Recent Results from VEPP-2000: Data and Generators

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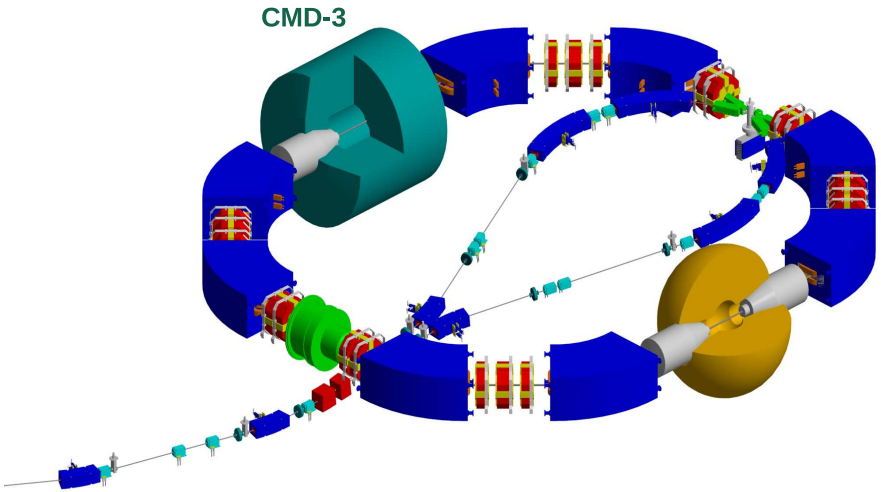
Outline

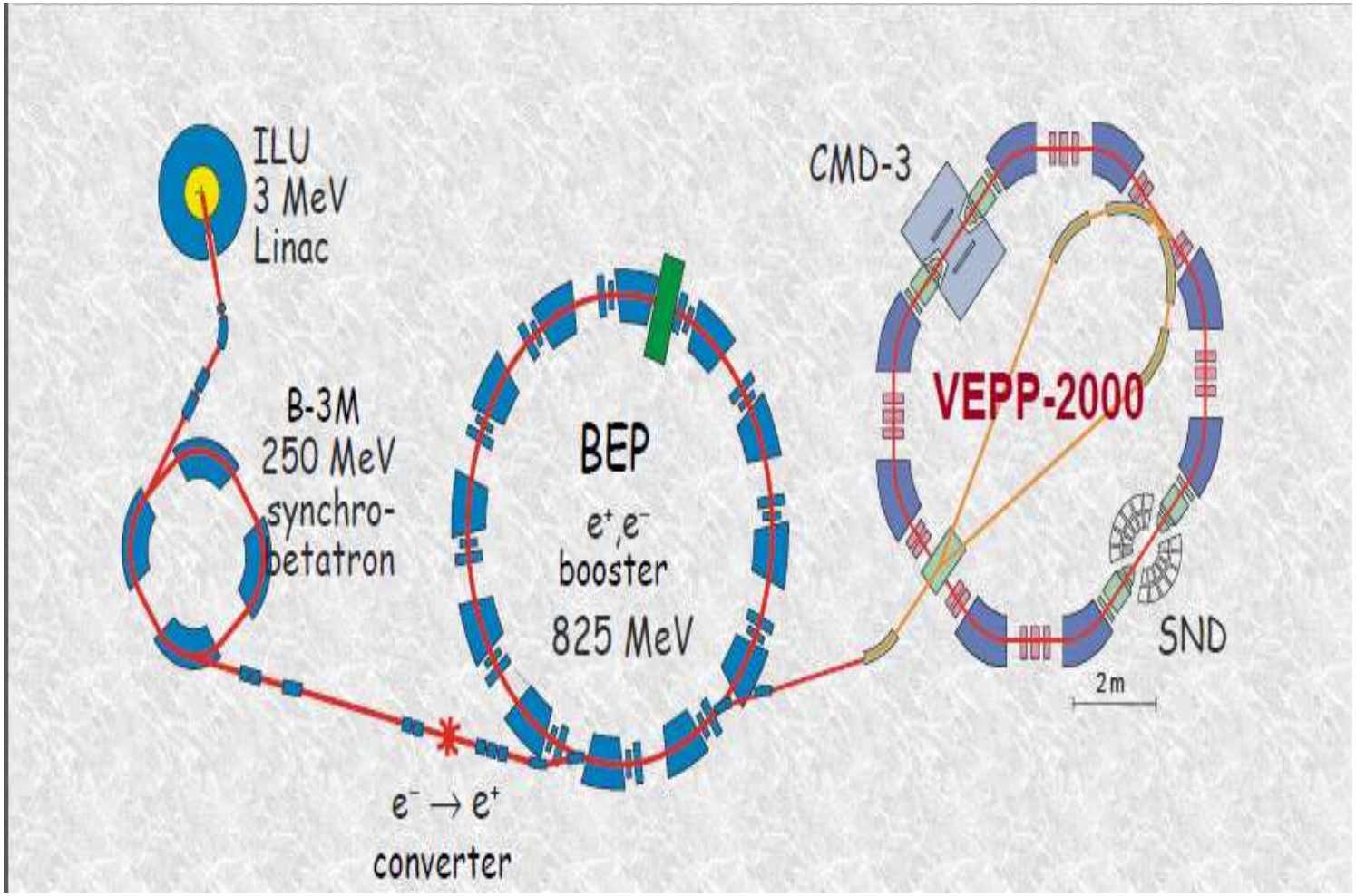
1. VEPP-2000
2. Recent results from CMD-3 and SND
3. MC Generators
4. Conclusions

VEPP-2000 – I

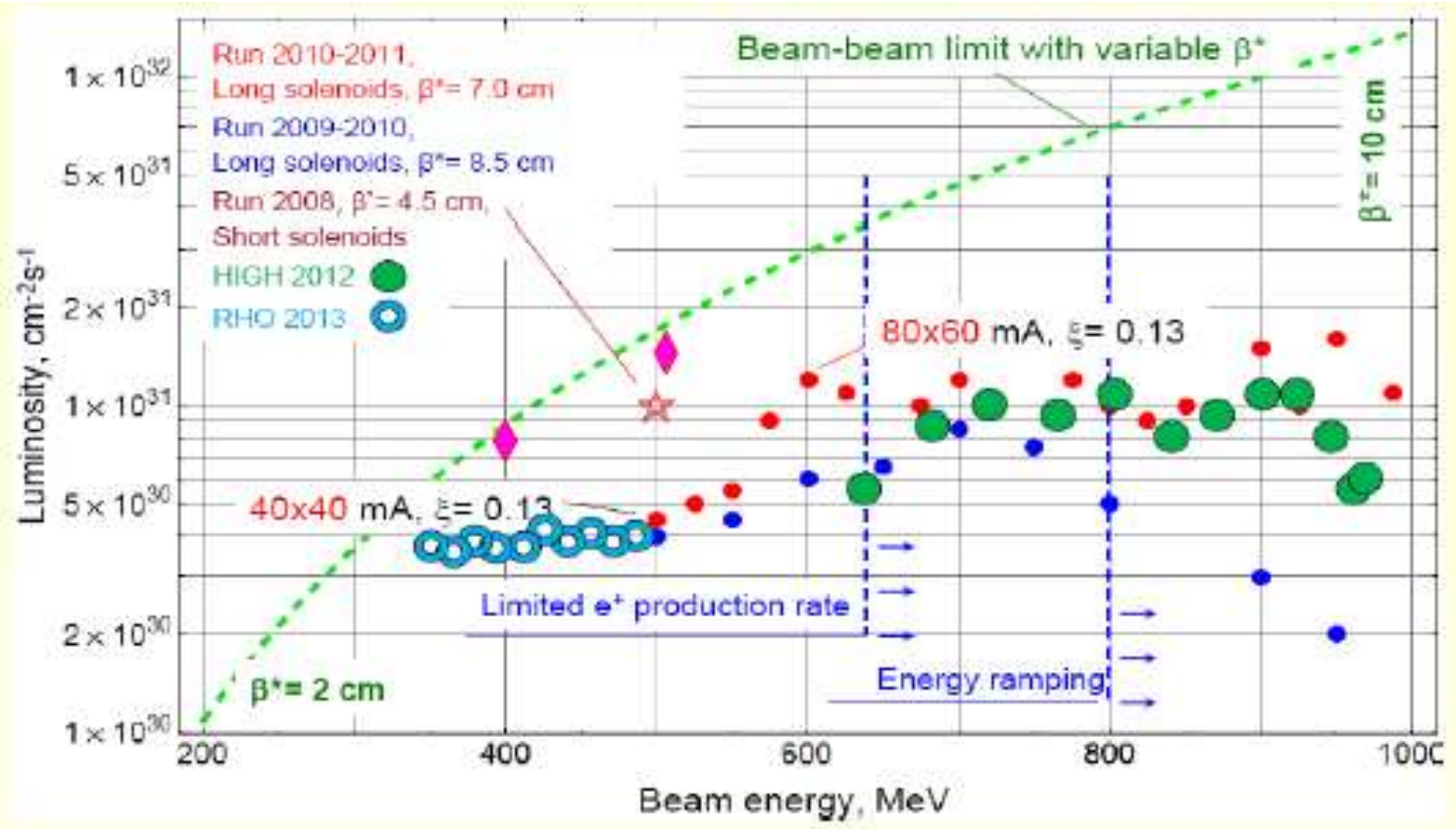


Collider	Operation	$\sqrt{s}$, MeV	$\mathcal{L}, 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
VEPP-2M	1975-2000	[360,1400]	3
VEPP-2000	2010-	$[2m_\pi, 2000]$	100

