Recent results on e^+e^- annihilation to hadrons in the SND experiment

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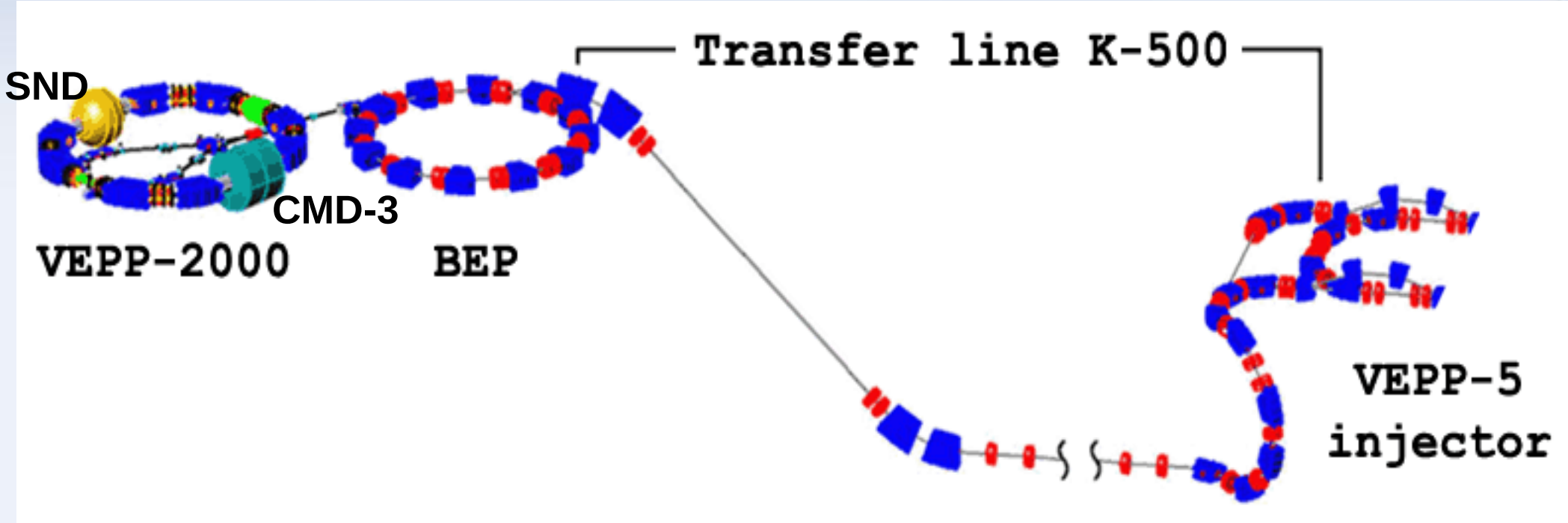
VEPP-2000 e^+e^- collider



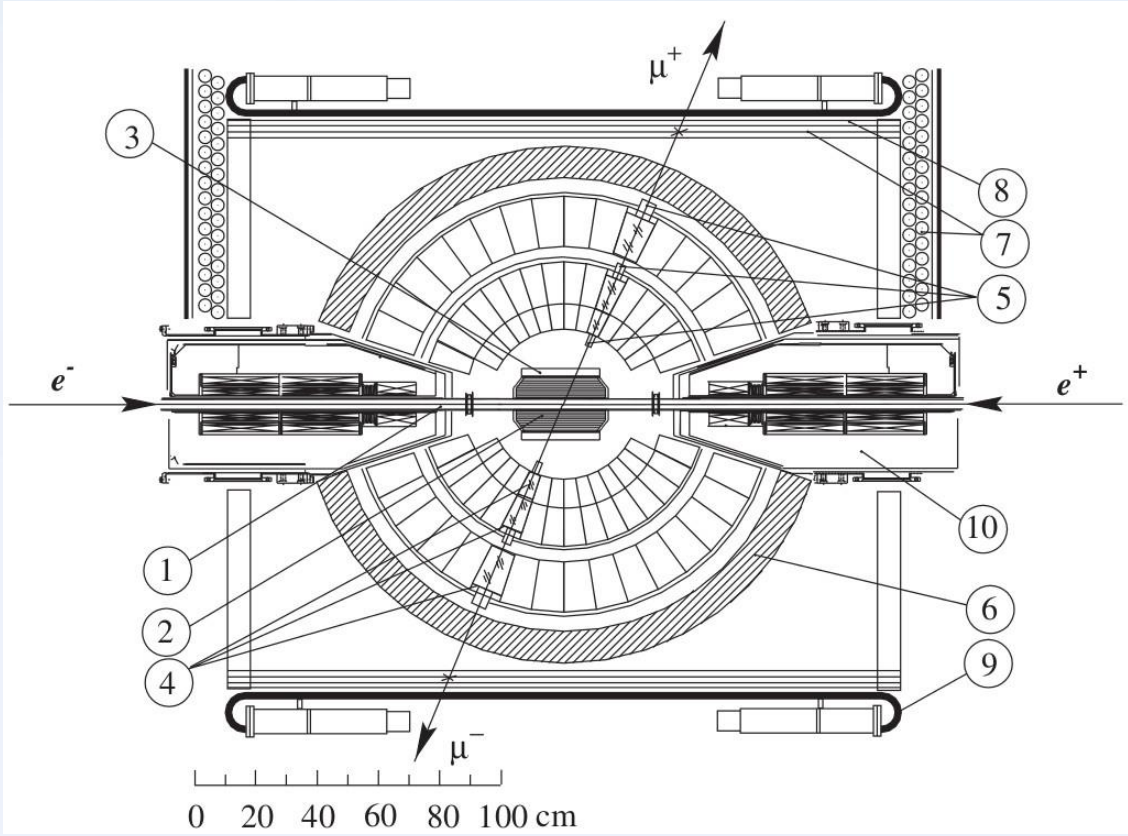
VEPP-2000 parameters:

- c.m. energy E=0.3 – 2.0 GeV
- circumference – 24.4 m
- round beam optics

- Luminosity at E=1.8 GeV
  1×10^{32} cm^{-2} sec^{-1} (project)
  4×10^{31} cm^{-2} sec^{-1} (achieved)
- Two detectors: SND and CMD-3

