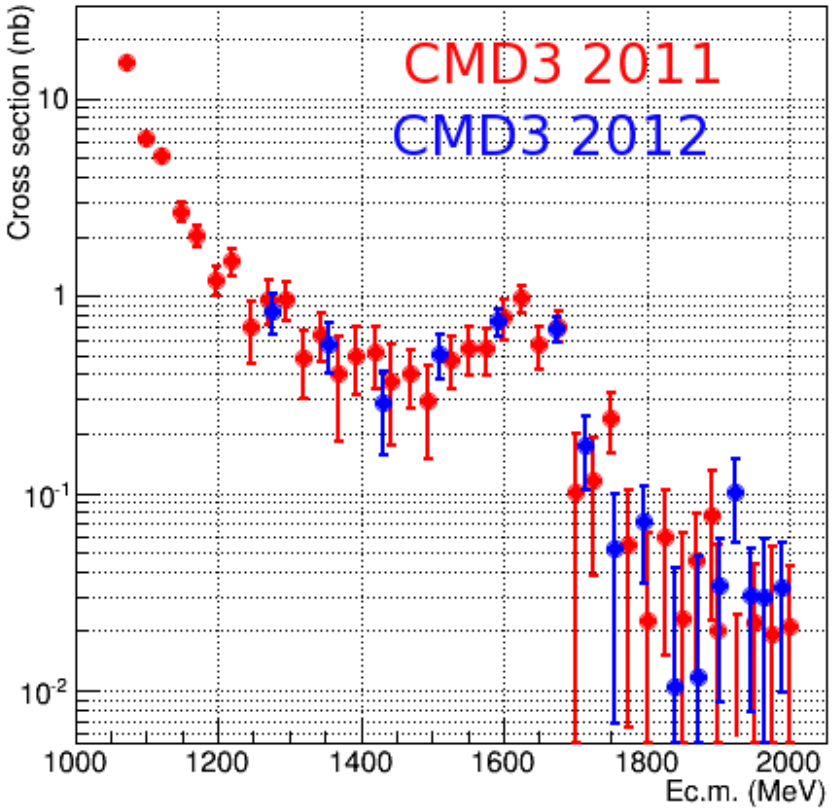
BaBar data higher than CMD-3

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



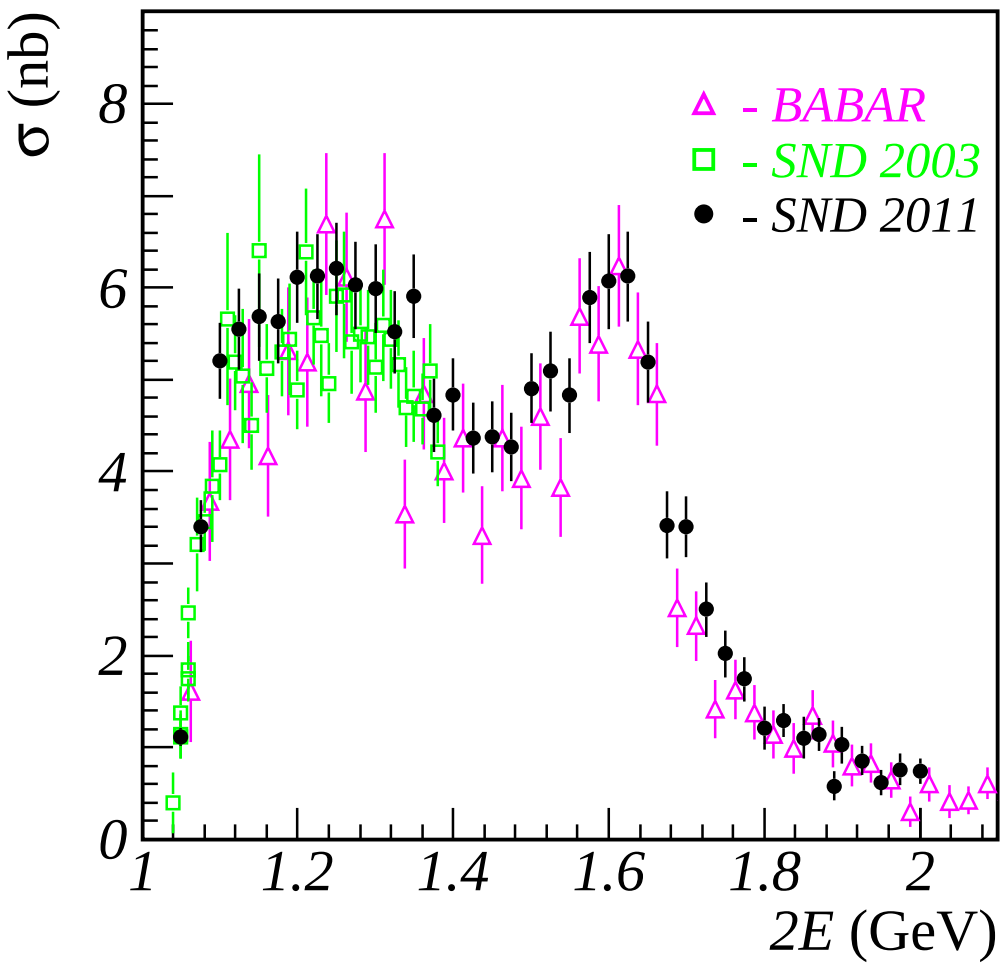
Very preliminary SND data agree with BaBar

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



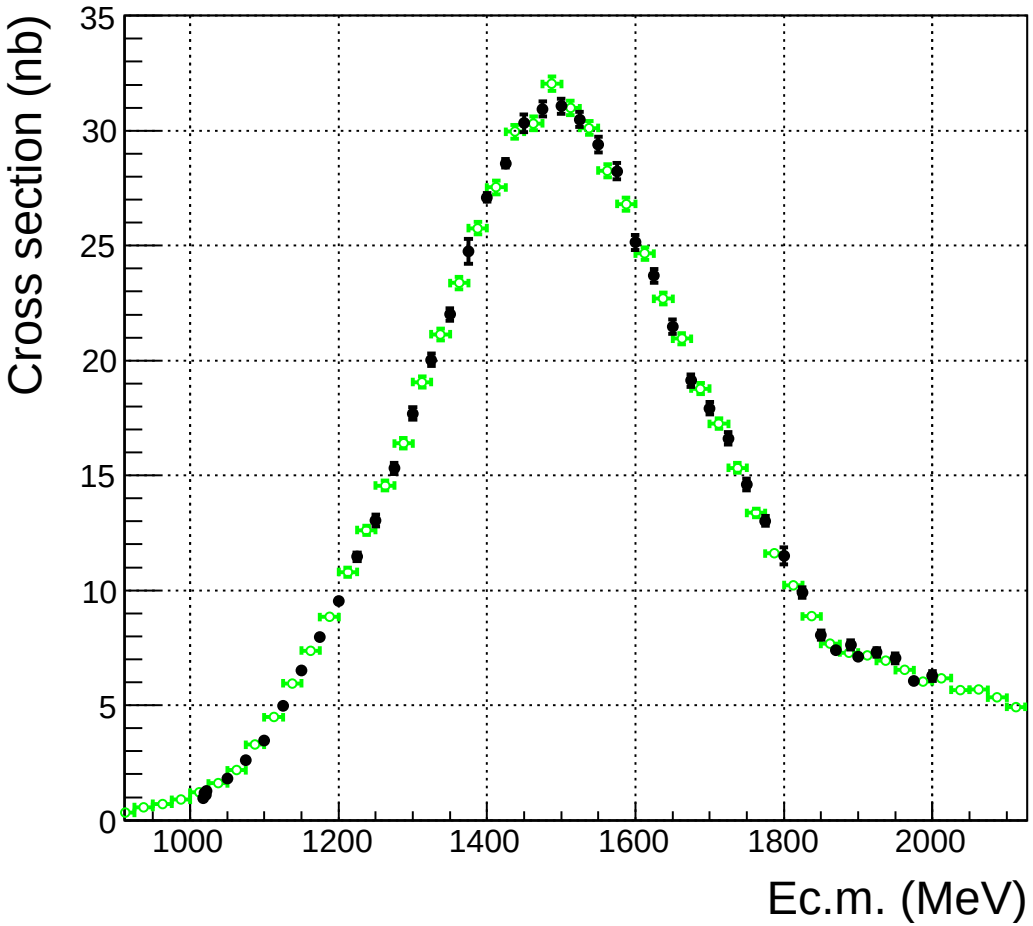
Fair agreement between different seasons