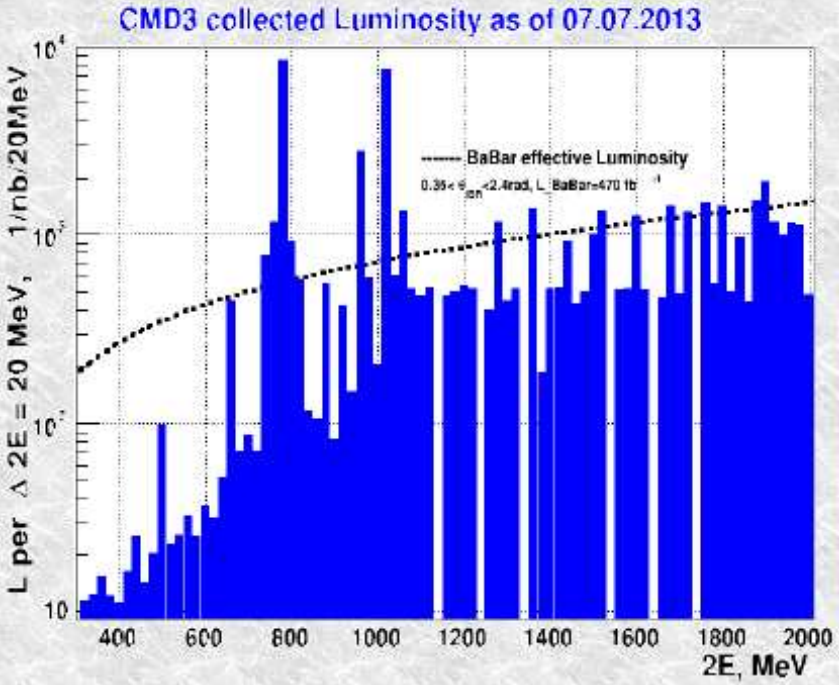
VEPP-2000 – II


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

VEPP-2000 – III



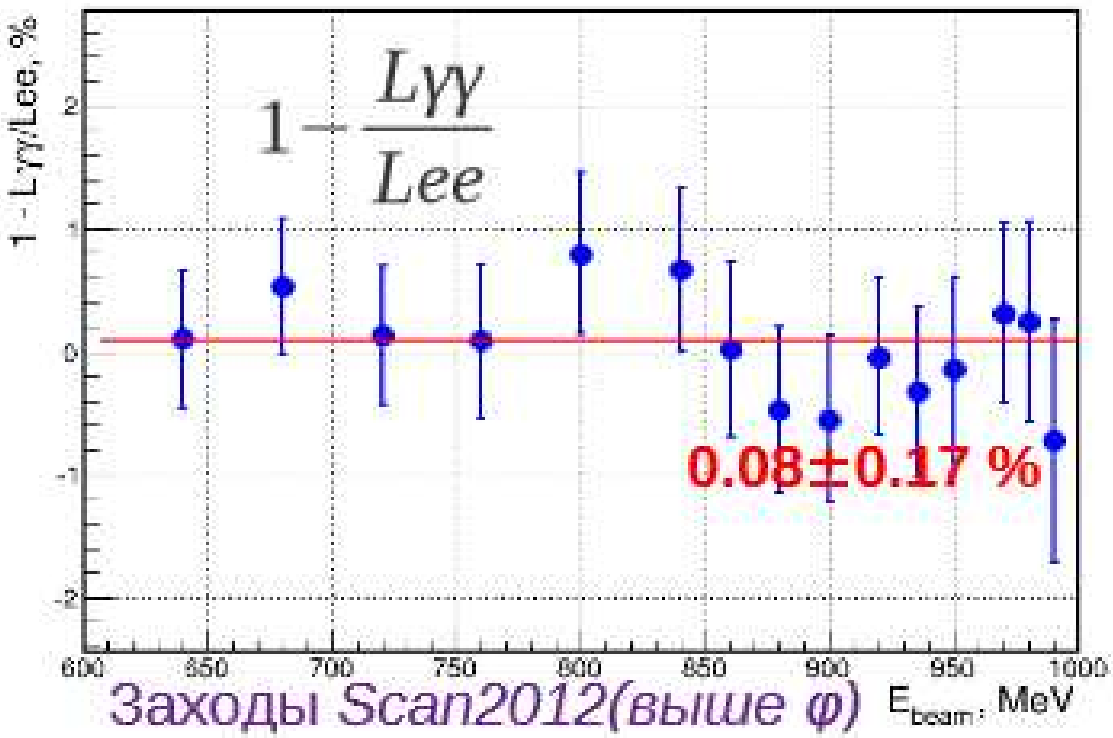
Data Taking at VEPP-2000



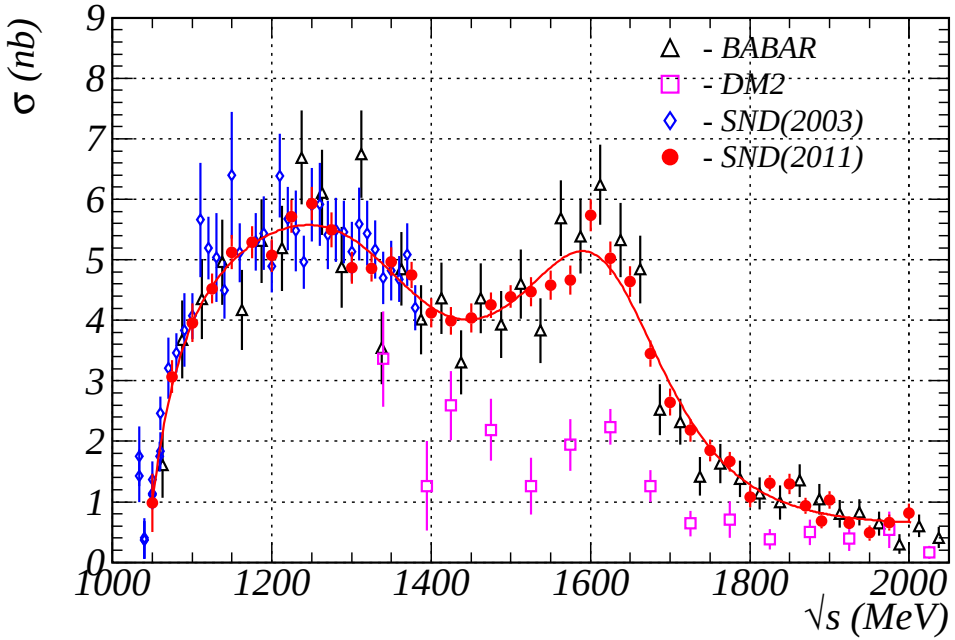
Collected L ~ 60 pb^{-1} per detector

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

Luminosity Measurements at CMD-3

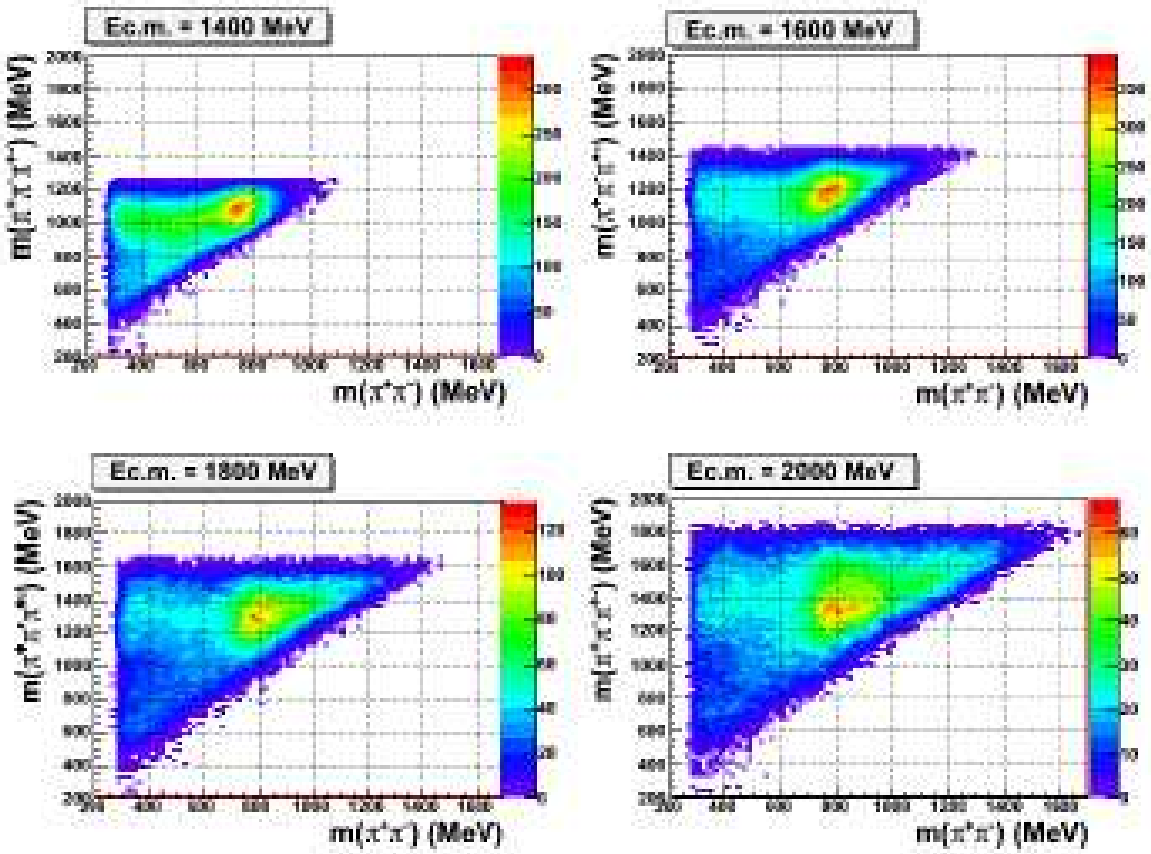


$e^+e^- \to \pi^+\pi^-\pi^0$ at SND



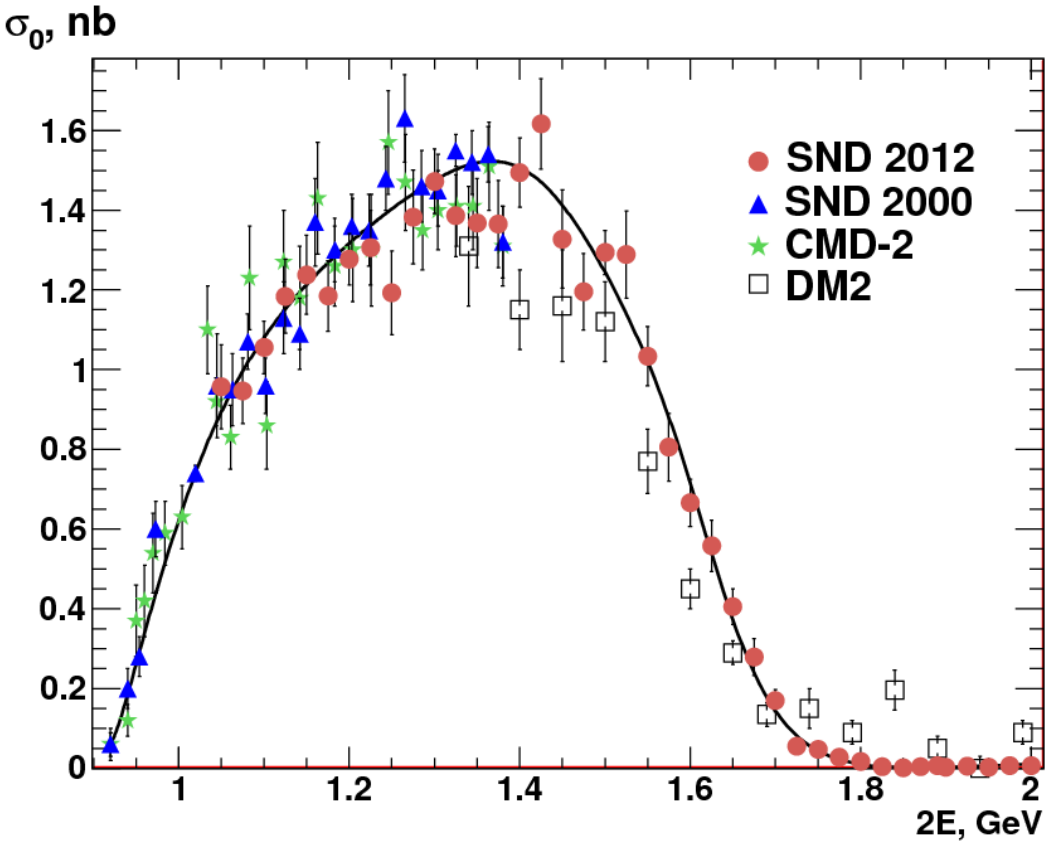
It's interesting to disentangle the $\rho^{(\prime)}\pi$ and direct 3π modes,
currently the $\rho\pi$ mechanism only is assumed
