Study of the processes of electron-positron annihilation into hadron states with SND at VEPP-2000 collider

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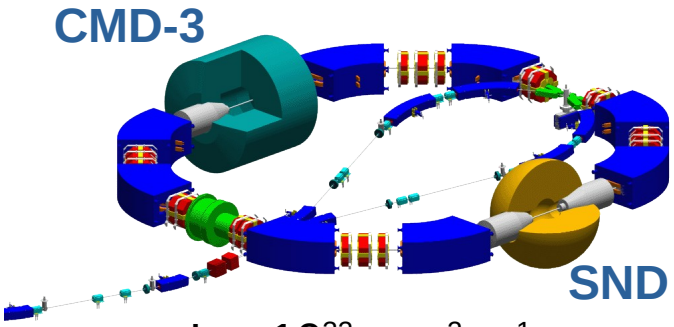
12 July 2023

XII International Conference on New Frontiers in Physics,
Crete, Greece

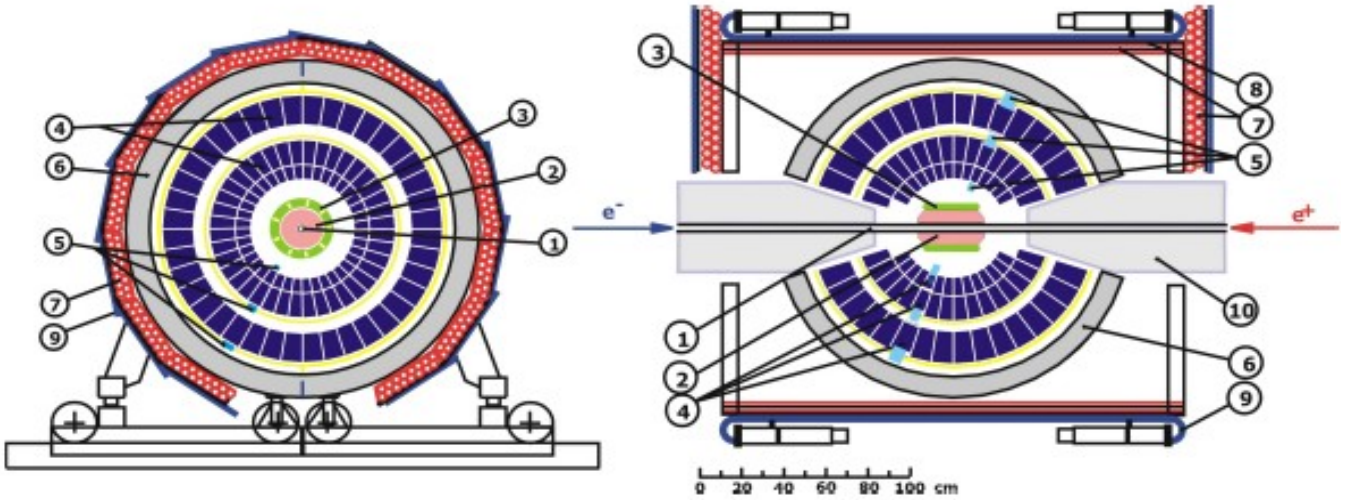
SND experiment at VEPP-2000



$L = 10^{32}\ cm^{-2}\ s^{-1}$

$E_{CM} = 0.3–2.0\ GeV$

Spherical Neutral Detector



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

Integrated luminosity is measured using:

- $e^+e^- \to e^+e^-$ for charged final states
- $e^+e^- \to \gamma\gamma$ for neutral final states

Total IL=885 pb^{-1} for June, 2023

Until 2021 — 300 pb^{-1}

2022 and 2023 — 585 pb^{-1} (not processed yet)