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

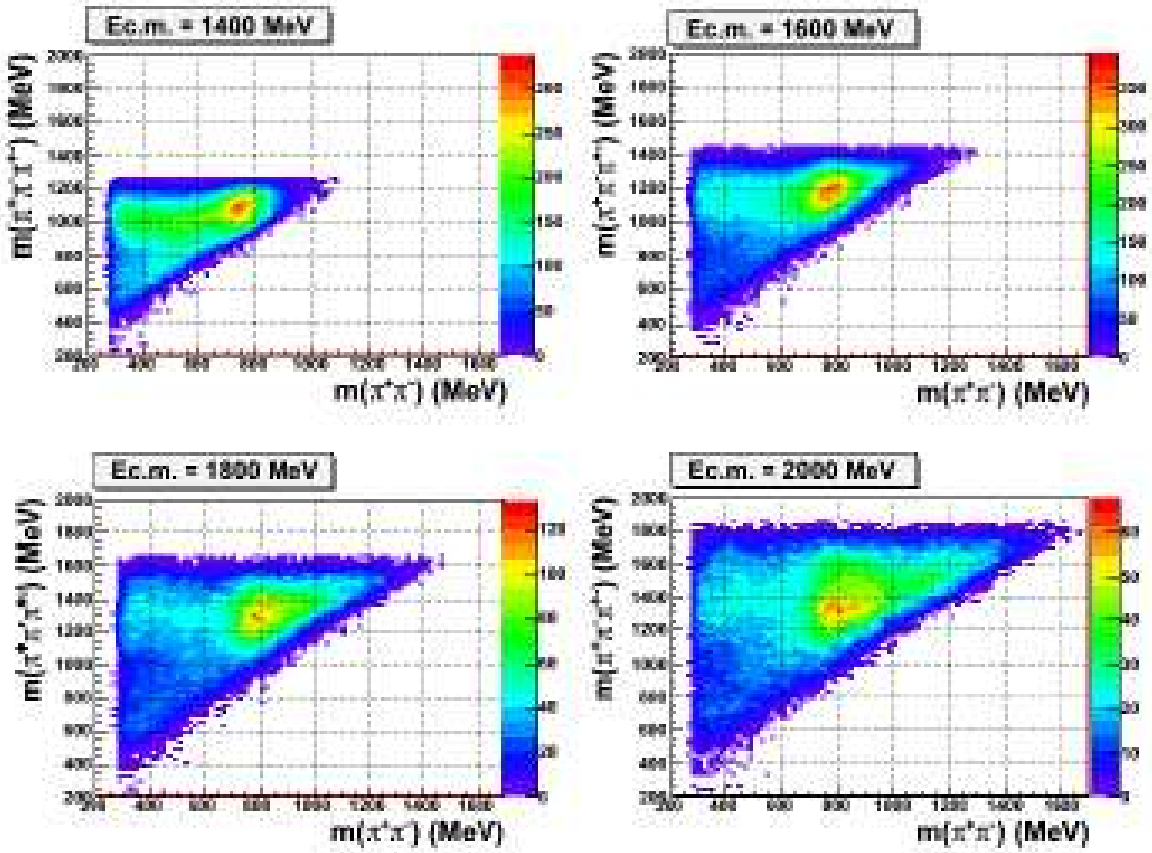


It's interesting to disentangle the $\rho\pi$ and direct 3π modes

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

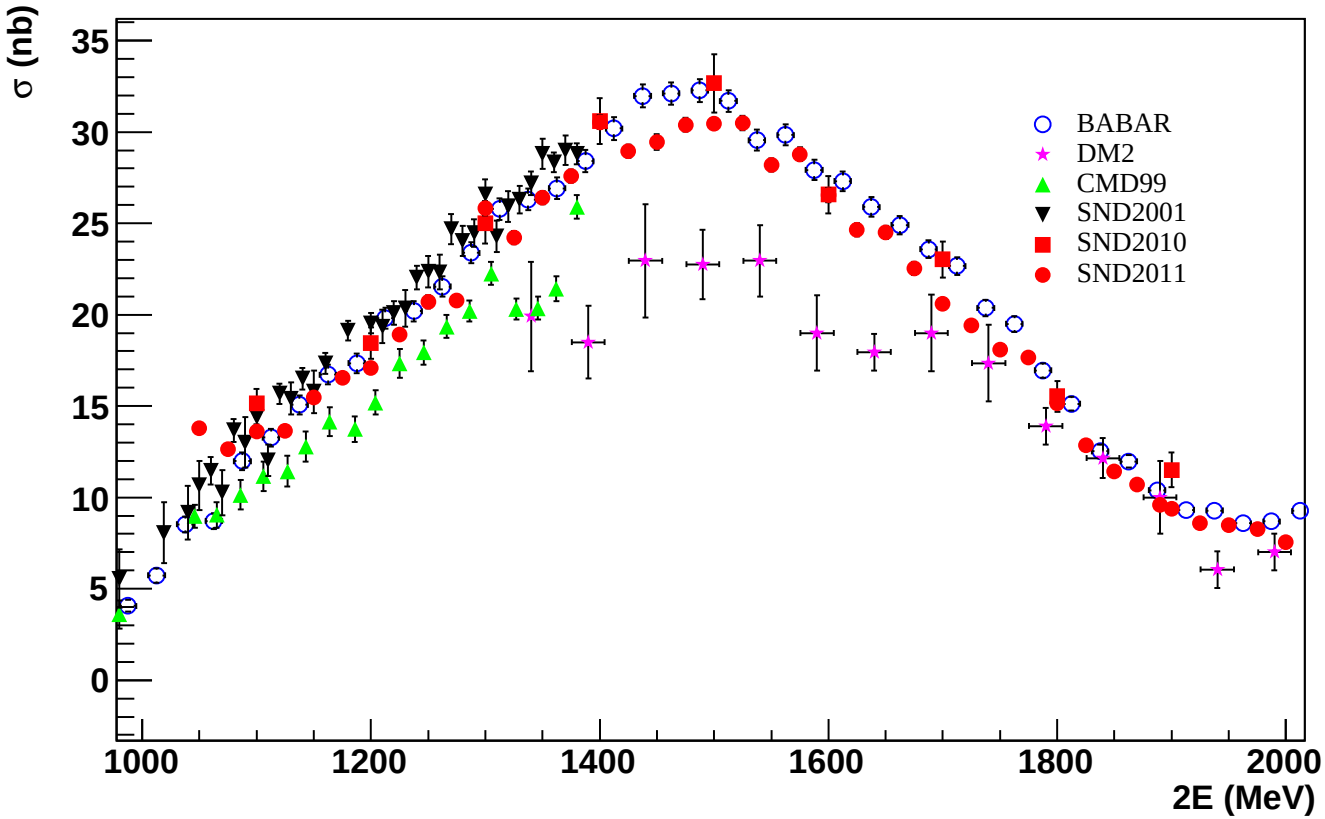


Dynamics of $e^+e^- \to 2\pi^+2\pi^-$ at CMD-3



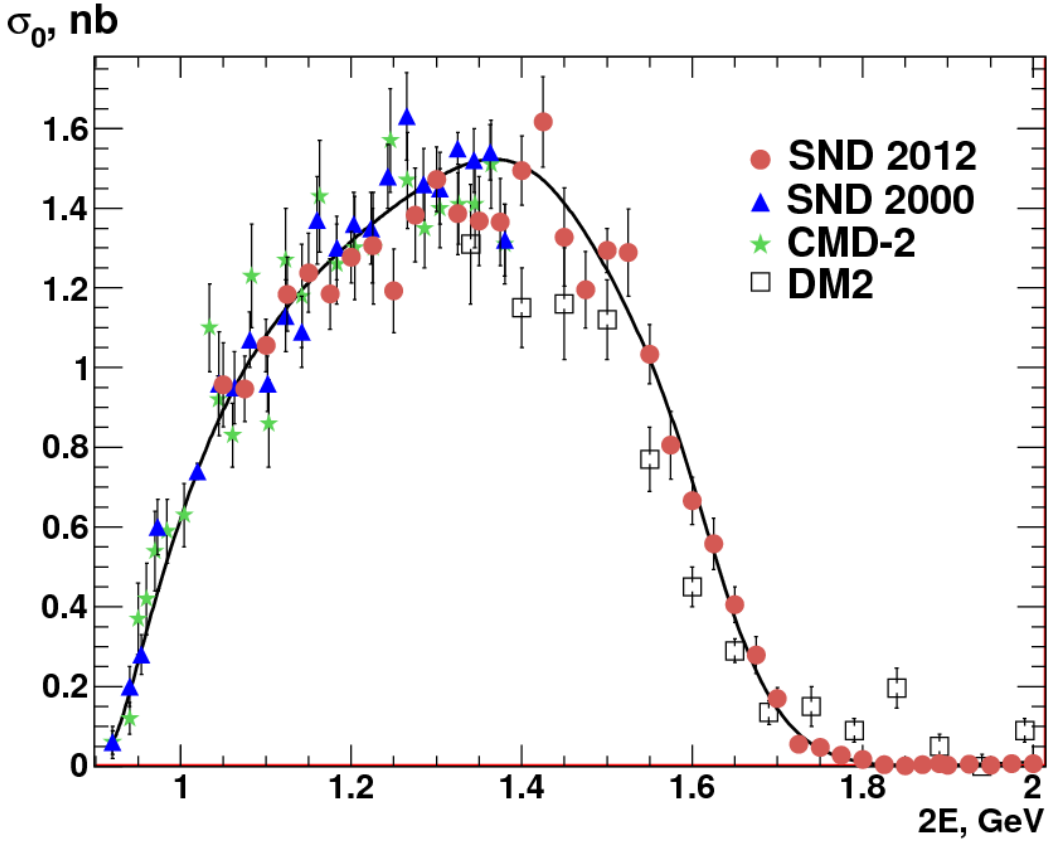
A ρ^0 is always present, $a_1^{\pm}(1260)\pi^{\mp}(a_2^{\pm}(1320)\pi^{\mp})$ significant, at higher $\sqrt{s}$ other mechanisms like $\rho^0 f_0$, $\rho^0 f_2(1270)$ appear

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



The new SND data lower than BaBar?