Determination of the $\omega^{\prime}$, $\omega^{\prime\prime}$ parameters awaits $\omega\pi\pi$, ...

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

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

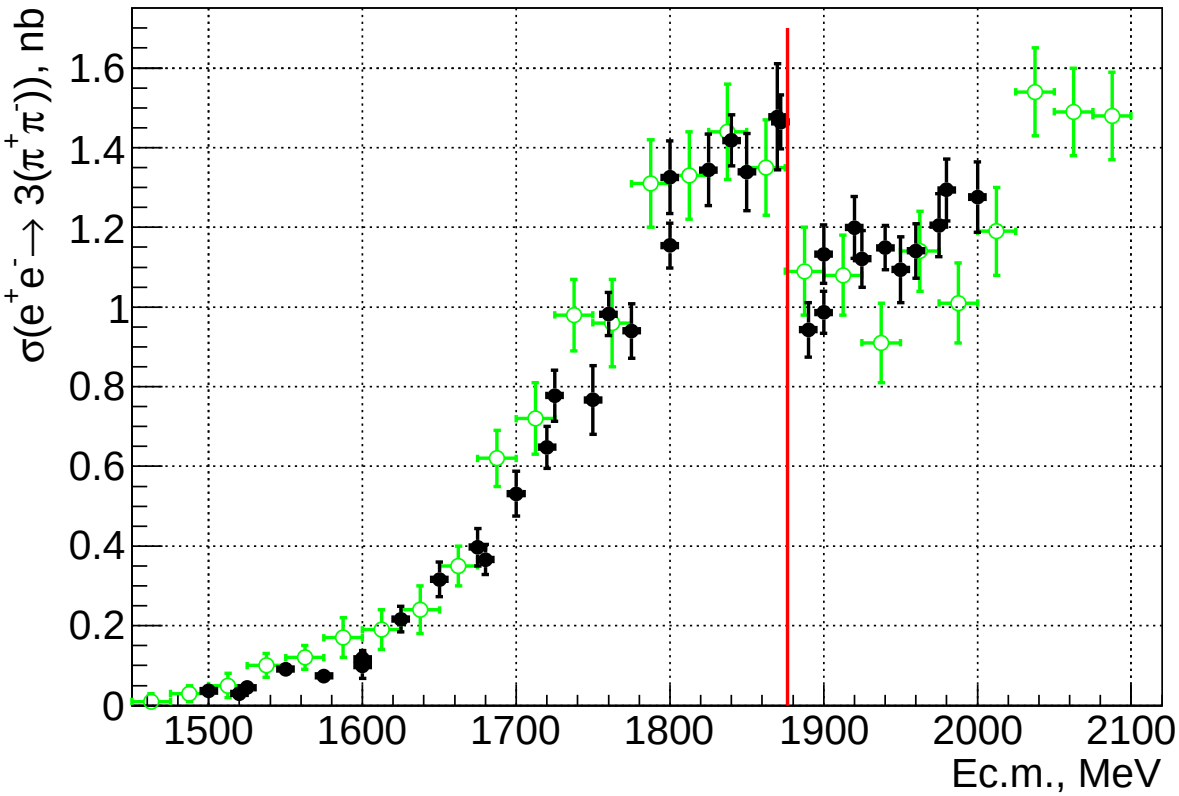
$e^+e^- \to 3\pi^+3\pi^-$ at CMD-3 – II

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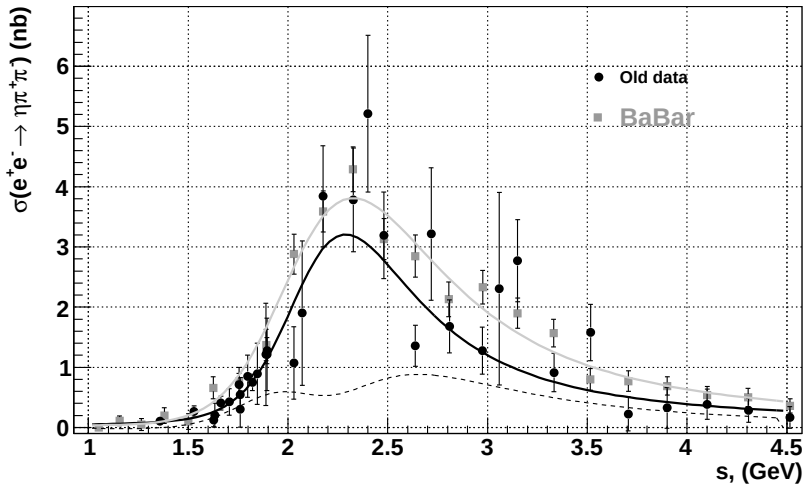
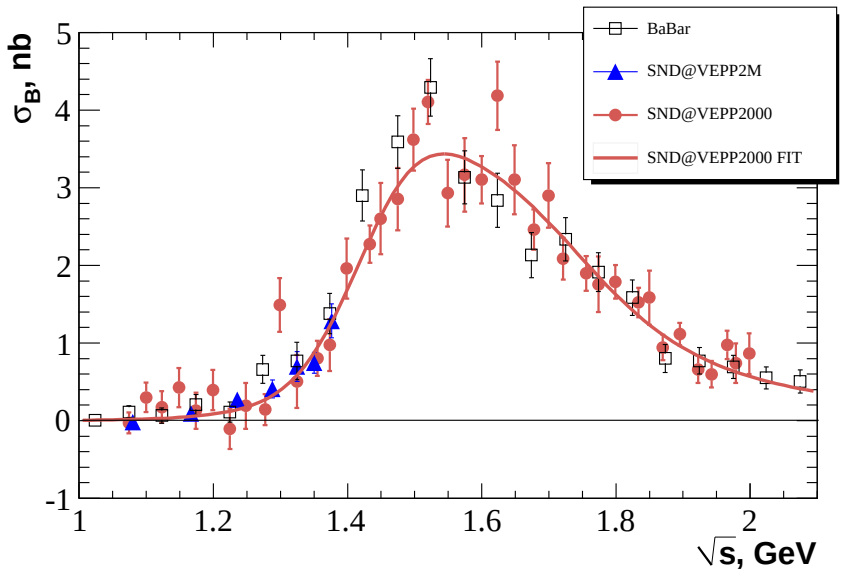
$e^+e^- \to \eta\pi^+\pi^-$ at SND



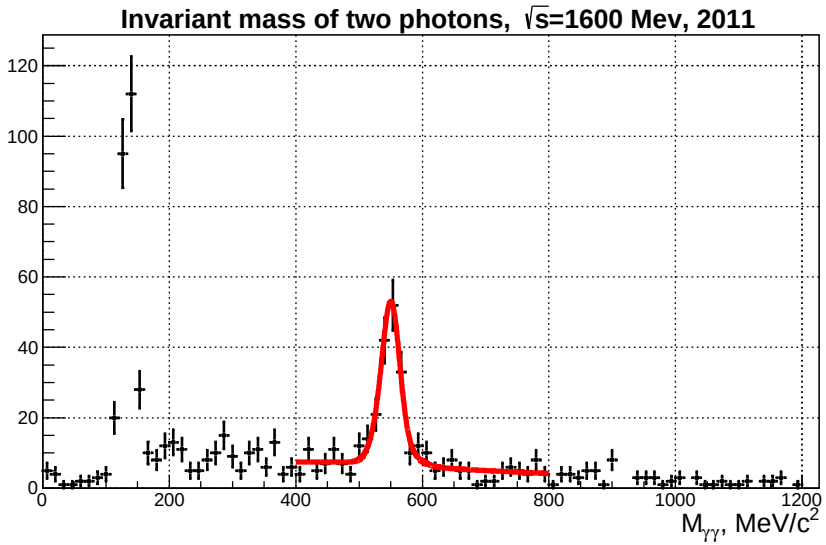


BaBar data higher than old data by $\sim 15\%$, not confirmed by new SND data?