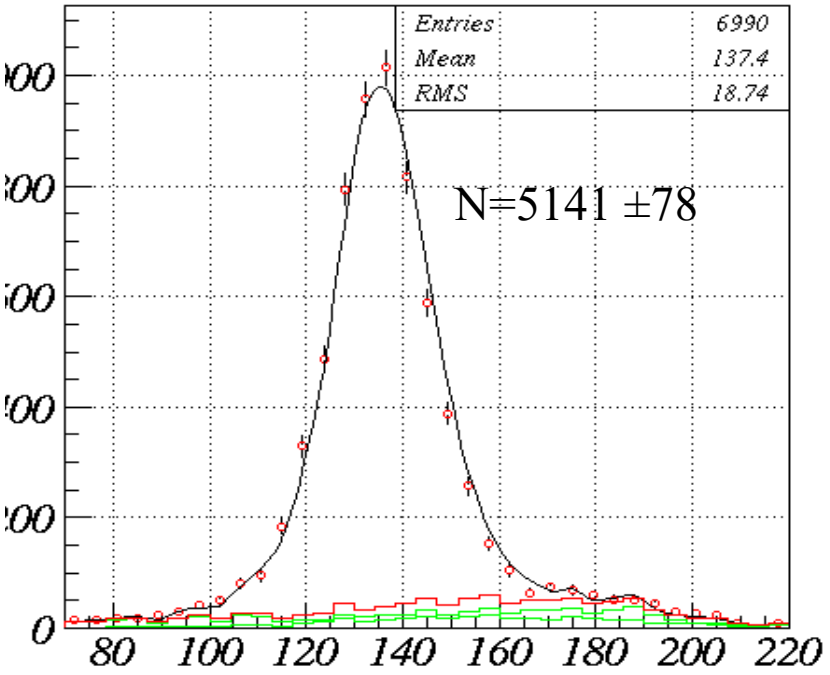
SND physics program

The physics program of experiments at VEPP-2000 includes the following main topics:

- Measurement of total hadronic cross section below 2 GeV for calculation HVP contribution to $(g-2)_\mu$.
- Study of dynamics of hadron production, i.e. separation between different intermediate states, for example, ωη, φη, etc.
- Hadron spectroscopy: study of light-vector-meson excitations.
- Search for rare and forbidden decays of the ρ, ω, and φ mesons.
- Study of nucleon-antinucleon pair production, extraction of the proton and neutron electromagnetic form factors.
- Search for production of C-even resonances: $e^+e^- \to \eta, \eta', f_1, f_2, a_2$, etc.
- Using the radiative return technique as alternative method for measurement of hadronic cross sections.

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

$\sqrt{s}$=1281 MeV (L~7.3 pb^{-1})



Number of events is calculated by fit of $M_{\gamma\gamma}$ spectrum

Fraction of ρπ and ρ′π measured by fit of Dalitz-plot $(M_{\pi\pm\pi0})^2$ vs $(M_{\pi+\pi-})^2$, using model

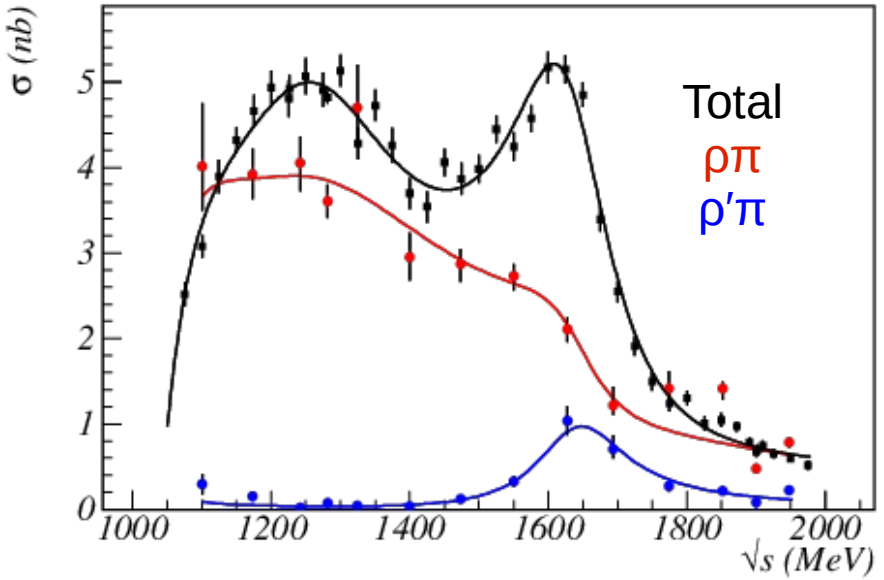
$$\frac{d\sigma}{d\Gamma} = \left|\alpha\, A_{\rho\pi} + \beta\, A_{\rho'\pi} + \gamma\, A_{\omega\pi}\right|^2$$