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

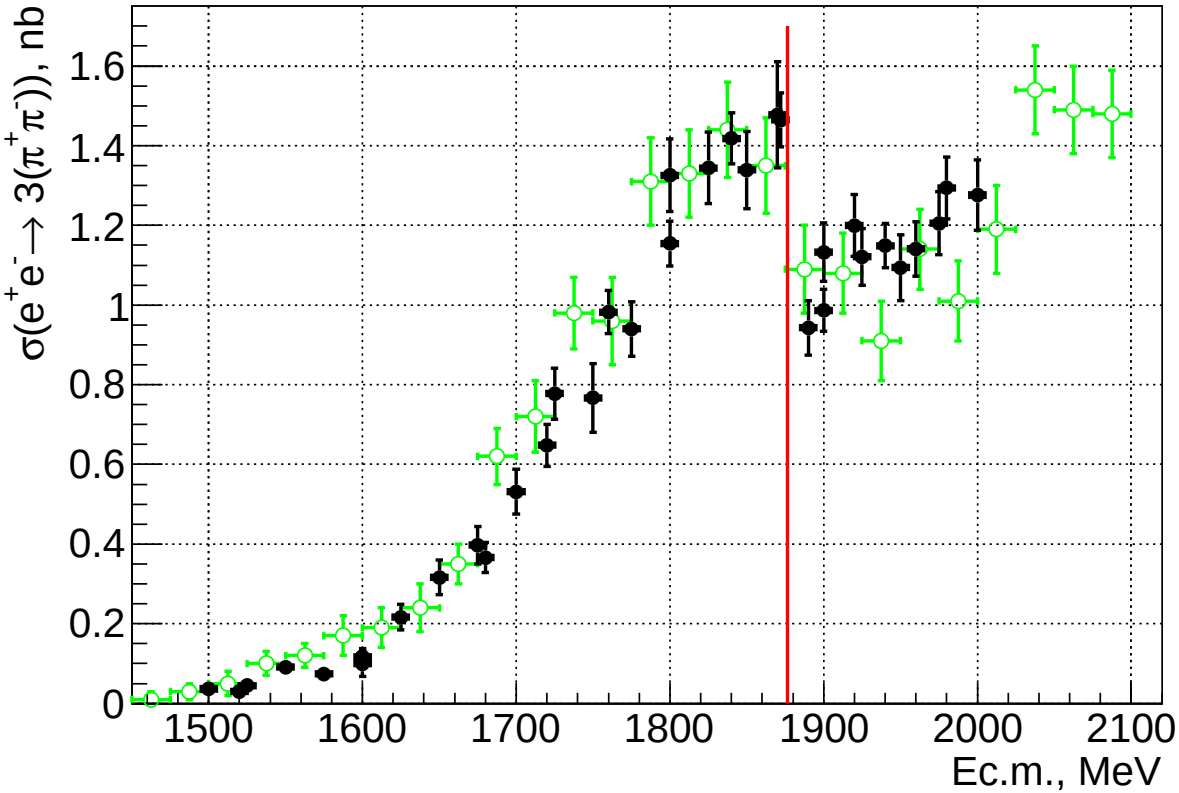
$e^+e^- \to 3\pi^+3\pi^-$ at CMD-3 – II

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

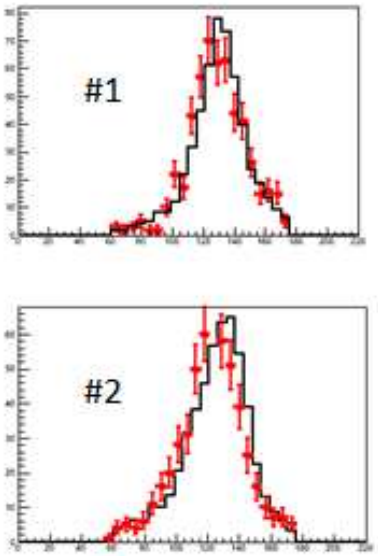


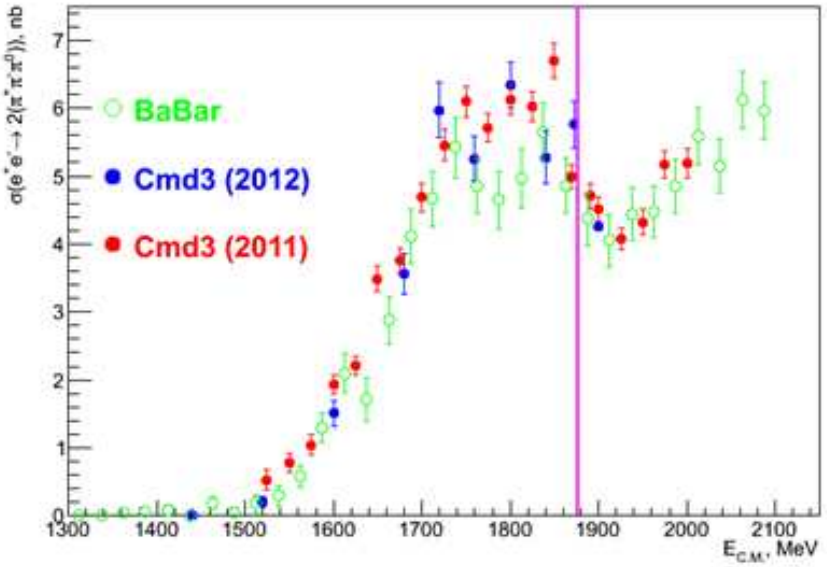
The dip structure near $N\bar{N}$ threshold is confirmed

Phys. Lett. B 723 (2013)82

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

We have relatively clean selection of 2 and 1 π^0 in addition to four charged tracks