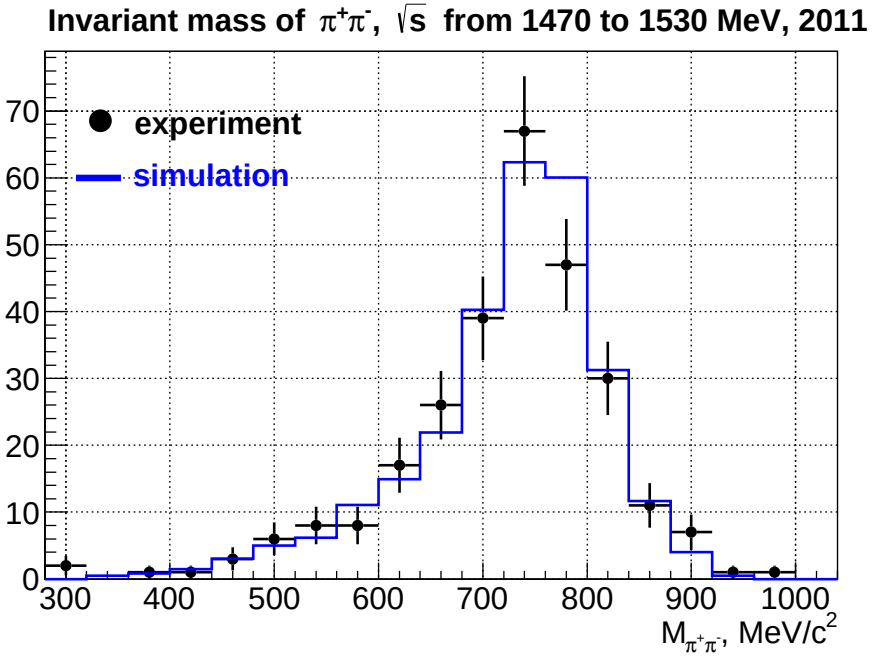
$e^+e^- \to \eta\pi^+\pi^-$ at CMD-3 – I

- CMD studied $e^+e^- \to \eta\pi^+\pi^-$ in 2 decay modes: $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$
- The $\pi^+\pi^-$ mass spectrum agrees with the ρ,
  but a search for a non-$\eta\rho$ contribution is in order
- A search for a possible D-wave $\eta\rho$ needed
- A CVC test by comparing the $\eta\pi^-\pi^0$ mass spectrum in τ^- decays with the energy dependence of $\sigma(e^+e^- \to \eta\pi^+\pi^-)$ needed
- A fit of the energy dependence of $\sigma(e^+e^- \to \eta\pi^+\pi^-)$ will determine the parameters of the $\rho(1450)$, $\rho(1700)$ and their interference

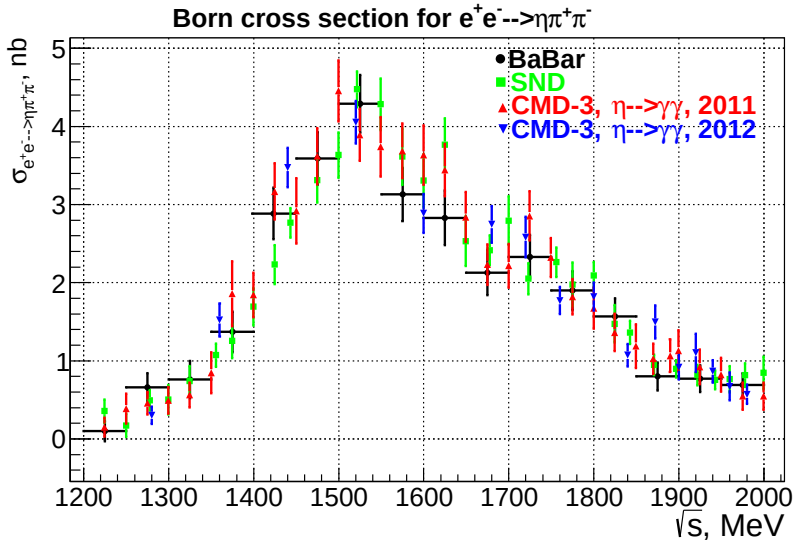
$e^+e^- \to \eta\pi^+\pi^-$ at CMD-3 – II

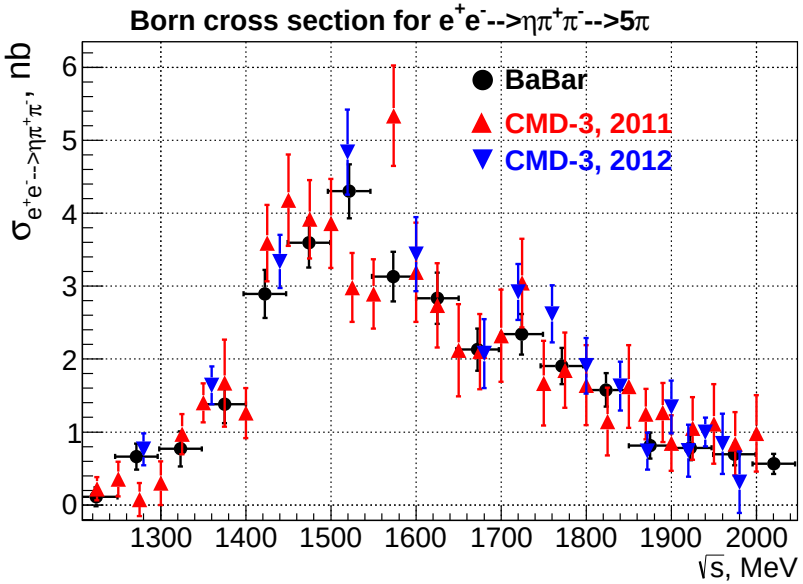


$e^+e^- \to \eta\pi^+\pi^-$ at CMD-3 – III



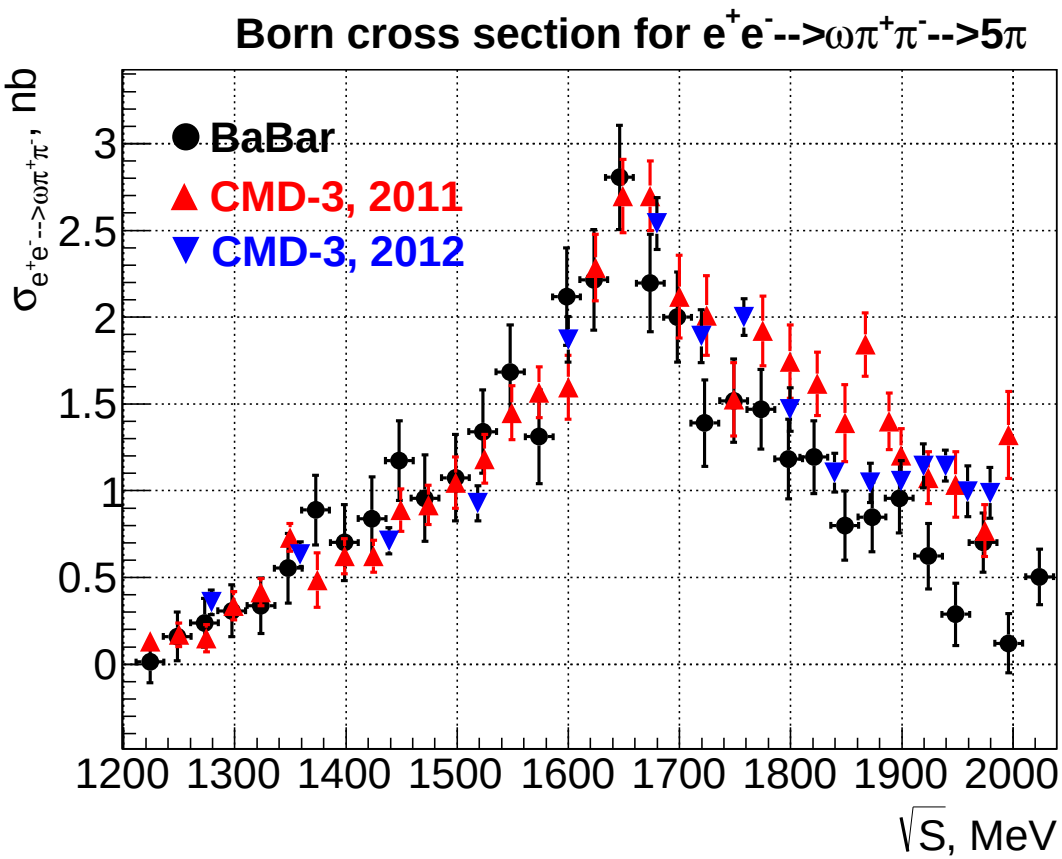
$e^+e^- \to \eta\pi^+\pi^-$ at CMD-3 – IV