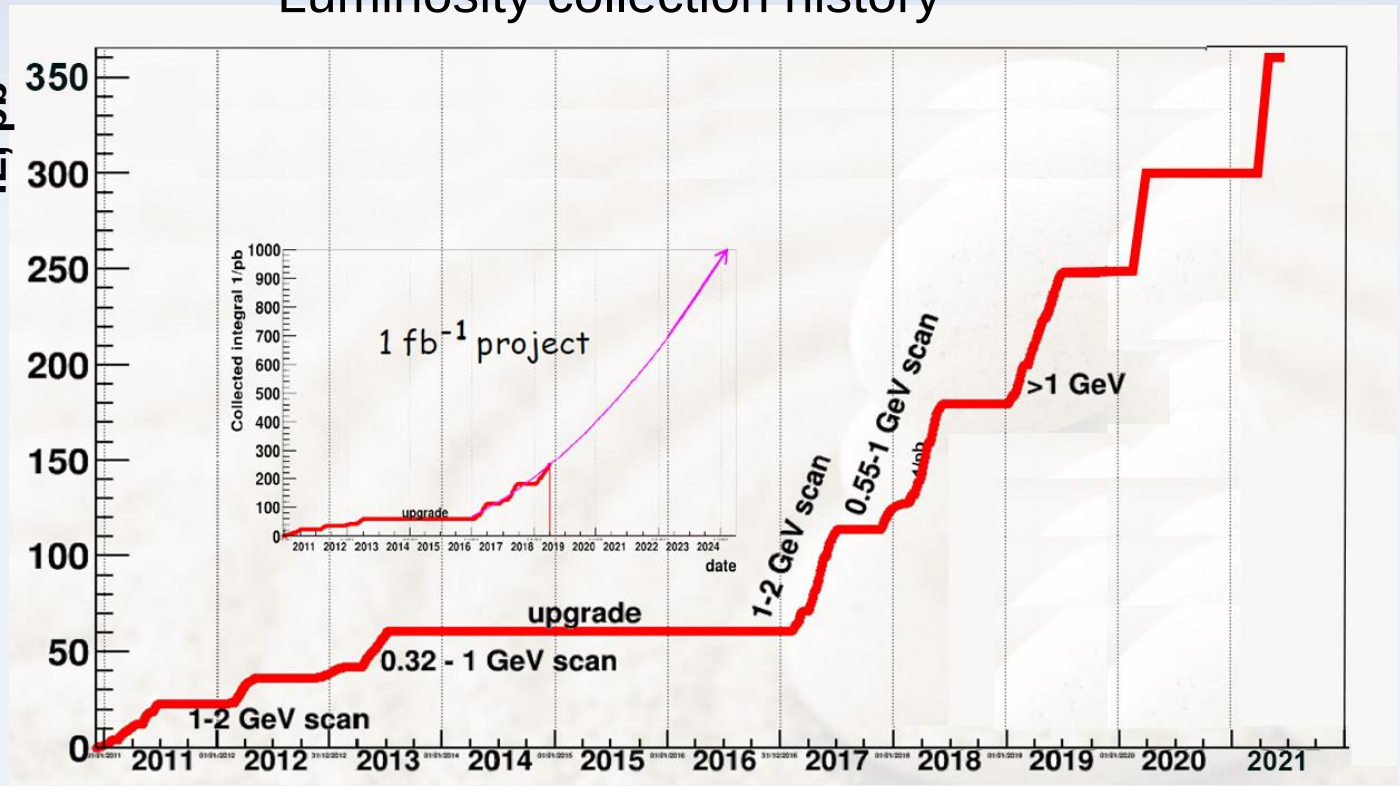
SND detector

Spherical Neutral Detector:
1 – beam pipe,
2 – tracking system,
3 – aerogel Cherenkov counter,
4 – NaI(Tl) crystals,
5 – phototriodes,
6 – iron muon absorber,
7–9 – muon detector,
10 – focusing solenoids

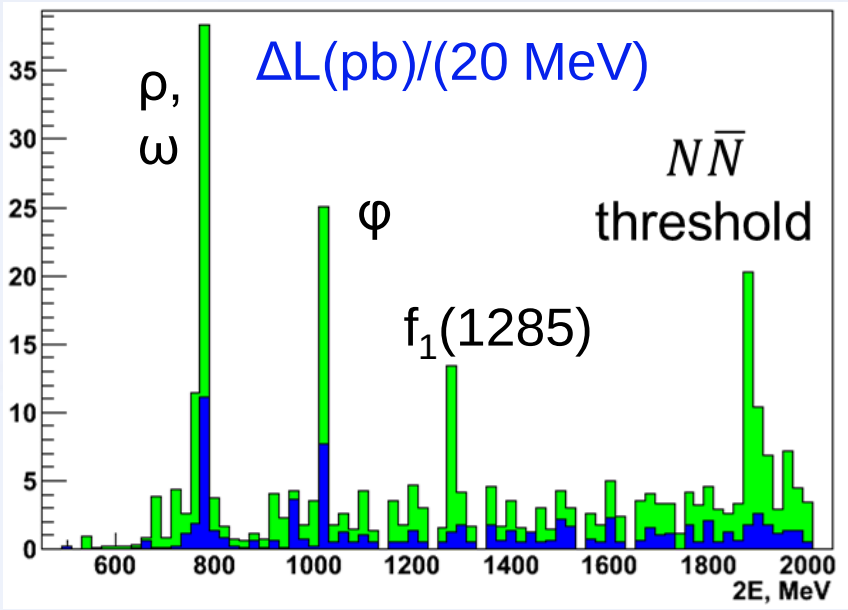


Experiments at VEPP-2000

Luminosity collection history

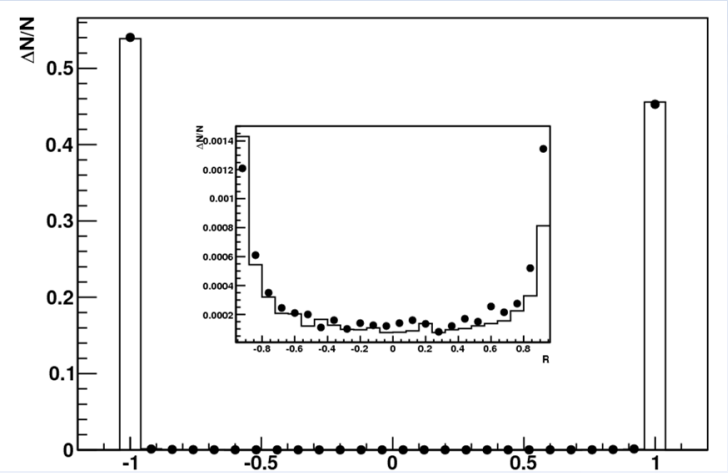


Collected luminosity



	Below φ	Near φ	Above φ	Total
IL, pb^{-1}	77	31	259	367
E_{cm}, GeV	0.30-0.97	0.98-1.05	1.05-2.00	0.30-2.00