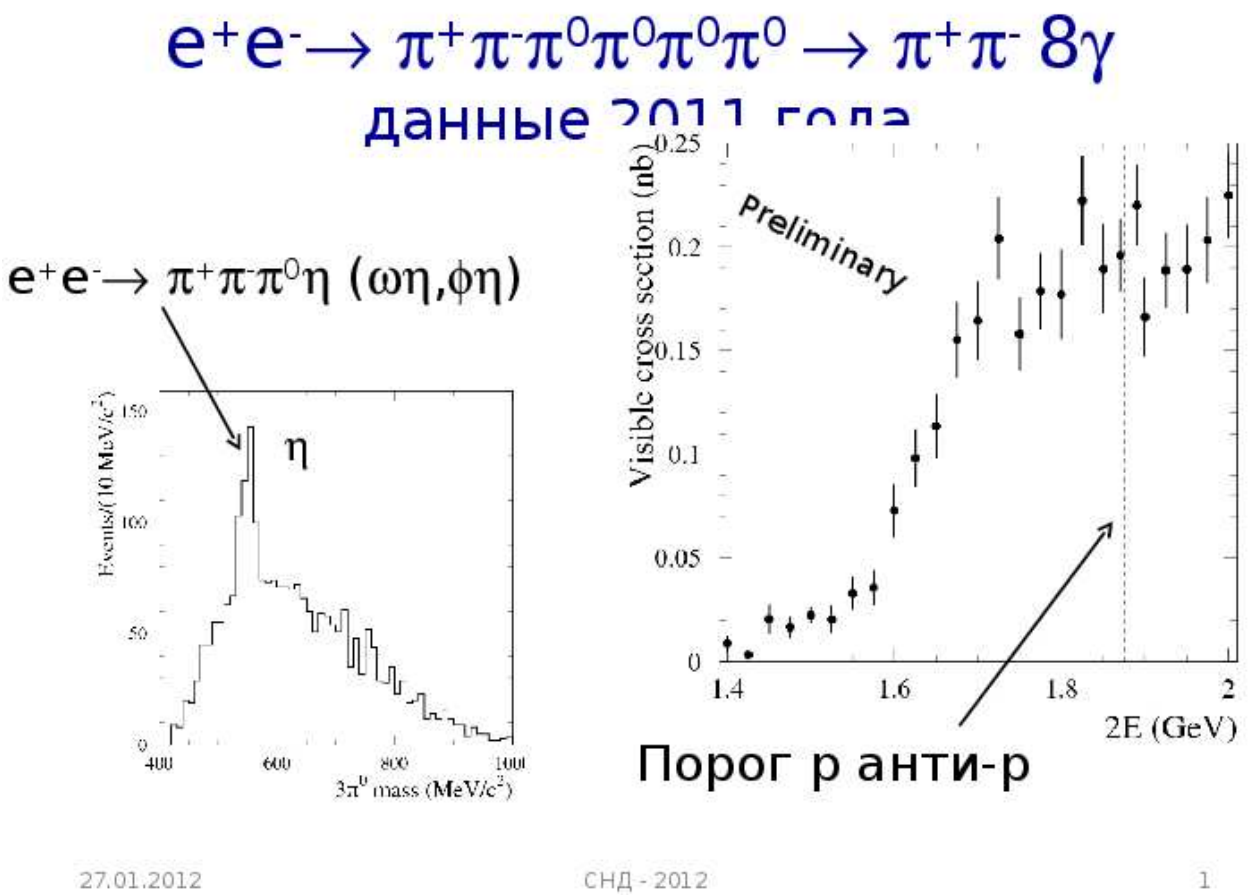


2011 – all reconstructed or a $\pi^\pm$ or π^0 lost, 2012 – all reconstructed

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

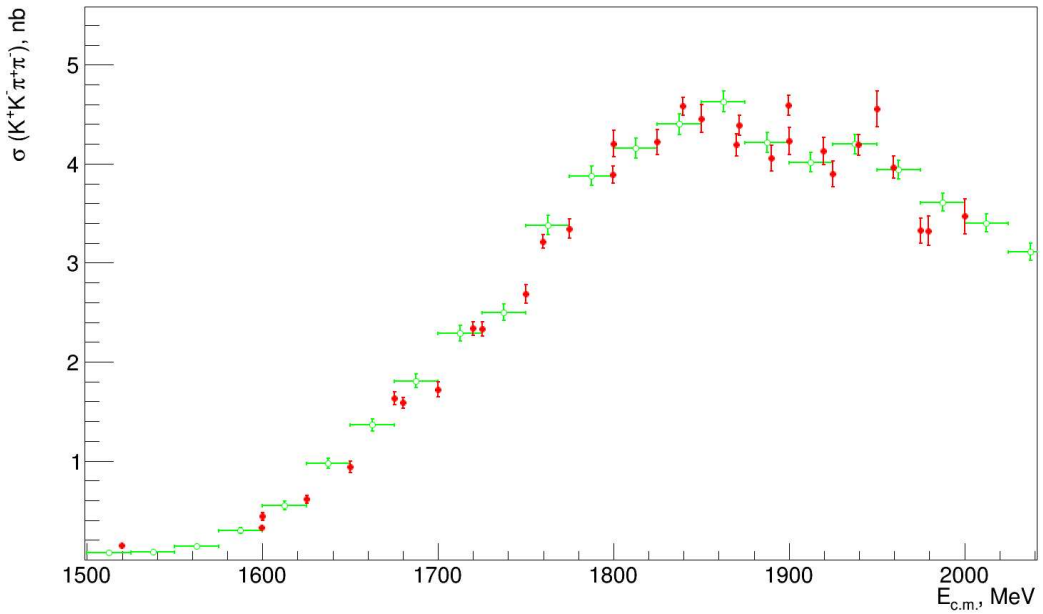
$\omega\pi^+\pi^-\pi^0$, $\eta\pi^+\pi^-\pi^0$ already selected

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



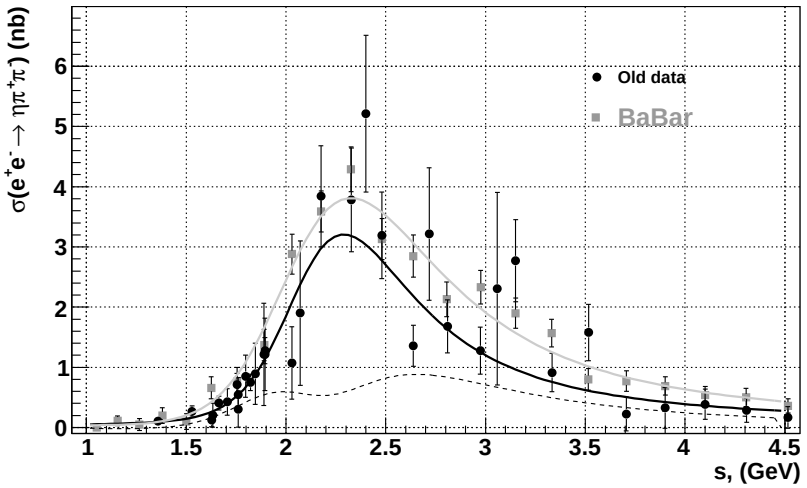
First ever measurement of this final state, very important for dynamics studies