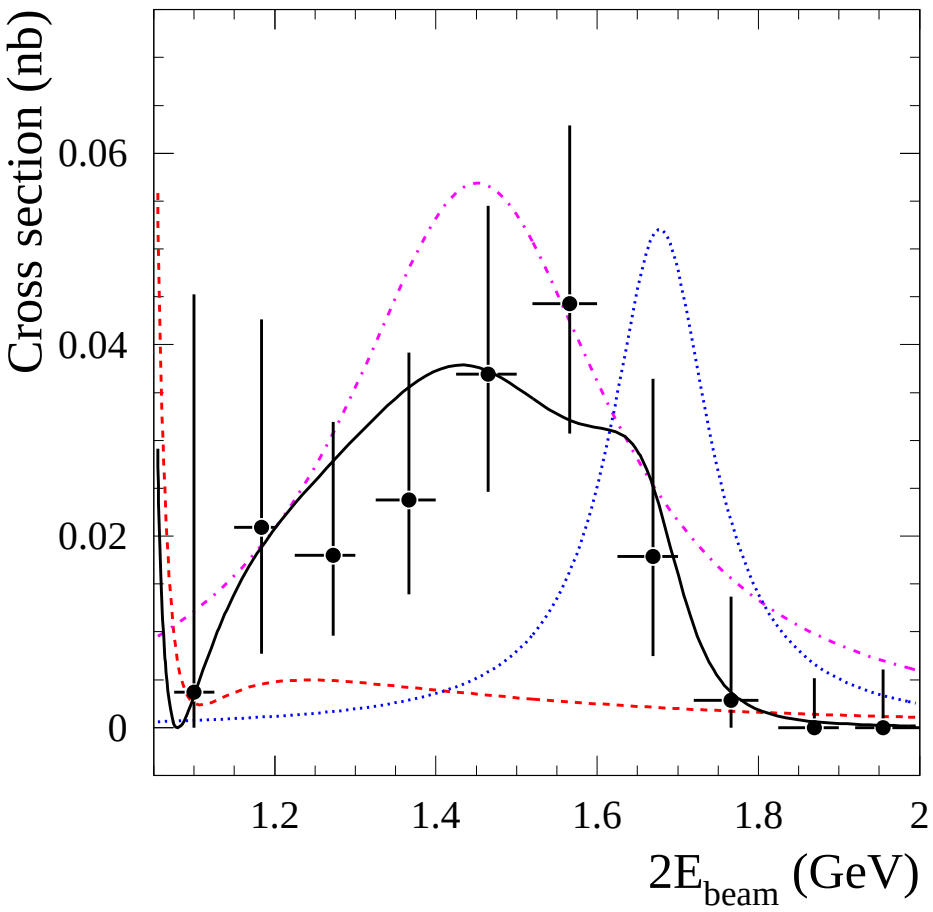


$e^+e^- \to \omega\pi^+\pi^-$ at CMD-3

3π mass spectra show η and ω signals



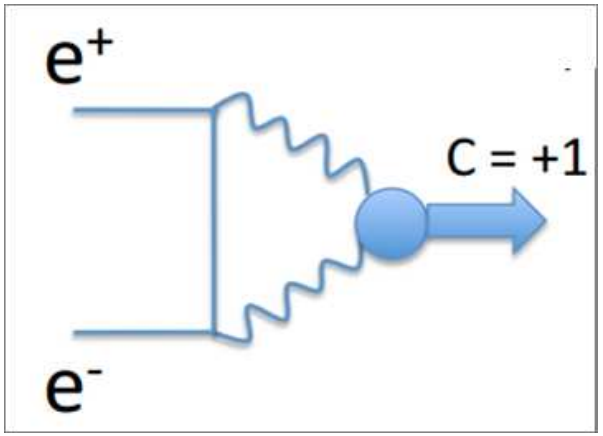
$e^+e^- \to \eta\gamma$ at SND



The first measurement of radiative decays above 1.4 GeV

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

Direct production of C-even resonances in e^+e^- collisions is possible via a $\gamma\gamma$ intermediate state.



The unitarity bound assuming 2 real photons is

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

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

"Standard" mechanism via $e^+e^- \to e^+e^-P$ involves two almost real photons and provides $\Gamma(P\to\gamma\gamma)$ only

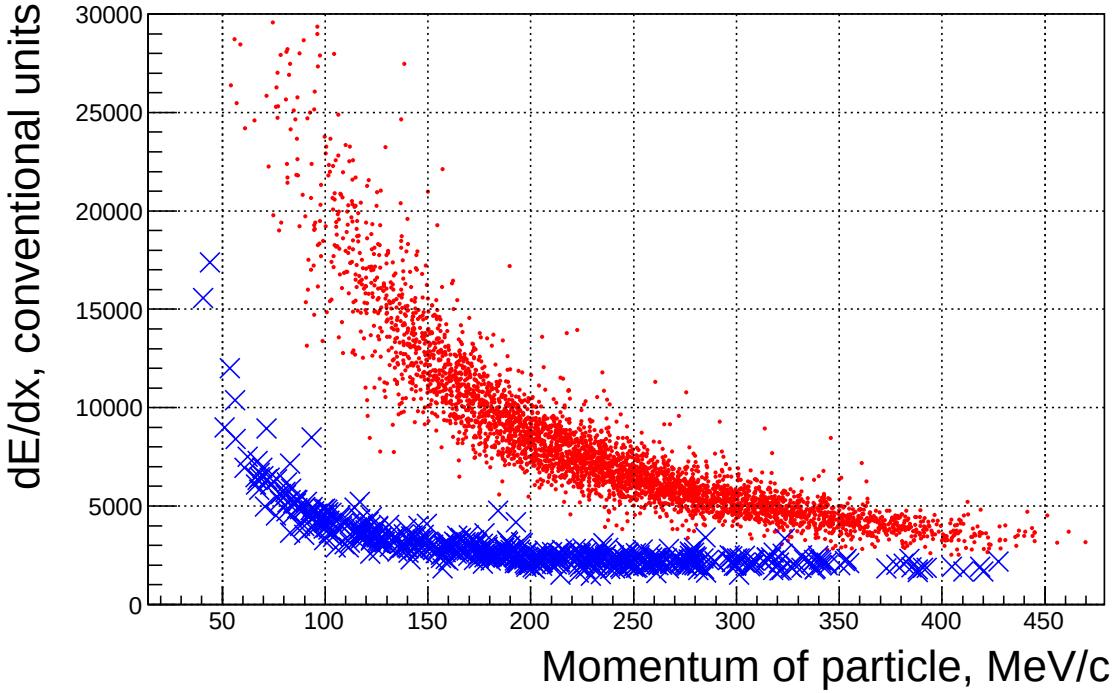
Search for $e^+e^- \to \eta'(958)$ at VEPP-2000

- CMD-3 used 2.69 pb^{-1} at $\sqrt{s} \sim m_{\eta'}$ to look for
  $e^+e^- \to \eta'(958)$, $\eta' \to \eta\pi^+\pi^-$, $\eta \to 2\gamma$,
  $\Gamma(\eta' \to e^+e^-) < 0.0024$ eV at 90%CL, Phys. Lett. B740 (2015) 273
- SND used 2.9 pb^{-1} to look for $e^+e^- \to \eta'(958)$:
  $\eta' \to \eta\pi^+\pi^-$, $\eta \to 2\gamma$, $3\pi^0$,
  $\eta' \to \eta\pi^0\pi^0$, $\eta \to 2\gamma$, $3\pi^0$, $\pi^+\pi^-\pi^0$,
  $\Gamma(\eta' \to e^+e^-) < 0.0020$ eV at 90%CL, arXiv:1504.01245
- SND combines their data with CMD-3:
  $\Gamma(\eta' \to e^+e^-) < 0.0011$ eV at 90%CL,
  $\mathcal{B}(\eta' \to e^+e^-) < 5.6 \cdot 10^{-9}$ at 90%CL
- The unitarity limit $\mathcal{B}(\eta' \to e^+e^-) > 3.75 \cdot 10^{-11}$

Search for $e^+e^- \to \eta$ at VEPP-2000

- SND used 110 nb^{-1} to look for $e^+e^- \to \eta$, $\eta \to 3\pi^0$, $\eta \to 2\gamma$, $\pi^+\pi^-\pi^0$ dominated by QED background, $\mathcal{B}(\eta \to e^+e^-) < 3 \cdot 10^{-6}$ at 90%CL, Bachelor thesis by L. Korneev
- The best limit is by HADES in Phys. Lett. B731 (2014) 265, $\mathcal{B}(\eta \to e^+e^-) < 2.3 \cdot 10^{-6}$ at 90%CL
- The unitarity limit is $\mathcal{B}(\eta \to e^+e^-) > 1.8 \cdot 10^{-9}$

Multibody Final States with Charged Kaons

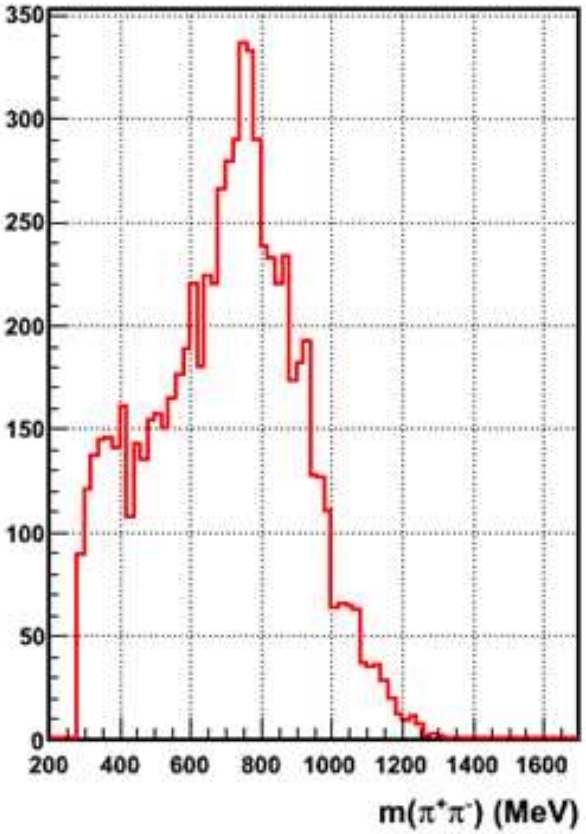


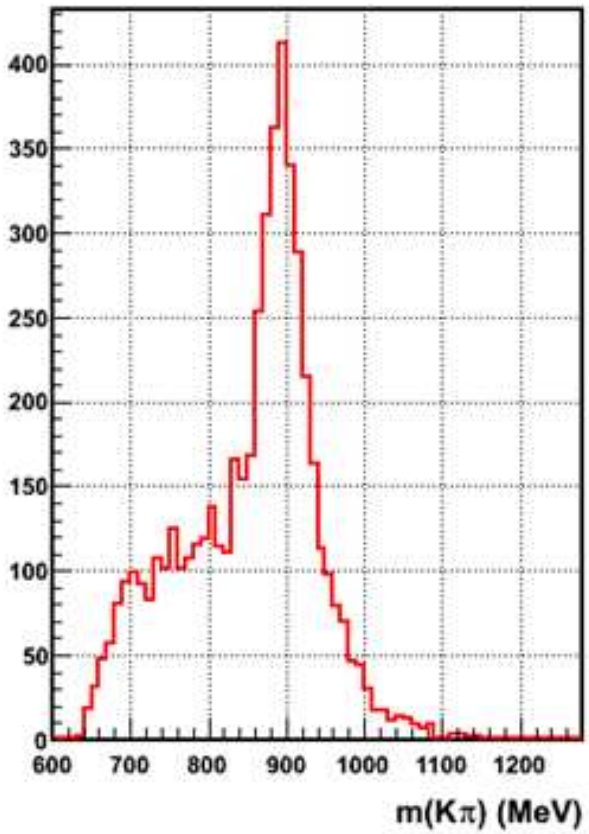
Ionization losses in DC (dE/dx) provide good K/π separation