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

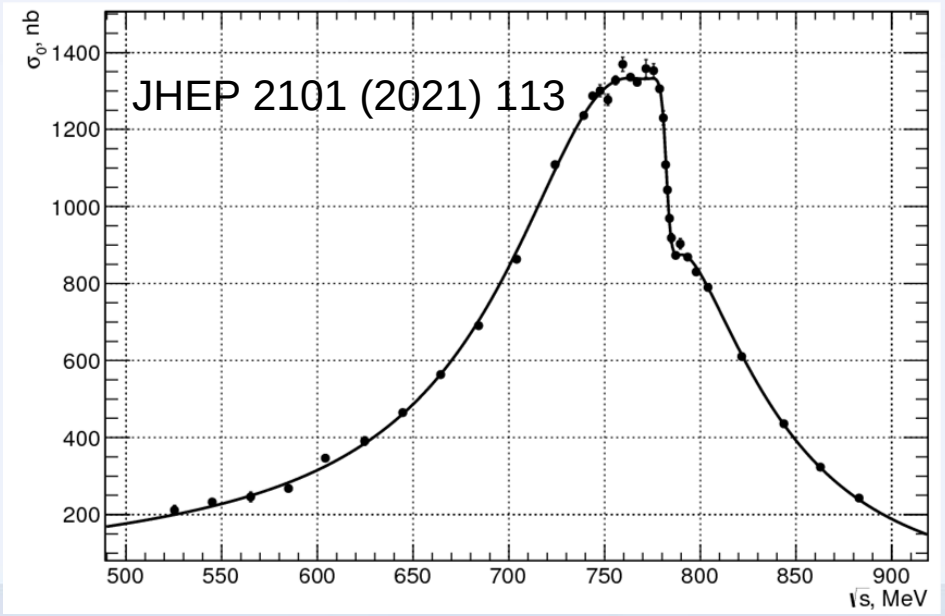


Systematic uncertainty of the cross section (%)

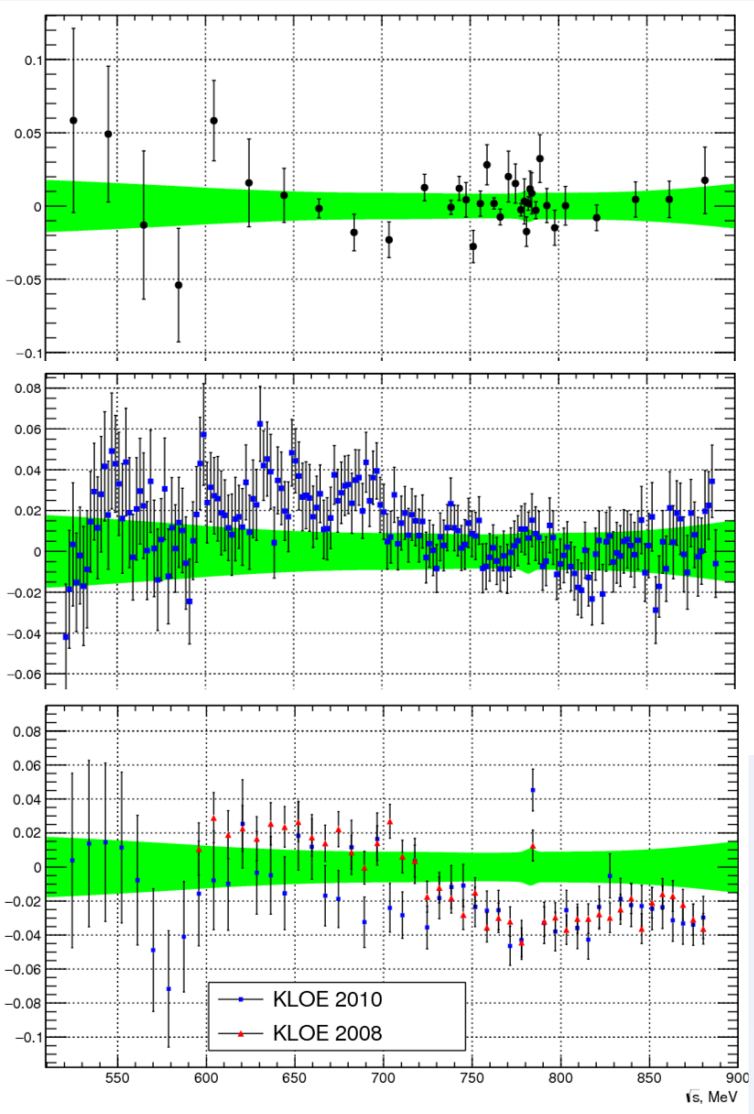
Source	< 0.6 GeV	0.6 - 0.9 GeV
Trigger	0.5	0.5
Selection criteria	0.6	0.6
e/π/μ separation	0.5	0.1
Nucl. interaction	0.2	0.2
Theory	0.2	0.2
Total	**0.9**	**0.8**

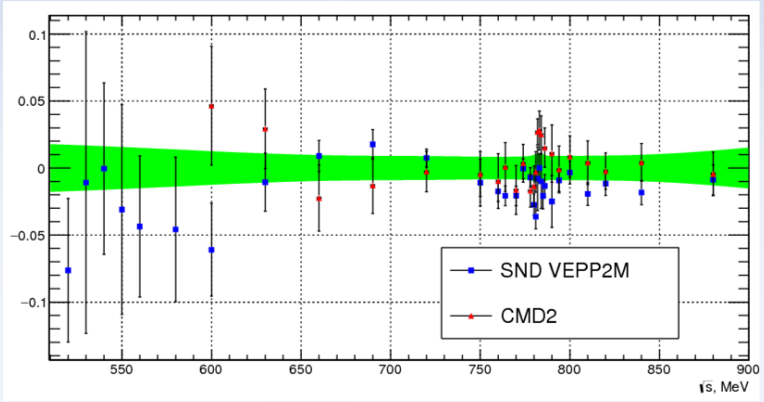
The analysis is based on 4.7 pb^{-1} data (1/10 full SND data set) recorded in 2013

	SND @VEPP-2000	SND @ VEPP-2M	PDG
M_ρ, MeV	775.3±0.5±0.6	775.6±0.4±0.5	775.3±0.3
Γ_ρ, MeV	145.6±0.6±0.8	146.1±0.8±1.5	147.8±0.9
$B_{\rho ee}\times 10^5$	4.89±0.02±0.04	4.88±0.02±0.06	4.72±0.05
$B_{\omega\pi\pi}$, %	1.77±0.08±0.02	1.66±0.08±0.05	1.53±0.06