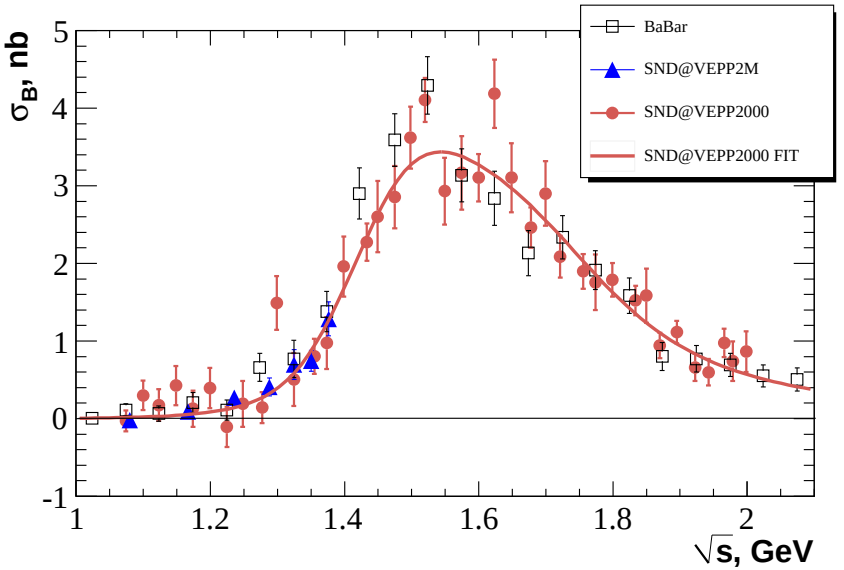
$e^+e^- \to K^+K^-\pi^+\pi^-$ at CMD-3



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

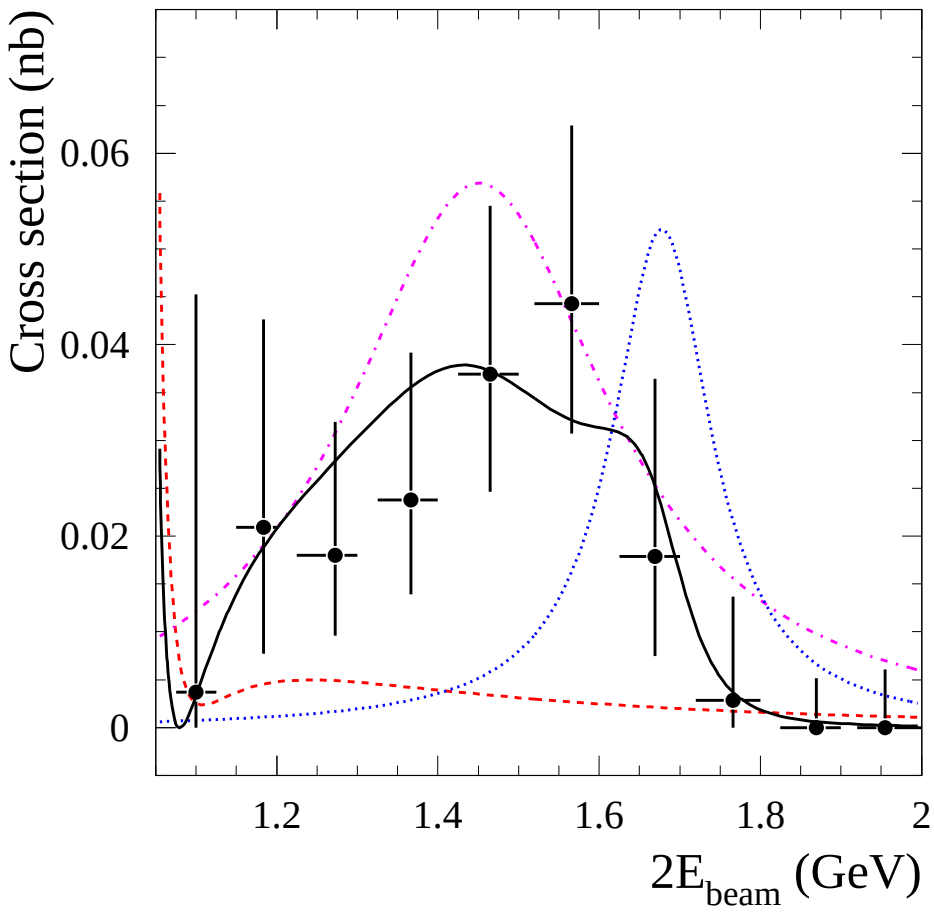
$e^+e^- \to \eta\pi^+\pi^-$ at SND





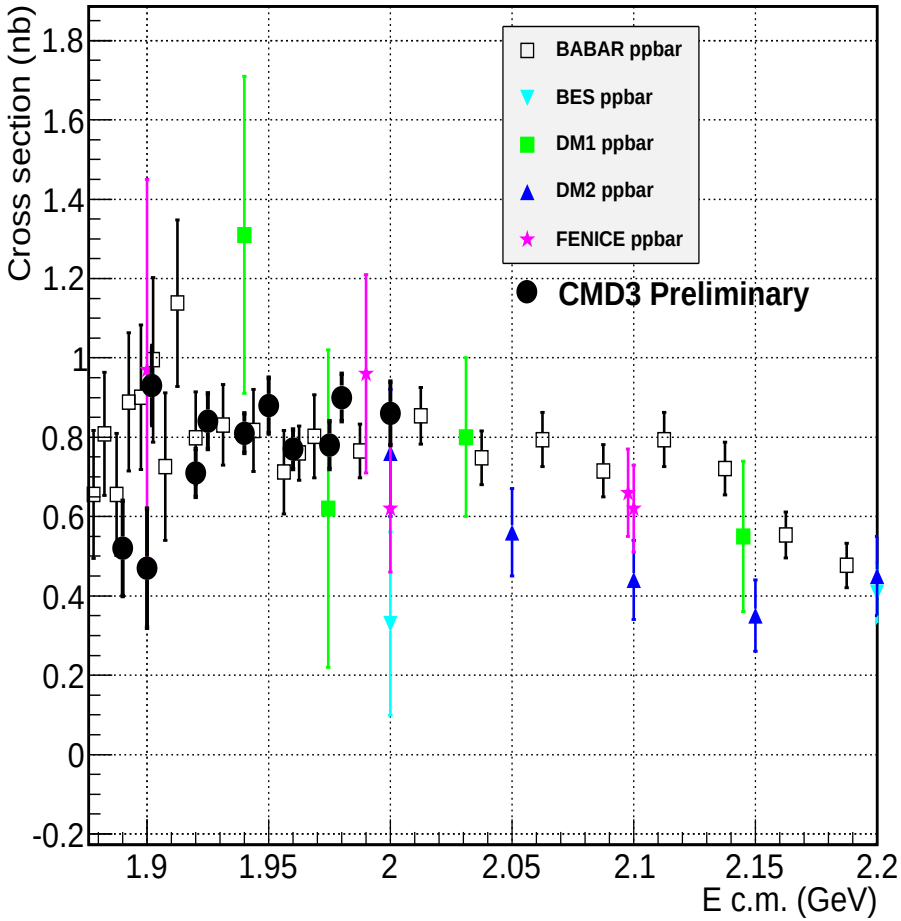