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

- CMD-3 studied $e^+e^- \to K^+K^-\pi^+\pi^-$ with 22 pb^{-1} between 1.5 and 2 GeV
- More than 10000 4-track and 3-track events observed
- Analysis of $\pi^+\pi^-$, $K^\pm\pi^\mp$, K^+K^- invariant masses shows clear ρ^0, $K^{*0}(892)$, ϕ signals
- Many different mechanisms seen: $K_1(1270)\bar{K} \to K\bar{K}\rho$, $K^*(892)\bar{K}\pi$, $K_1(1400)\bar{K} \to K^*(892)\bar{K}\pi$, $\phi\pi^+\pi^-$

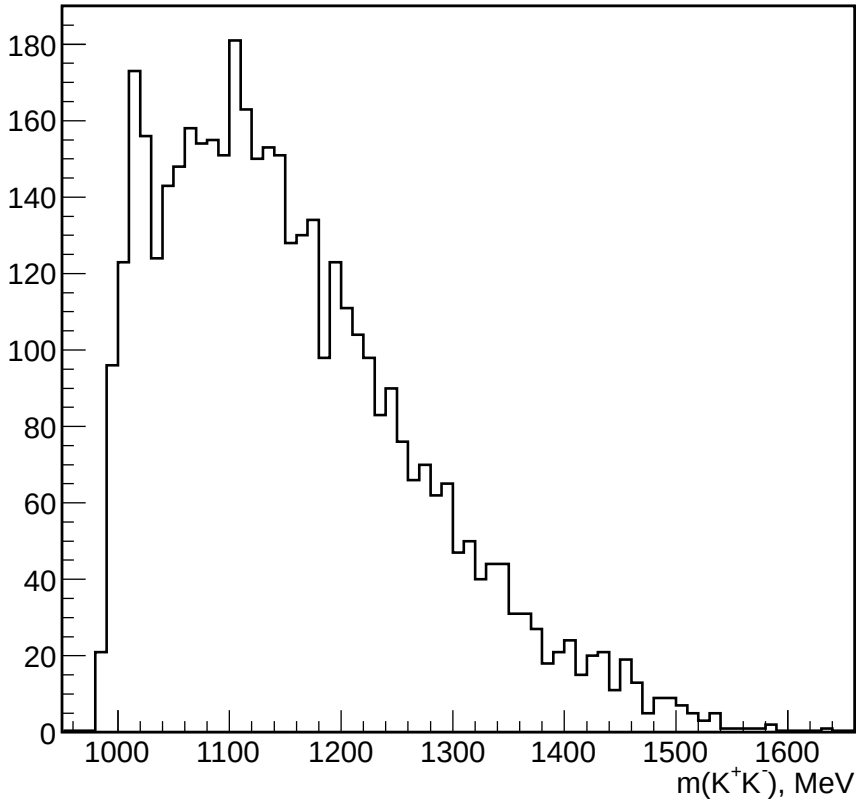
$e^+e^- \to K^+K^-\pi^+\pi^-$ at CMD-3 – II





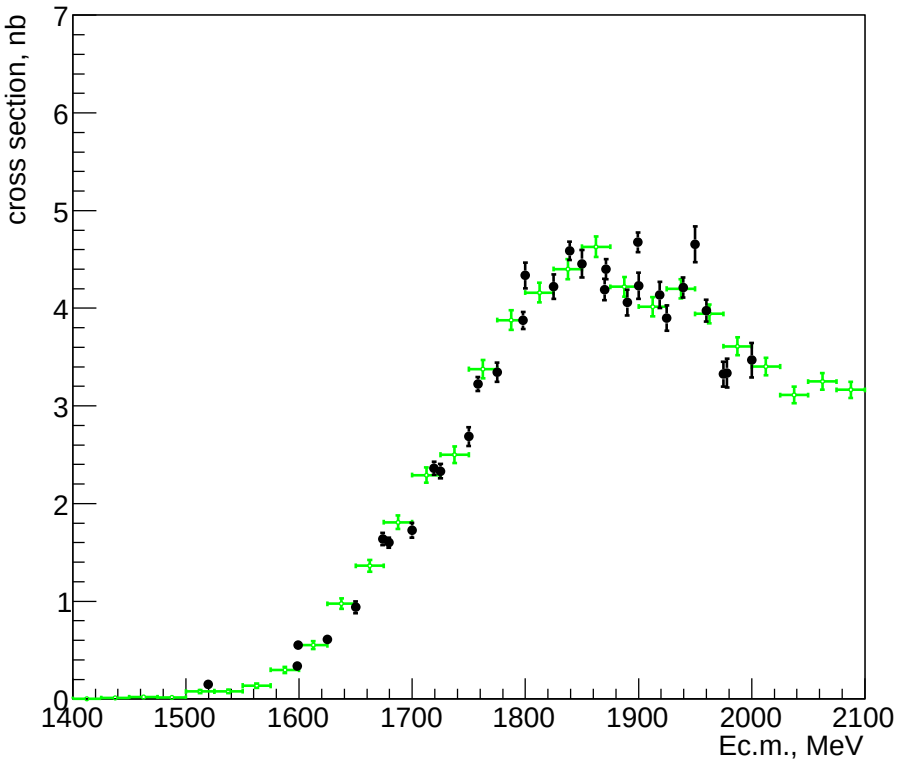
ρ^0 in $\pi^+\pi^-$ and $K^{*0}(892)$ in $K^\pm\pi^\mp$

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



ϕ in K^+K^- combinations

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

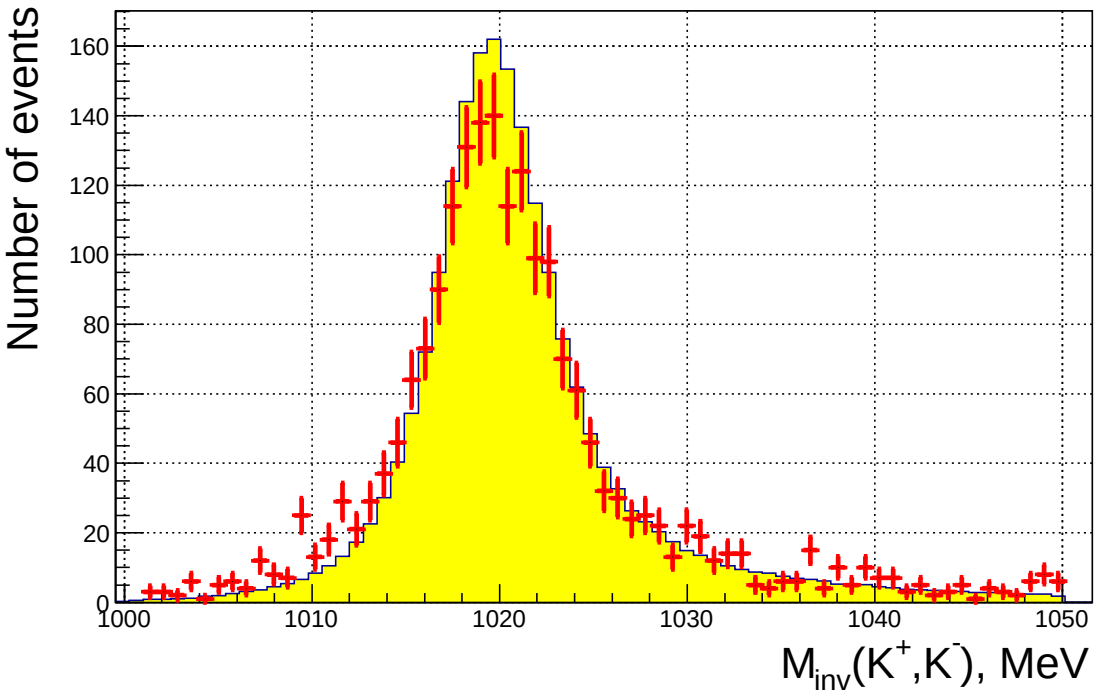


The cross section for a combination of various mechanisms obtained after a fit describing mass spectra, the $\phi(1680)$ is expected in some (all?) mechanisms