Where |γ| was fixed using $\omega\pi^0$ data, parameters of fit are |α|,|β| and two phases $\varphi_{\rho\pi-\omega\pi}$, $\varphi_{\rho\pi-\rho'\pi}$

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

$$\sigma_{\rm vis}(E) = \frac{N_{\rm exp}}{\varepsilon L} \qquad \sigma_{\rm born}(E) = \frac{N_{\rm exp}}{\varepsilon L(1+\delta)}$$

$$\sigma_{\rm vis}(E) = \int_0^{\epsilon} F(x,E)\ \sigma_{\rm born}\left(E\sqrt{1-x}\right) dx$$



Systematics error estimate 7.3%

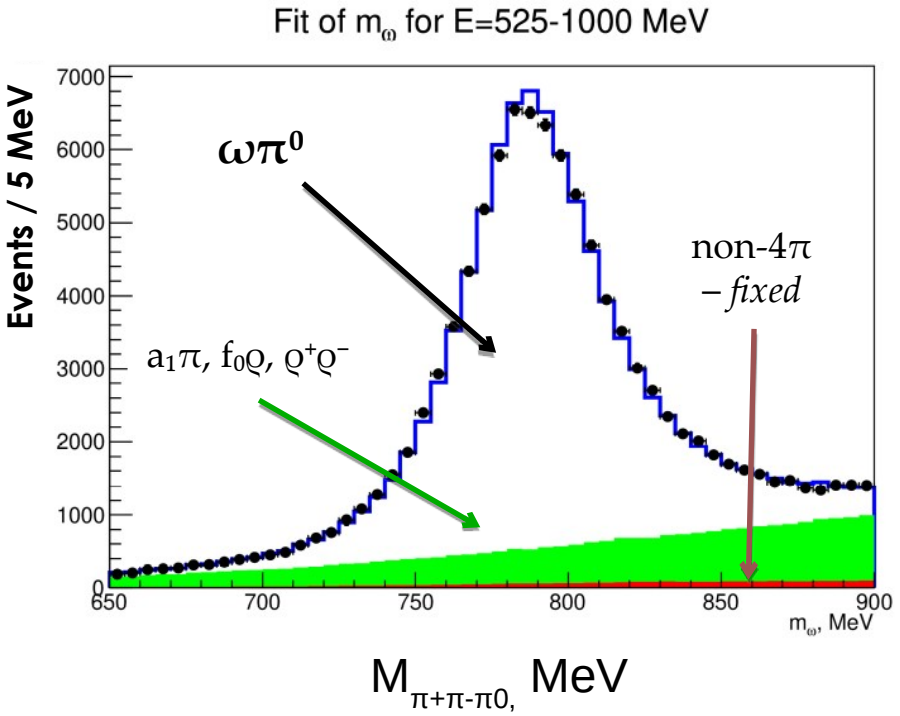
Model includes mechanisms:
$e^+e^- \to (\omega, \varphi, \omega', \omega'') \to \rho\pi \to \pi^+\pi^-\pi^0$
$e^+e^- \to (\varphi, \omega', \omega'') \to \rho'\pi \to \pi^+\pi^-\pi^0$