BaBar data higher than old data by $\sim 15\%$, not confirmed by new SND data?

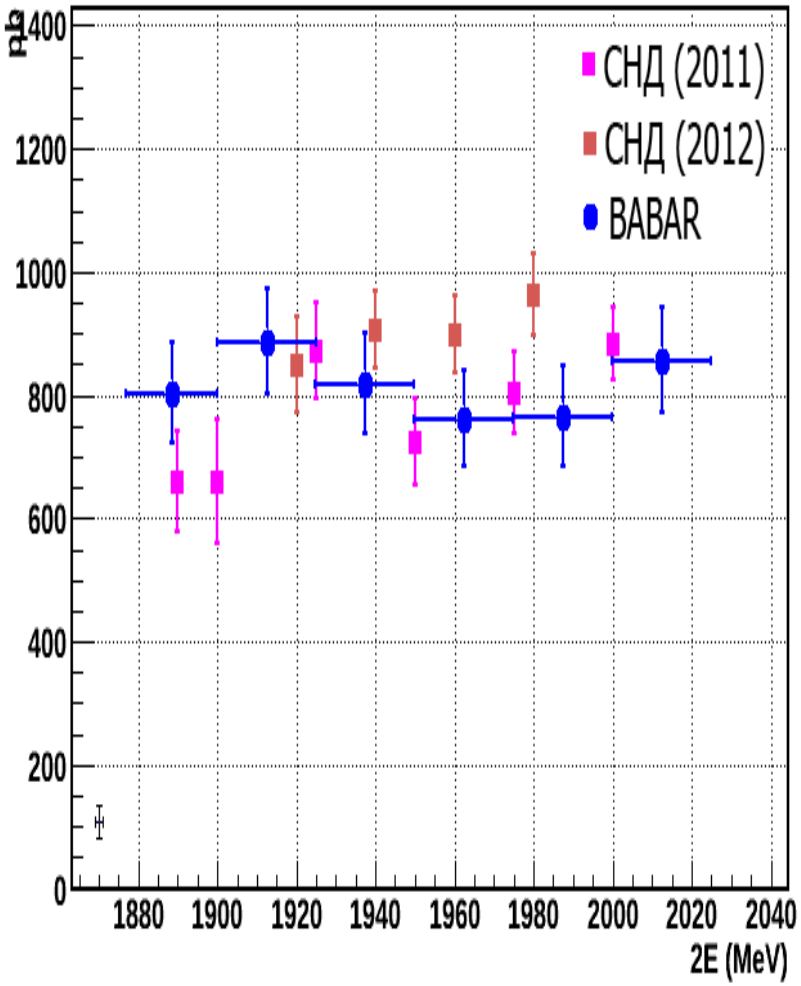
$e^+e^- \to \eta\gamma$ at SND



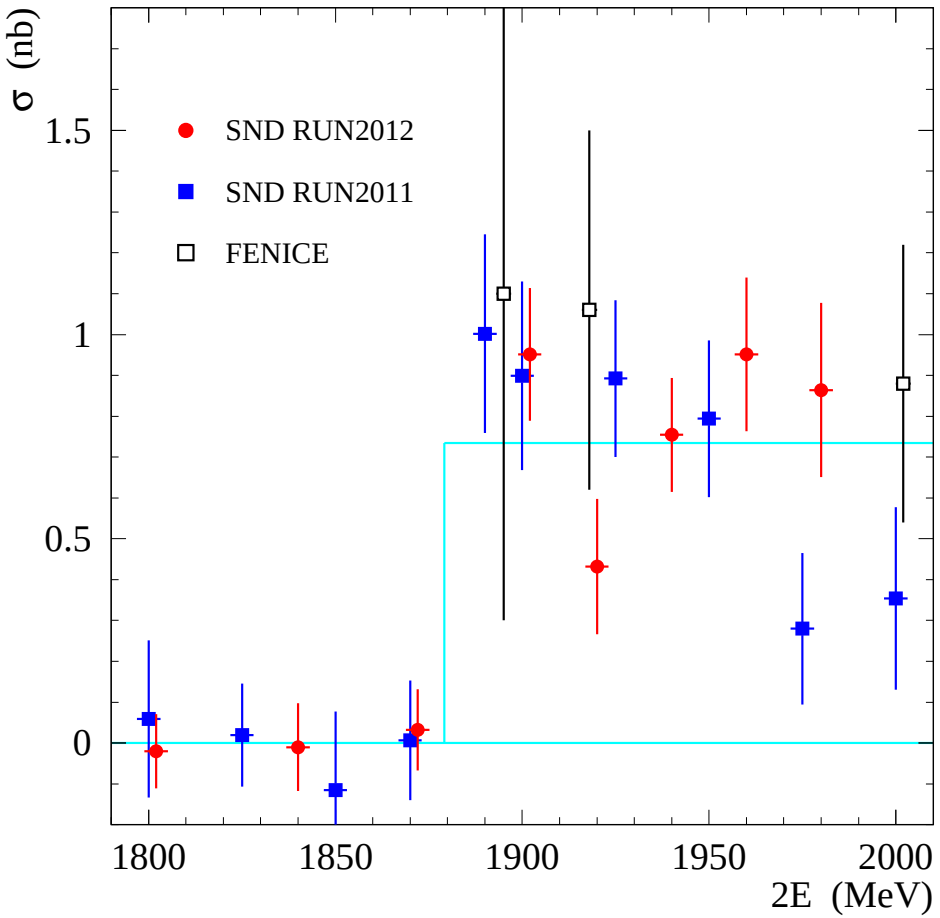
The first measurement of radiative decays above 1.4 GeV