$e^+e^- \to K^+K^-\eta$ at CMD-3 – I

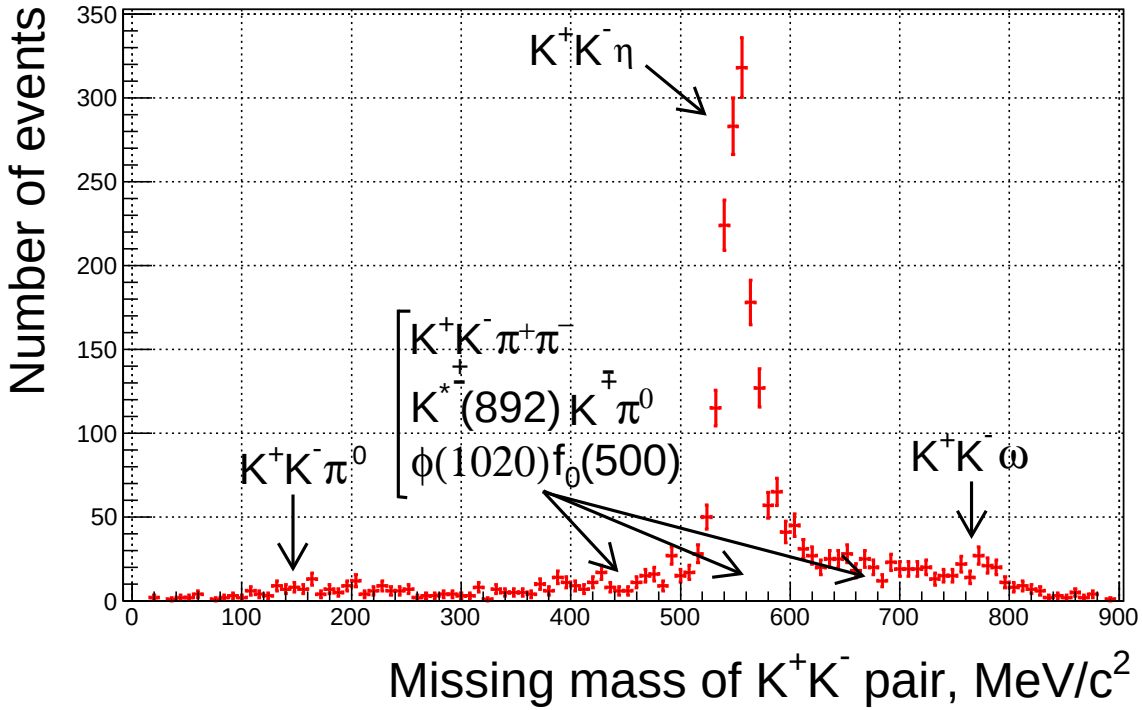
- A data sample of 22 pb^{-1} collected in 2011-2012 is used to study $e^+e^- \to K^+K^-\eta$
- 23 c.m. energy points between 1.57 and 2.0 GeV
- Analysis method emphasizes the dominant $\phi\eta$ signal, studies of non-resonant $K^+K^-\eta$ needed
- Rich background with numerous components seen
- The data sample includes 1600 events of the signal and $\sim$ 600 background events

$e^+e^- \to K^+K^-\eta$ at CMD-3 – II



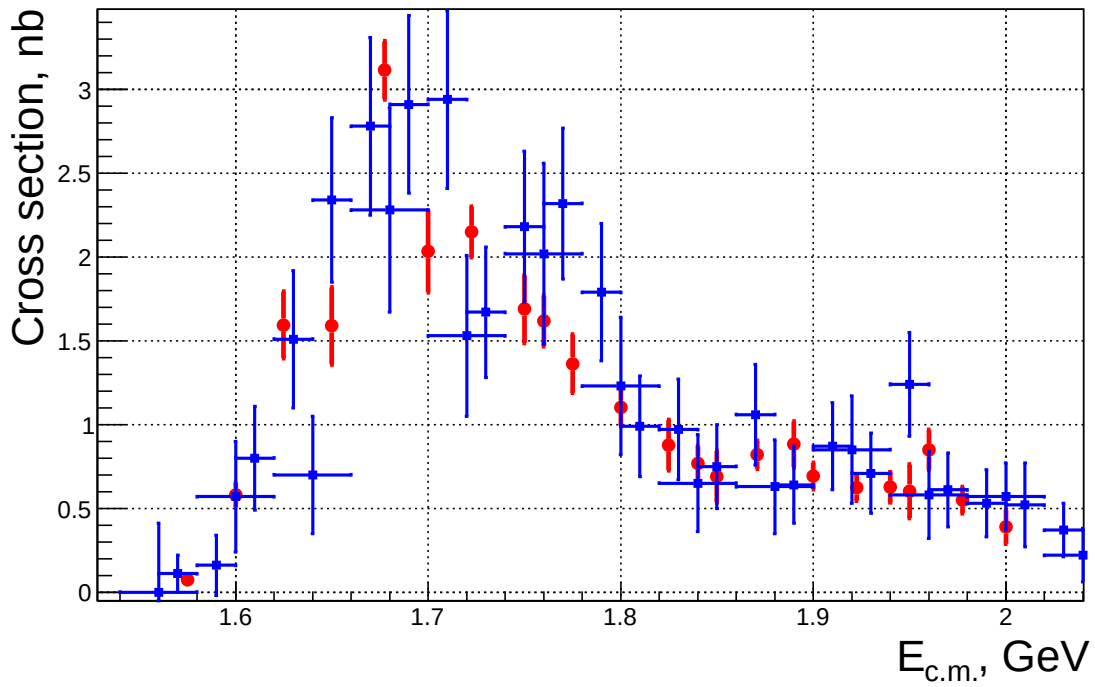
Dynamics dominated by the $\phi\eta$, $\phi \to K^+K^-$ channel