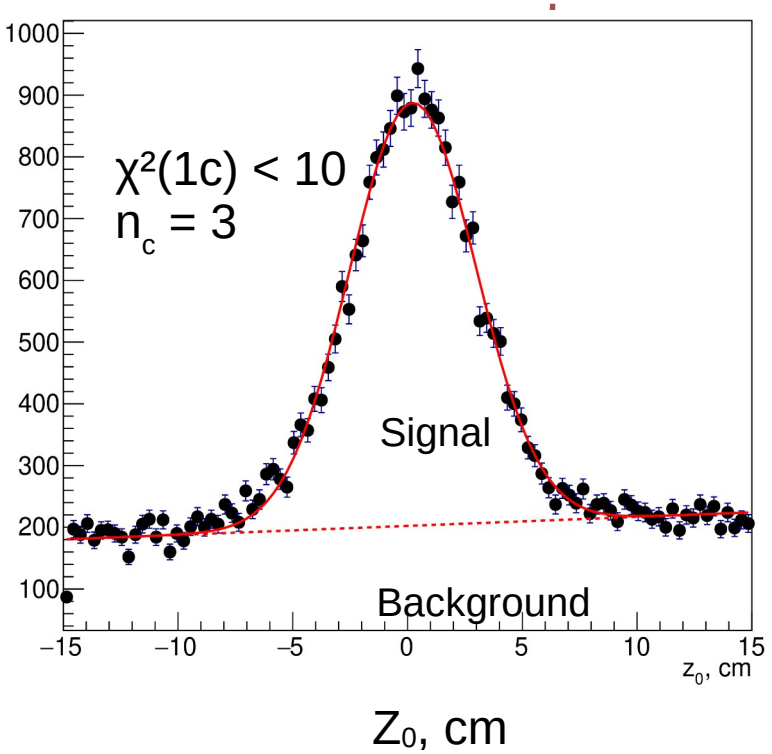
$M(\omega') = 1190 \pm (45/38)$	(1450 ± 60)
$\Gamma(\omega') = 380 \pm (42/31)$	(450 ± 300)
$M(\omega'') = 1640.7 \pm (7.1/7.8)$	(1670 ± 150)
$\Gamma(\omega'') = 159 \pm (15/14)$	(300 ± 200)

Phases for ρπ:
$\varphi_{\omega\omega'} = 176° \pm (12/14)$
$\varphi_{\omega\omega''} = -40° \pm (15/18)$
Phases for ρ′π:
$\varphi_{\varphi\omega'} = 173° \pm (11/14)$
$\varphi_{\varphi\omega''} = 30° \pm (15/19)$
Phase for ρπ is measured relatively to ω, for ρ′π - relatively φ.
Input of ρ′π on φ mass taken from KLOE data and was fixed
$\sigma(\varphi \to \rho'\pi) = 47 \pm 14$ (40 ± 15)

Preliminary

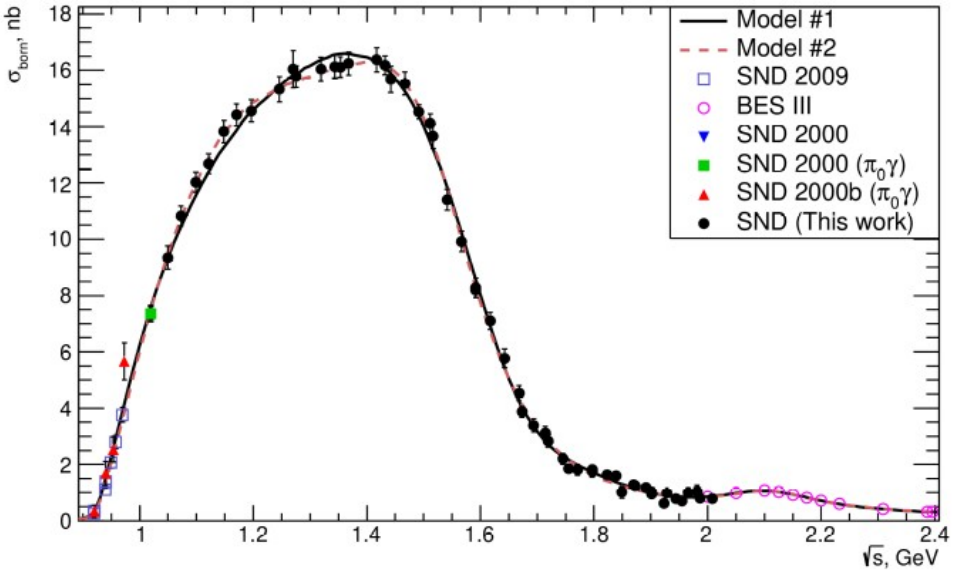
$e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$