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



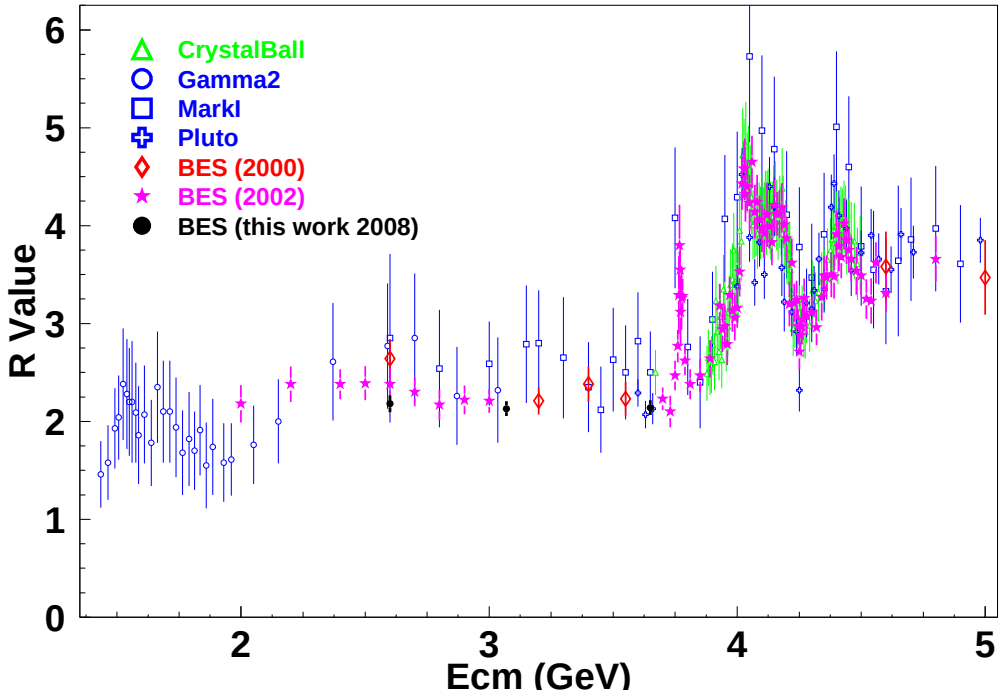


$e^+e^- \to n\bar{n}$ at SND



The first and more precise measurement after FENICE

R Measurement Below 5 GeV

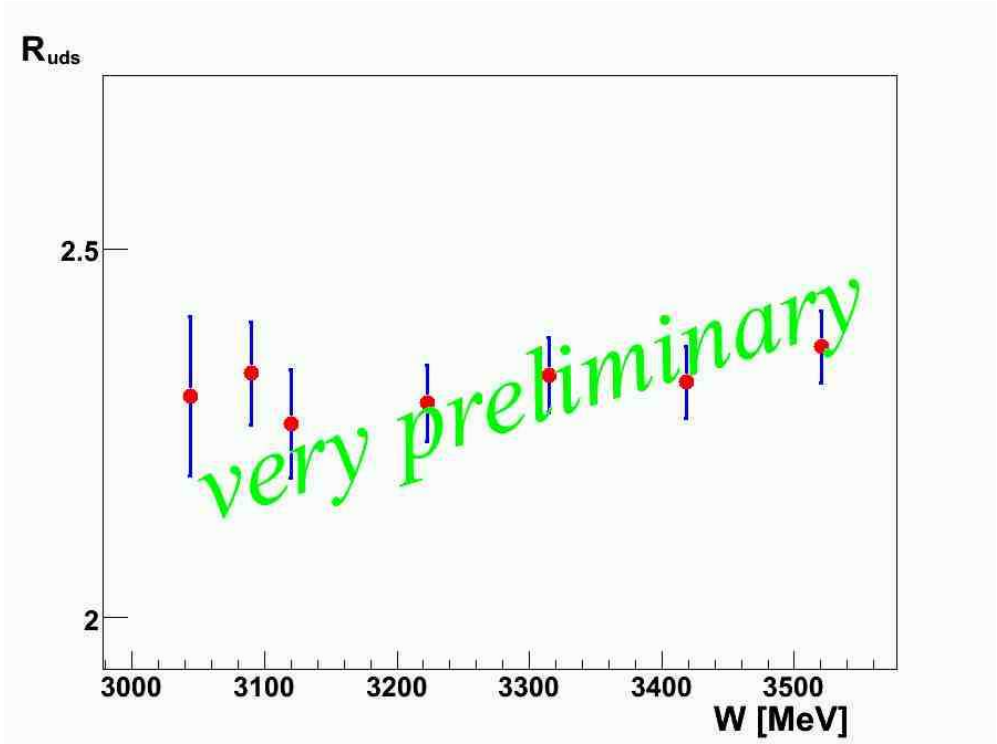


Dominated by BES: stat. errors (3-5)%, syst. errors (5-8)%

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

R Measurement at KEDR from 3.1 to 3.7 GeV



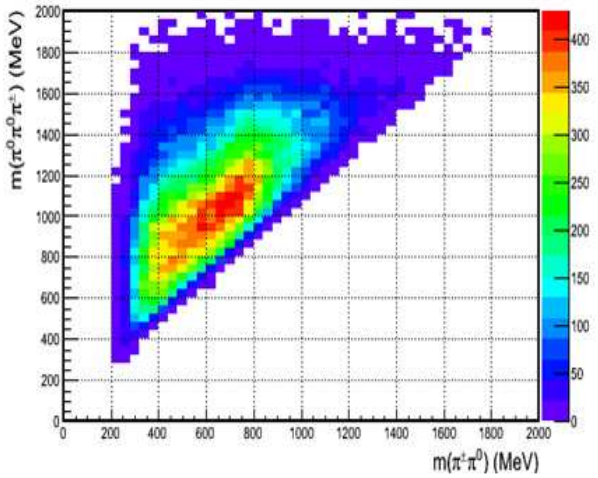
2k events per point, aimed at 4% systematics