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



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

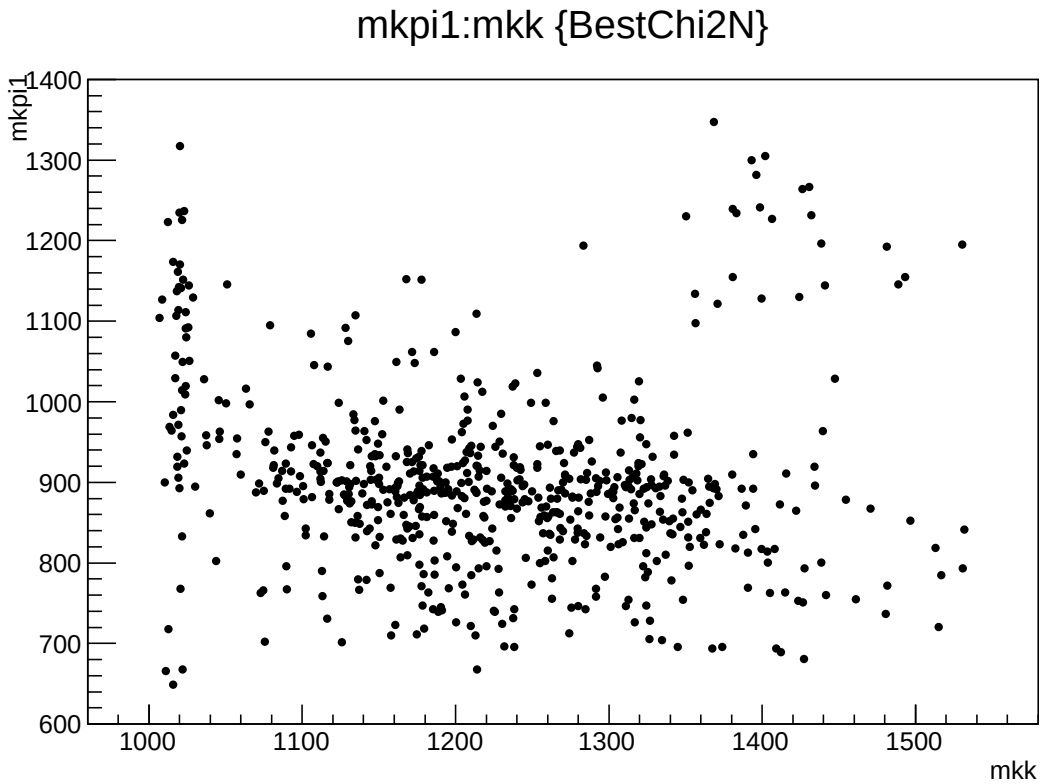
$e^+e^- \to K^+K^-\eta$ at CMD-3 – IV



Cross section is consistent with and more precise than BaBar

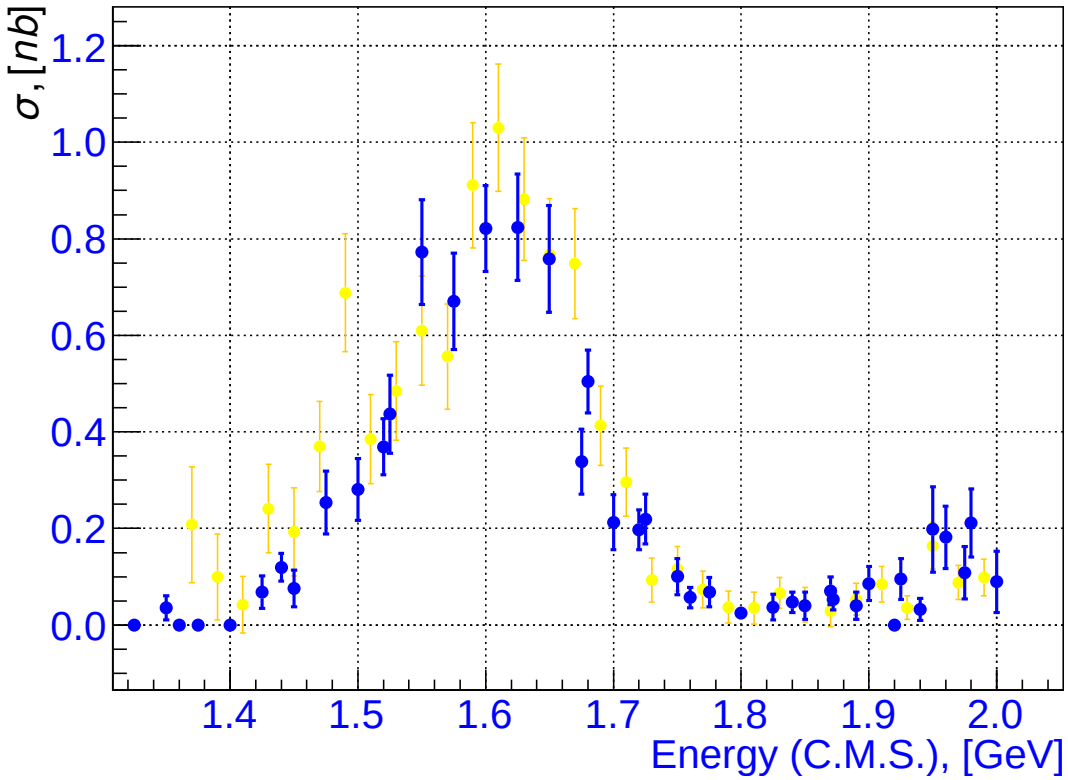
$e^+e^- \to K^+K^-\pi^0$ at CMD-3 – I

About 600 signal events selected



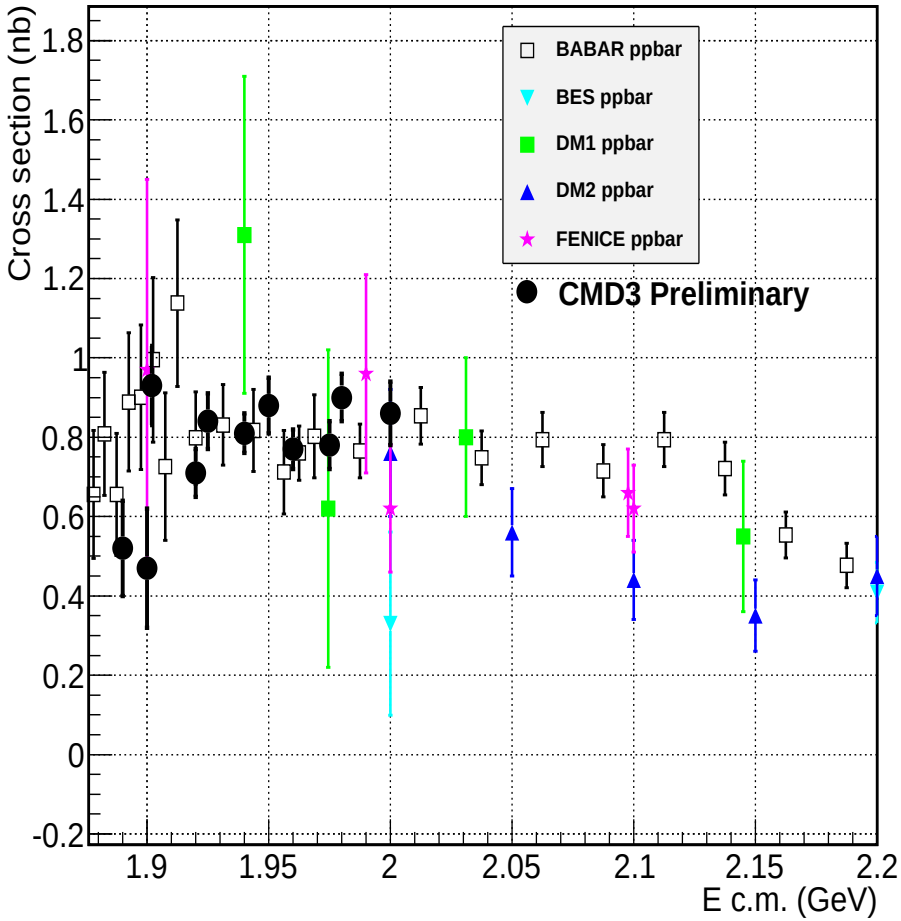
The $K\pi$ vs. K^+K^- plot clearly shows the $\phi\pi^0$ and $K^{*\pm}(892)K^{\mp}$ mechanisms

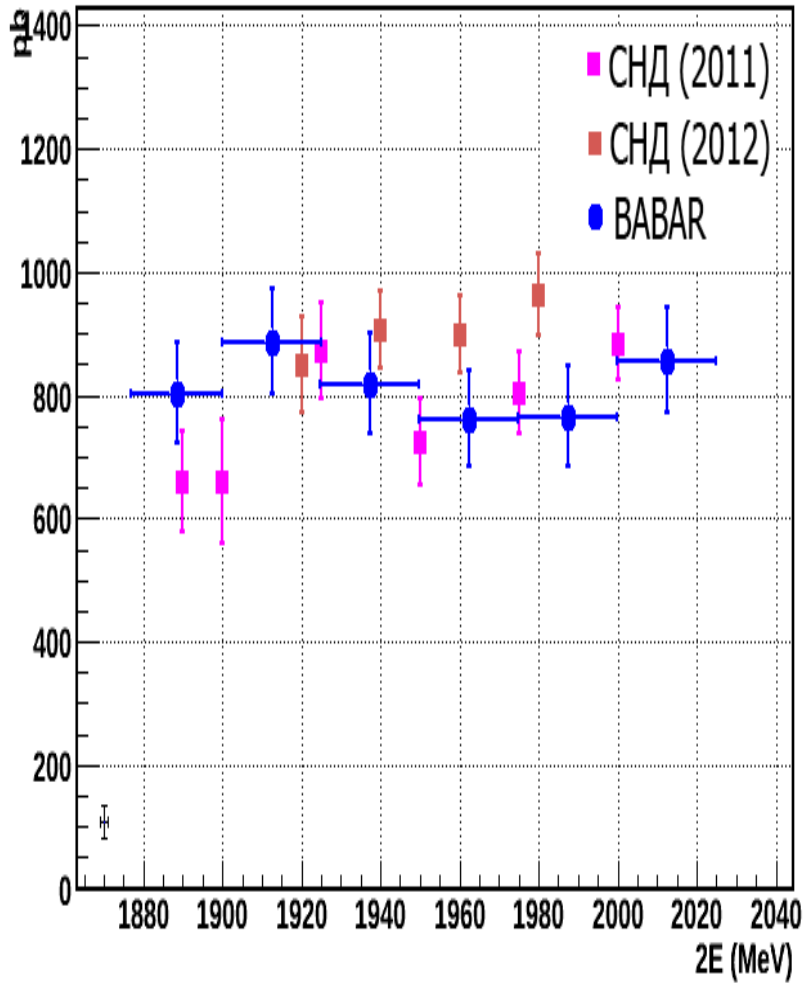
$e^+e^- \to K^+K^-\pi^0$ at CMD-3 – II



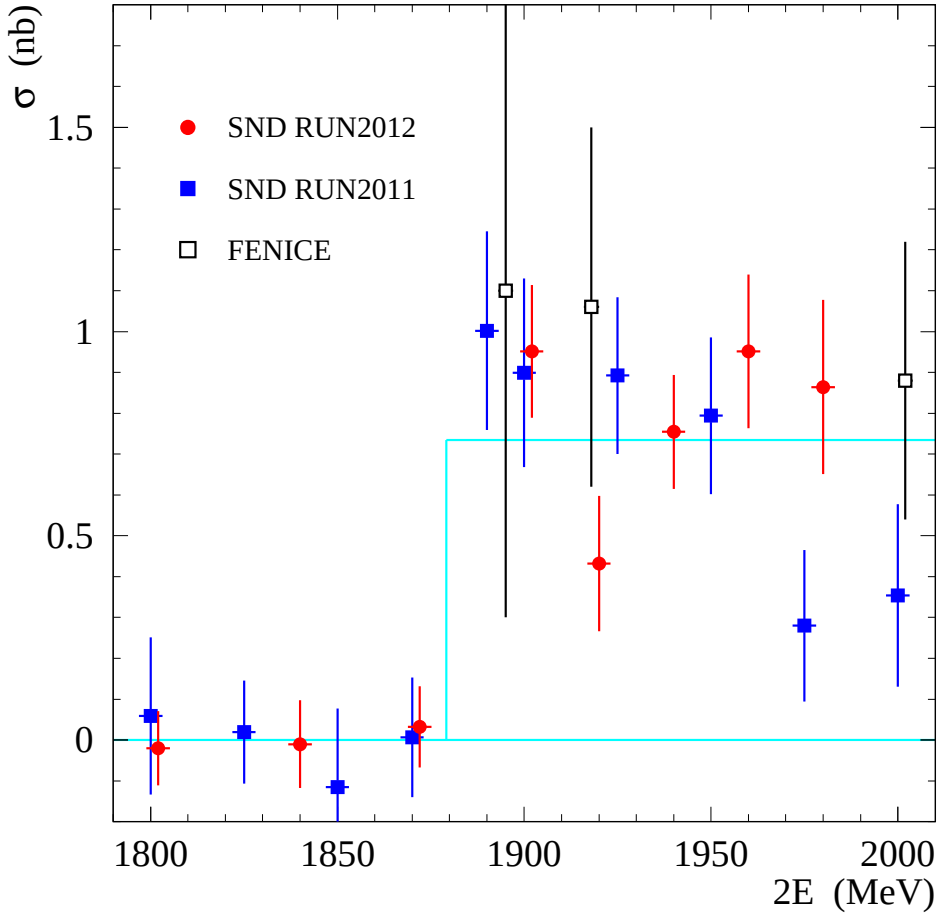
Cross section is consistent with and more precise than BaBar

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





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



The first and more precise measurement after FENICE

Monte Carlo Generators

- Studies of dynamics demand MC generators which properly take into account interference effects and all symmetries
- An important question is about radiative corrections: include in generators?, PHOKHARA, QED processes
- Generic MC generator of $e^+e^- \to$ hadrons used for BG studies
- A lot of efforts already spent on generators for 3 pseudoscalar, 4π and 6π final states
- Tomsk State and Polytechnical Universities joined SND and CMD-3

Conclusions

- VEPP-2000 was running smoothly with CMD-3 and SND in 2011-2013 and collected about 60 pb^{-1} per detector
- New channels observed: $\pi^+\pi^-4\pi^0$, $n\bar{n}$, $\eta\gamma$, $\ldots$
- CMD-3 and SND at VEPP-2000 will provide high accuracy, comparable or better than ISR measurements for HVP, the tentative goals are 0.35%(0.5%) for $\pi^+\pi^-$ and 3% for multibody modes
- Extensive studies of multibody dynamics demand MC generators
- Various studies of transition form factors are in progress: $e^+e^- \to \pi^0\gamma$, $\eta\gamma$, $\pi^0e^+e^-$, ηe^+e^-, η', η, $\ldots$
- In fall 2015 experiments with an upgraded booster and new injection complex will resume to provide $L \sim 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- New collaborators badly needed for data analysis