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

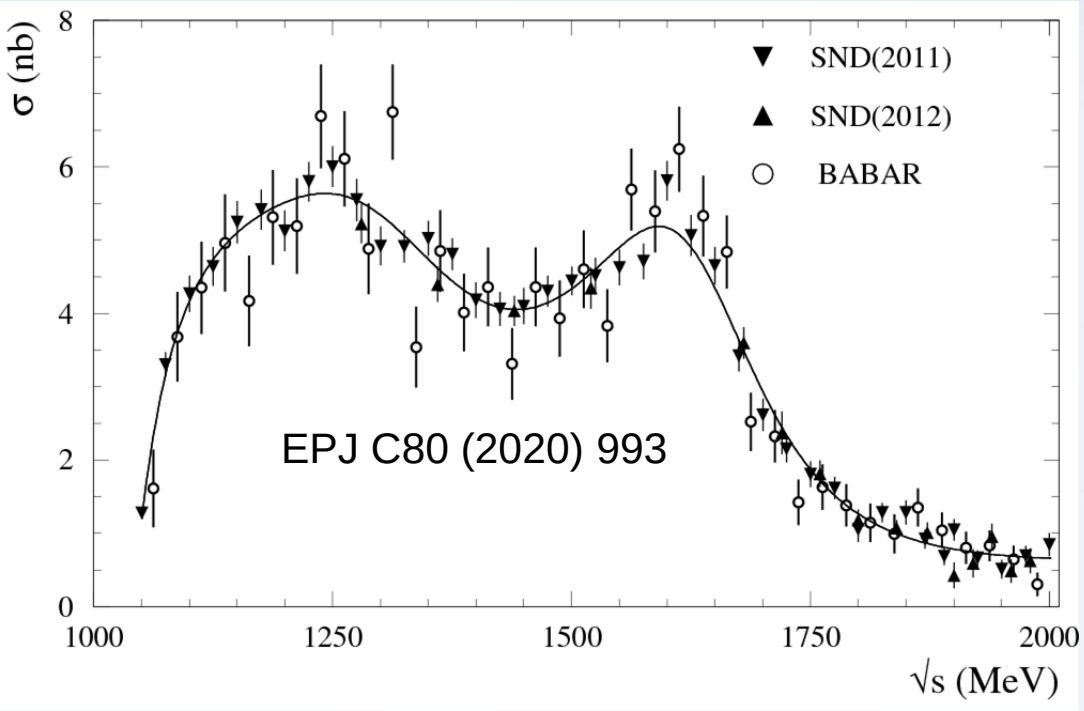




$$0.53 < \sqrt{s} < 0.88 \text{ GeV}$$

	$a_\mu \times 10^{10}$
SND @ VEPP-2000	409.79 ± 1.44 ± 3.87
SND @ VEPP-2M	406.47 ± 1.74 ± 5.28
BABAR	413.58 ± 2.04 ± 2.29
KLOE	403.39 ± 0.72 ± 2.50

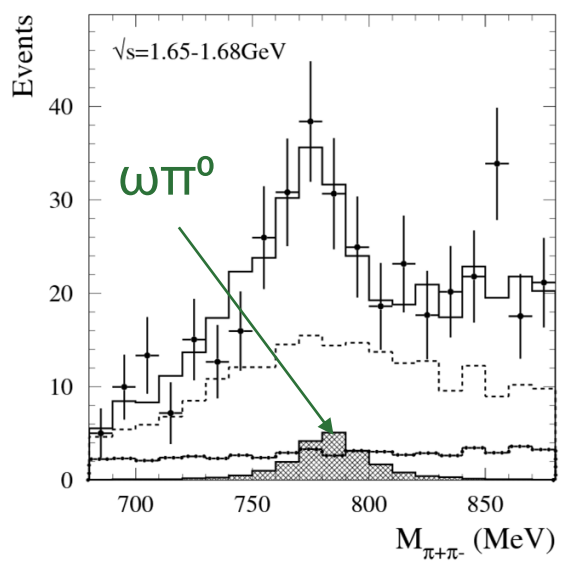
$e^+e^- \to \pi^+\pi^-\pi^0$ cross section

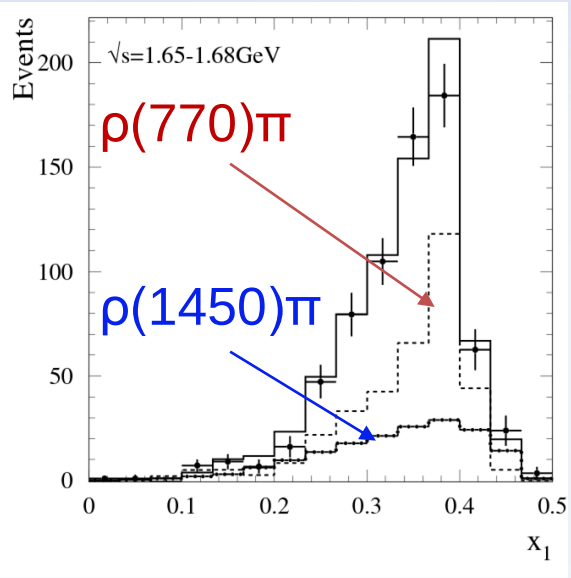


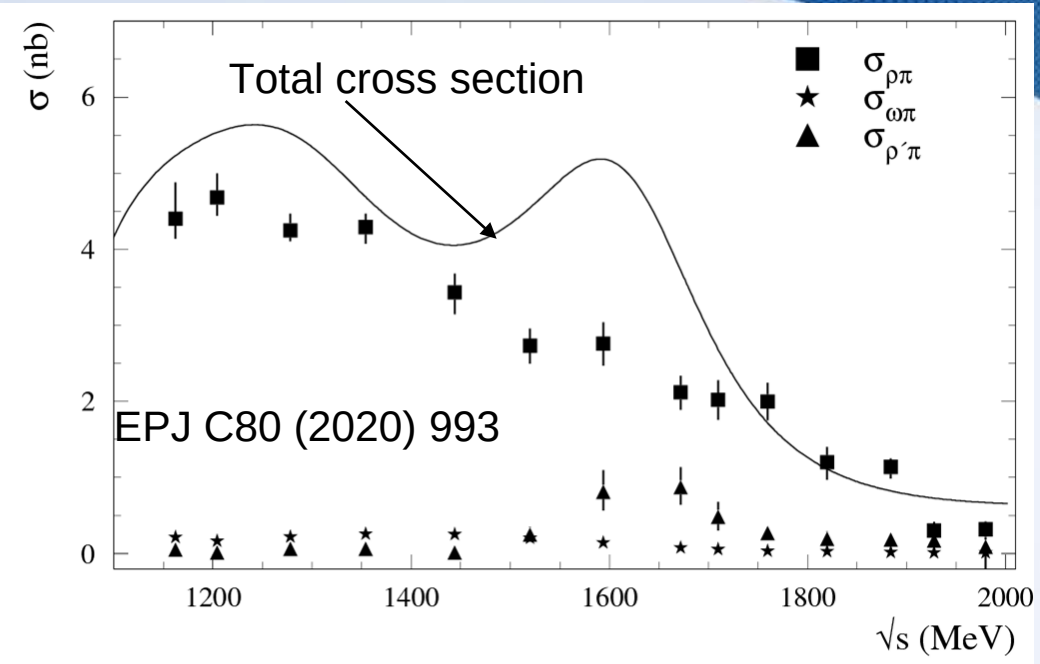
- Both SND measurements are consistent with each other and with the BABAR measurement.
- Two peaks in the cross section corresponds to the ω (1420) and ω (1650) resonances.
- The systematic uncertainty on the cross section is 4.4%.

The previous SND measurement [J. Exp. Theor. Phys. 121, 27 (2015)] is based on 2011 data set. The 2012 data set has been added.