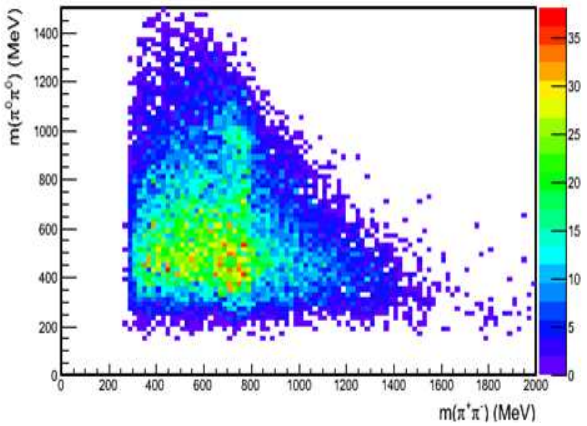
Conclusions

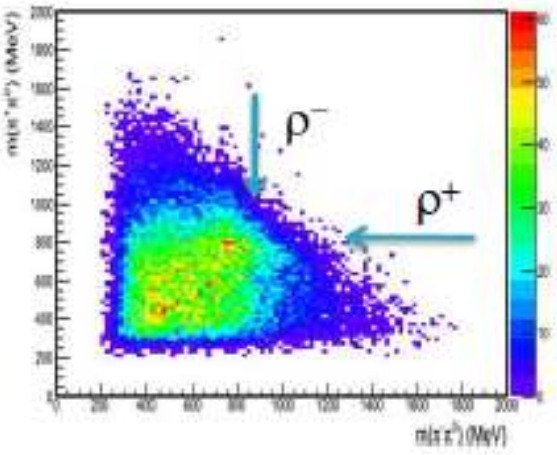
- VEPP-2000 is running smoothly with CMD-3 and SND
- New channels with many neutrals observed
- CMD-3 and SND at VEPP-2000 will provide high accuracy, comparable or better than ISR measurements, the tentative goals are 0.5% for $\pi^+\pi^-$ and 3% for multibody modes
- Below 2 GeV progress (a factor of 2-3) expected in exclusive σ's due to scans in Novosibirsk and ISR from KLOE, BaBar, Belle, BES3 and Belle2
- Above 2 GeV R measurements with 3-4% accuracy at BES3 and KEDR
- More precise measurements of Γ_{ee} for the narrow ψ and Υ at KEDR and Belle
- Various high-statistics experiments will substantially improve the accuracy of vacuum polarization calculations for $(g_\mu - 2)/2$

Back-up

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

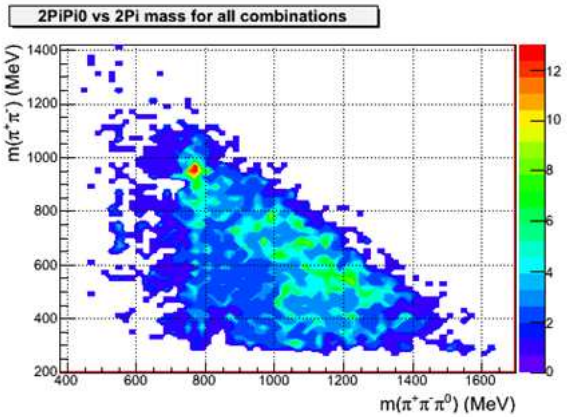


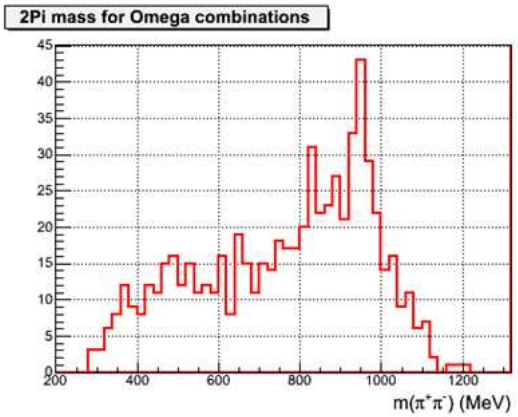


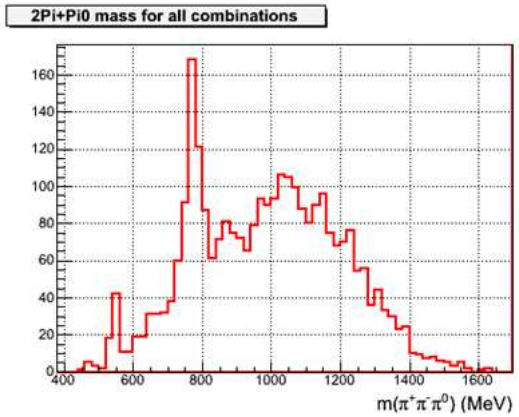


$a_1^{\pm}(1260)\pi^{\mp}$, $\rho^0 f_0$ and $\rho^+\rho^-$ intermediate states seen,
other mechanisms possible: $a_2^{\pm}(1320)\pi^{\mp}$, $\pi^{\pm}(1300)\pi^{\mp}$, ...

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

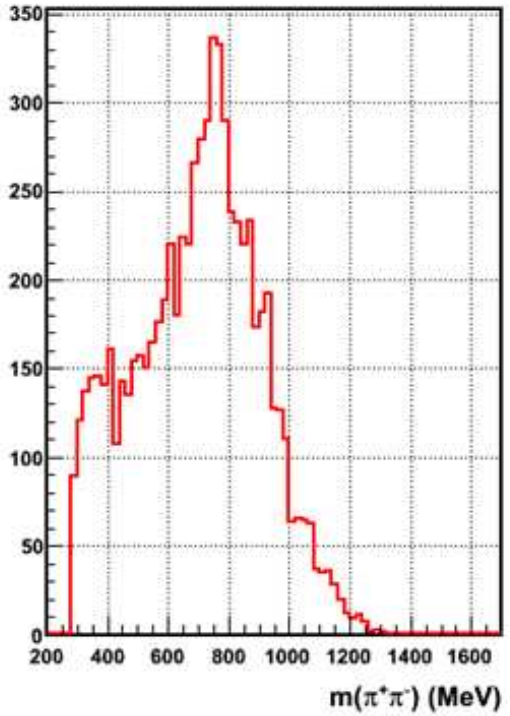


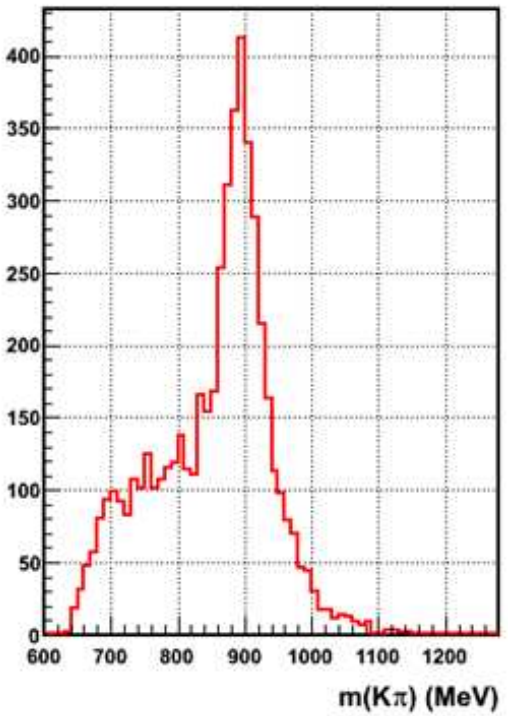




Various mechanisms seen: $\omega\pi^+\pi^-$, $\eta\pi^+\pi^-$, $\omega f_0(980)$

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





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