$e^+e^- \to \pi^+\pi^-\pi^0$ dynamics



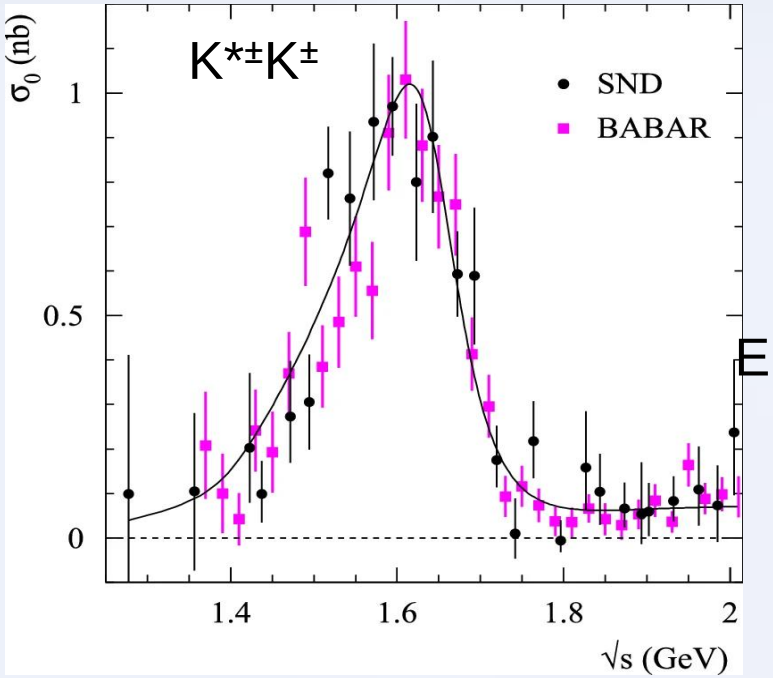




- We fit the two-dimensional distribution of the charged-pion momenta and the $\pi^+\pi^-$ mass spectrum with a model including the ρ(770)π, ρ(1450)π and $\omega\pi^0$ intermediate states.
- A significant fraction of the ρ(1450)π intermediate state is observed in the energy region 1.55 – 1.75 GeV, where the ω(1650) resonance is located.
- We conclude that the ρ(1450)π intermediate state gives a significant contribution to the decay $\omega(1650) \to \pi^+\pi^-\pi^0$ and that the $\omega(1420) \to \pi^+\pi^-\pi^0$ decay is dominated by the ρ(770)π intermediate state.

$e^+e^- \to K^+K^-\pi^0$

The analysis is based on 26 pb^{-1} data recorded in the c.m. energy range 1.27 – 2 GeV.
The cross sections for the processes $e^+e^- \to K^{*\pm}K^\pm \to K^+K^-\pi^0$ and $e^+e^- \to \phi\pi^0 \to K^+K^-\pi^0$ are measured separately.



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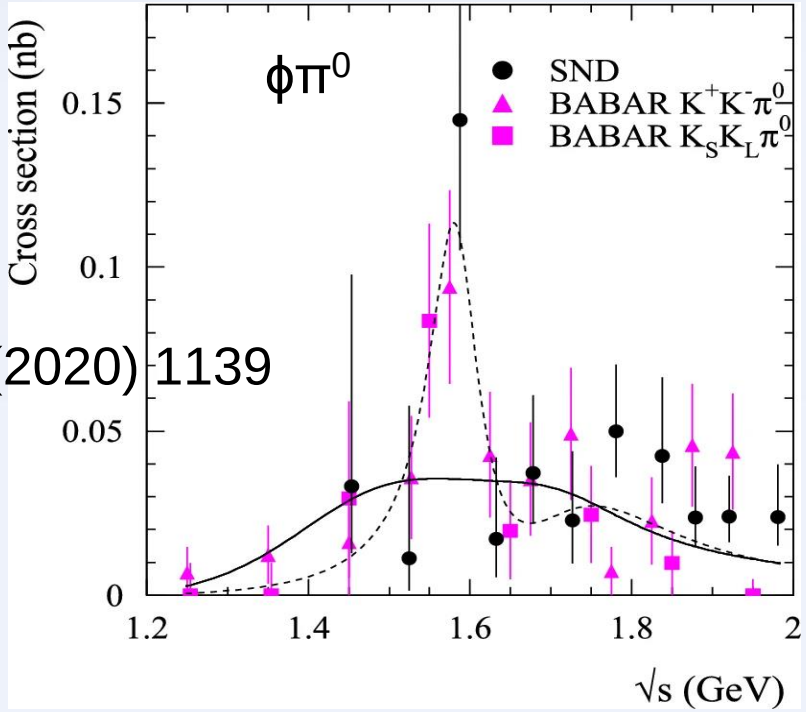
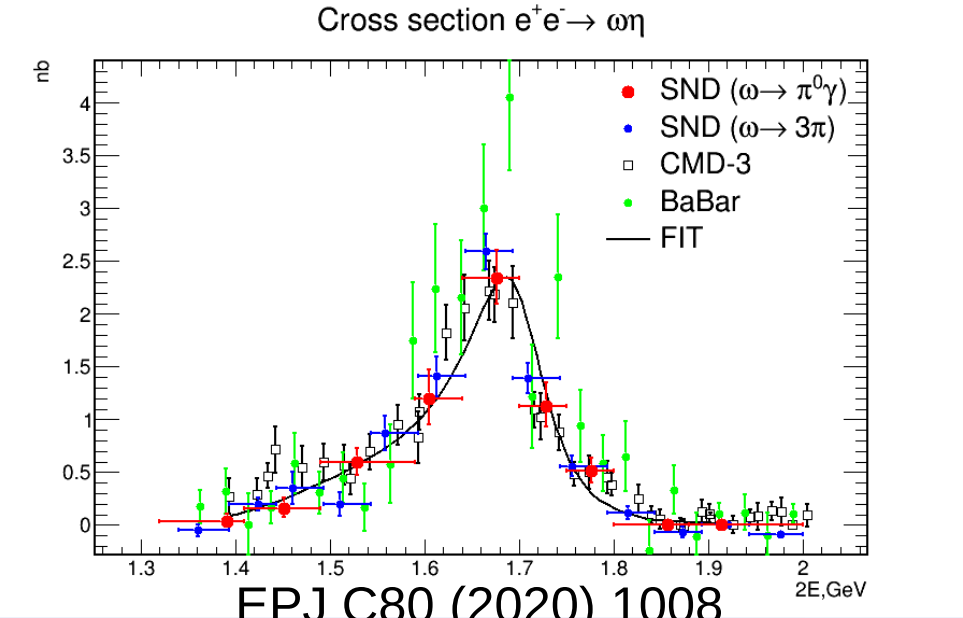


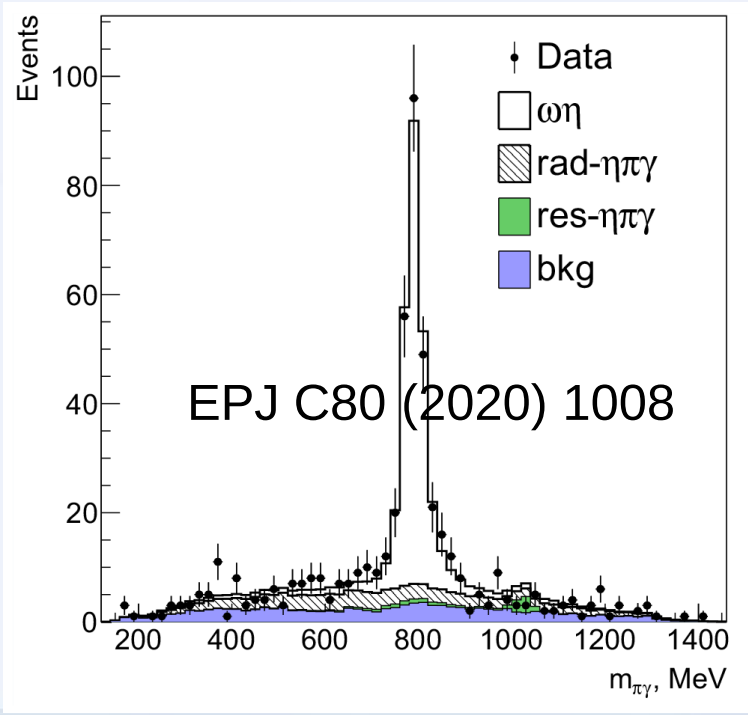
ϕ(1680) gives the main contribution to the $e^+e^- \to K^{*\pm}K^\pm \to K^+K^-\pi^0$ cross section

The $e^+e^- \to \phi\pi^0 \to K^+K^-\pi^0$ cross section can not be described by ρ(1450) and ρ(1700). It can be fitted with inclusion of an unknown resonance with m=1585±15 MeV and Γ=75±30 MeV.

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

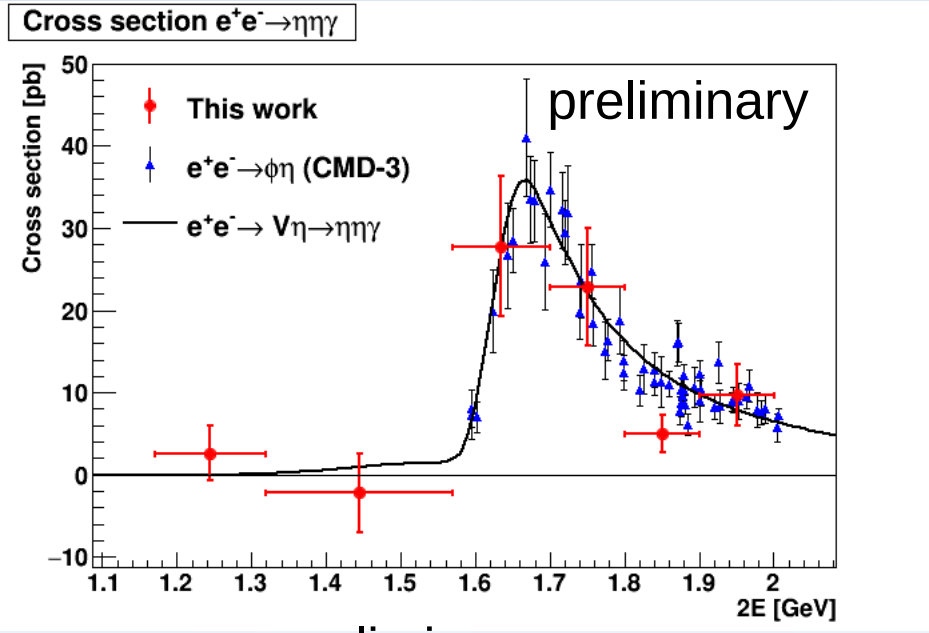


- The process $e^+e^- \to \eta\pi^0\gamma$ above 1.05 GeV is studied for the first time.
- The analysis is based on 100 pb^{-1} data set recorded in 2010 – 2012 and 2017.
- Five-photon final state is used.



- The numbers of events for each intermediate state are determined by fitting the $\pi^0\gamma$ invariant-mass distribution.
- The measured $e^+e^- \to \omega\eta$ cross section is in good agreement with the SND and CMD-3 measurements in the $\omega \to \pi^+\pi^-\pi^0$ mode.

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



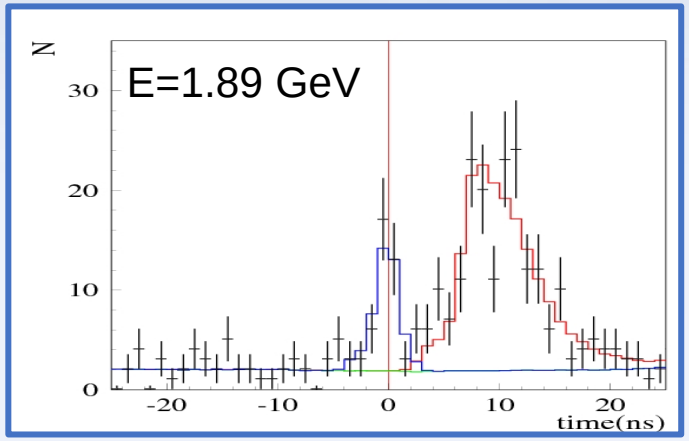
preliminary

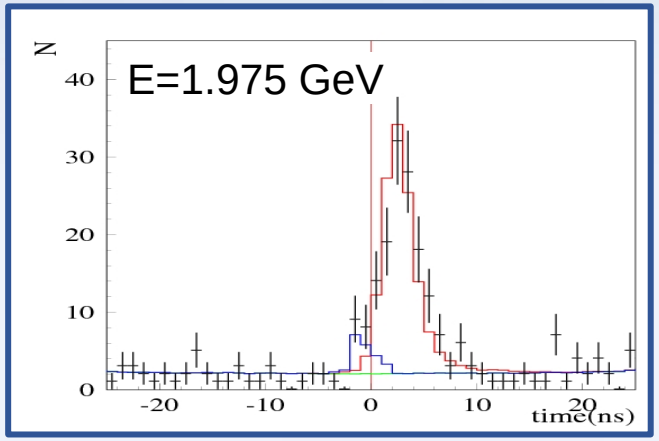
2E, GeV	95% CL Upper limit,pb
1.17-1.32	9
1.32-1.57	5
1.57-1.80	11
1.80-2.00	4

- The $e^+e^- \to \eta\eta\gamma$ cross section has been measured for the first time in the energy range 1.17 – 2.0 GeV
- The main intermediate state is $\varphi\eta$
- The measured cross section is consistent with CMD-3 result on $e^+e^- \to \varphi\eta$, $\varphi \to K^+K^-$
- The contribution from intermediate states other than $V\eta$ ($V=\varphi,\rho,\omega$) is not seen
- Upper limits on possible contribution of radiative intermediate states ($f_0(1500)\gamma$, $f'_2(1525)\gamma$) have been set

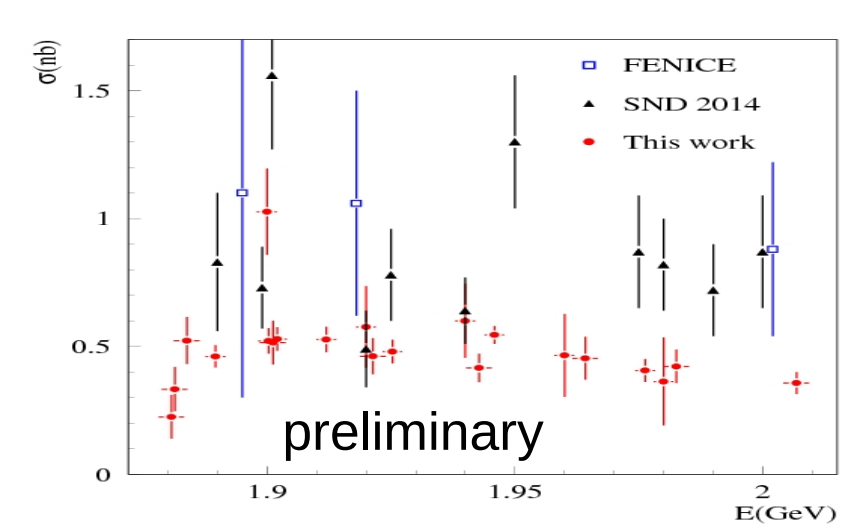
$e^+e^- \to n\bar{n}$

Time spectra in 2019 run





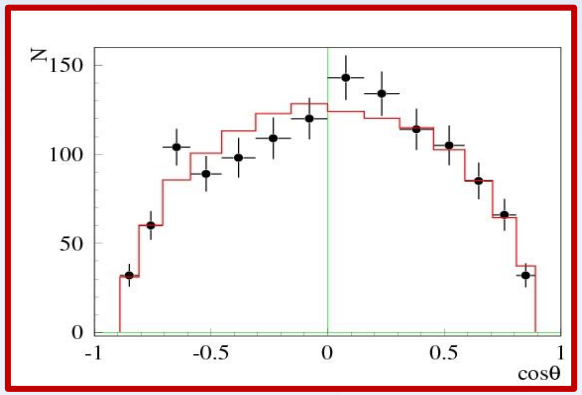
The analysis is based on 70 pb^{-1} data recorded in 2012, 2017, 2019 and 2020. Events are selected using event time measurement (calorimeter trigger time in 2012 and 2017, flash ADC in 2019 and 2020).



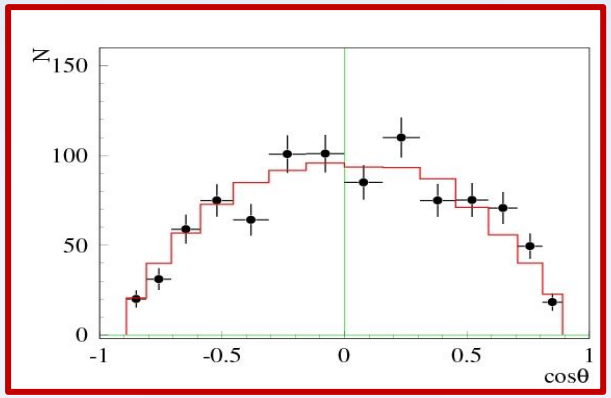
The cross section is measured from nucleon-antinucleon threshold up to 2 GeV. The cross section value is ≈0.4 nb.

$e^+e^- \to n\bar{n}$ G_E/G_M

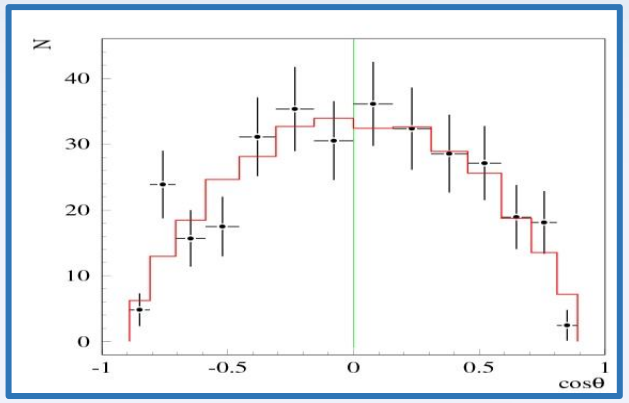
E=1.89 – 1.90 GeV

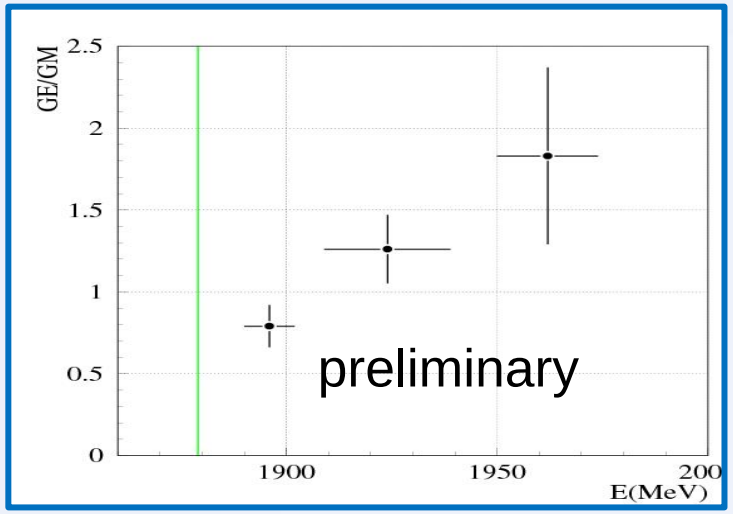


E=1.91 – 1.94 GeV



E=1.95 – 1.98 GeV



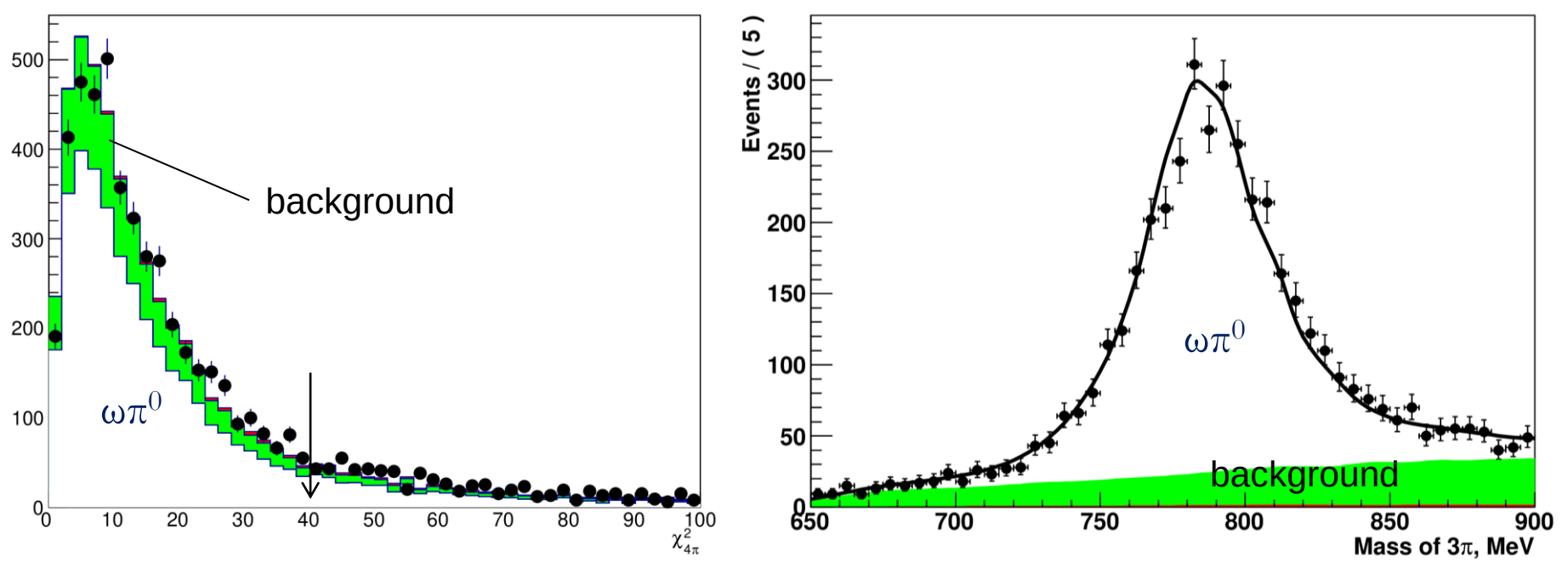


$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta}{4s}\left[|G_M(s)|^2(1+\cos^2\theta) + \frac{1}{\gamma^2}|G_E(s)|^2\sin^2\theta\right]$$

At the current level of statistics the measured ratio of neutron form factors below 2 GeV agrees with unity

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

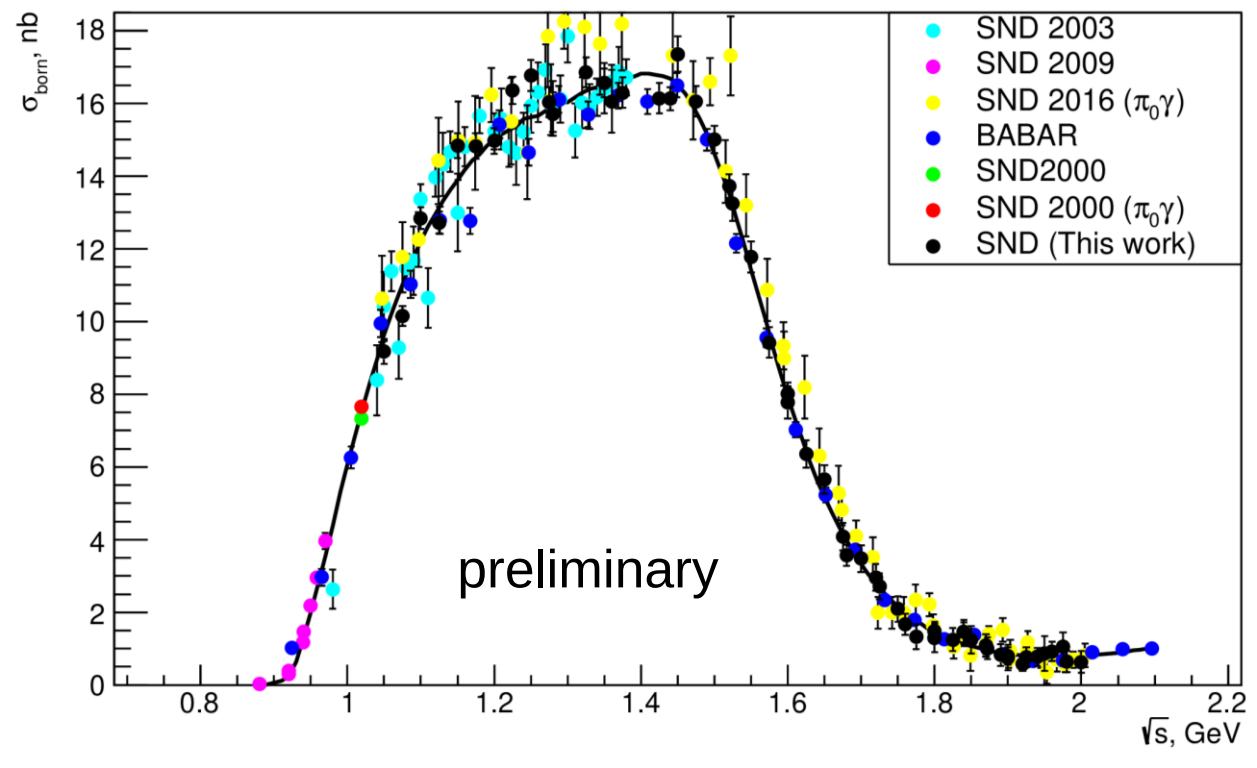
- The analysis is based on 35 pb^{-1} data collected in 2011 – 2012.
- The events with two tracks and at least four photons are selected for the analysis.
- $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ events are selected using kinematic fit, $\chi^2 < 40$.
- The $\omega\pi^0$ contribution is separated from other intermediate states by fitting to the $\pi^+\pi^-\pi^0$ invariant-mass spectrum in the range 650 – 900 MeV.



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

To obtain the radiative correction and the Born cross section, the measured $\omega\pi^0$ cross section is fitted with the VMD model including three states of the ρ family.

$$\sigma_{Born}(s) = \frac{4\pi\alpha^2}{s^{3/2}} \left| \sum_i \frac{A_i e^{i\varphi_i}}{m_i^2 - s - i\sqrt{s}\Gamma_i(E)} \right|^2 \underbrace{P_f(\sqrt{s})}_{\text{phase space factor}}$$



- The comparison with the $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$ cross section takes into account the phase space difference between $\omega \to \pi^+\pi^-\pi^0$ and $\omega \to \pi^0\gamma$ decays.
- The $\omega\pi^0$ cross section obtained by limiting ω invariant mass below 0.9 GeV is expected to be independent of the model for the ω line shape.
- The measured $e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$ cross section is in agreement with previous measurement but has better accuracy.

Summary

- The SND detector accumulated 370 pb^{-1} of integrated luminosity in the energy range 0.3 – 2 GeV on VEPP-2000 from 2010 to 2021
- The $e^+e^- \to K^+K^-\pi^0$ process has been studied in the energy range 1.27 – 2.0 GeV, the cross sections of the $e^+e^- \to K^{*\pm}K^\pm \to K^+K^-\pi^0$ and $e^+e^- \to \phi\pi^0 \to K^+K^-\pi^0$ processes have been measured separately
- The rare radiative processes $e^+e^- \to \eta\pi^0\gamma$ and $e^+e^- \to \eta\eta\gamma$ have been studied for the first time.
- The accuracy of the $e^+e^- \to n\bar{n}$ cross section measurement has been significantly improved
- The dynamics of the $e^+e^- \to \pi^+\pi^-\pi^0$ process has been studied in the energy range 1.15 – 2.0 GeV
- The $e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$ cross section has been measured with high precision
- The $e^+e^- \to \pi^+\pi^-$ cross section has been measured by SND with systematic uncertainty better than 1%