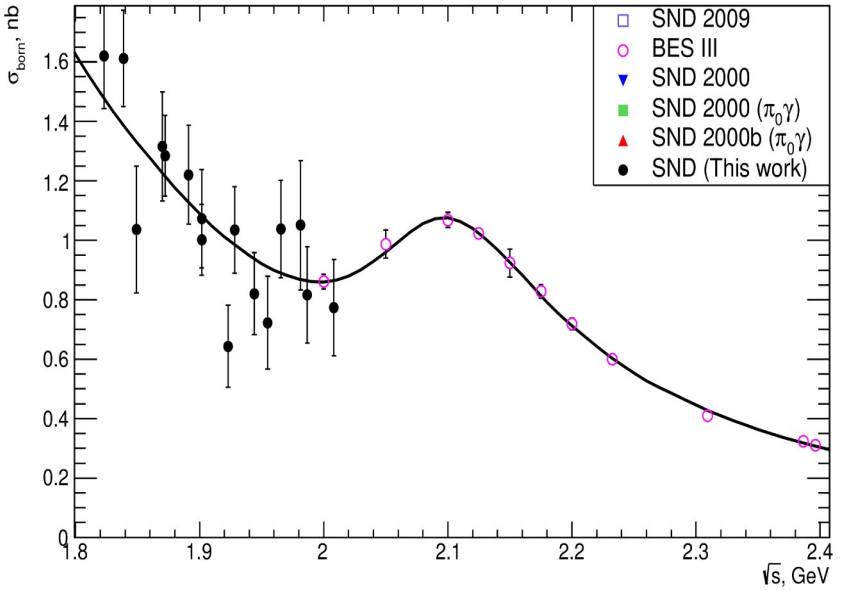


- Events are selected using kinematic reconstruction in $\pi^+\pi^-\pi^0\pi^0$ hypothesys
- For background processes subtraction a distribution of $M_{\pi+\pi-\pi0}$ is used
- Subtraction of beam and cosmic background was done using Z_0 distribution (only when calculating efficiency corrections)

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



Model includes ρ(770), ρ(1450), ρ(1700) and ρ(2150)

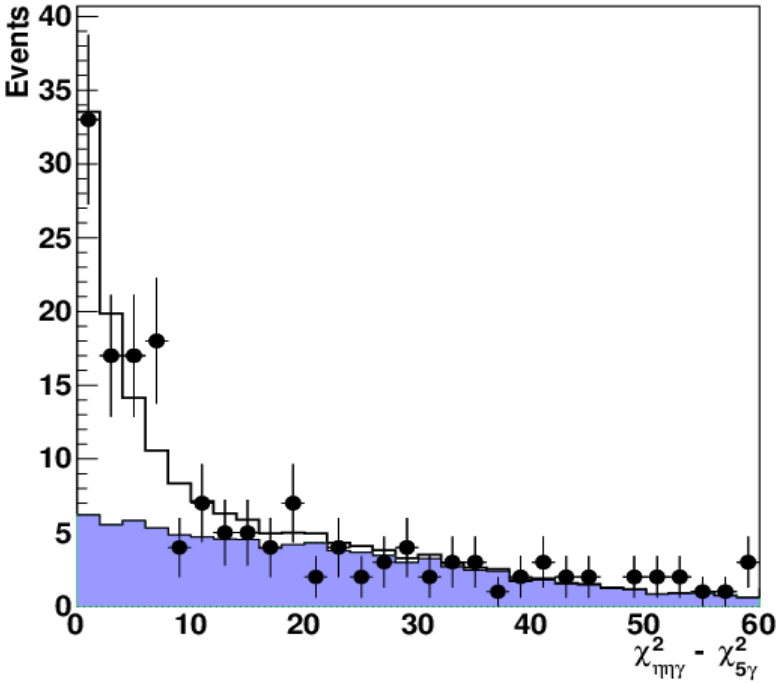


ρ(2150) region (SND and BESIII data)

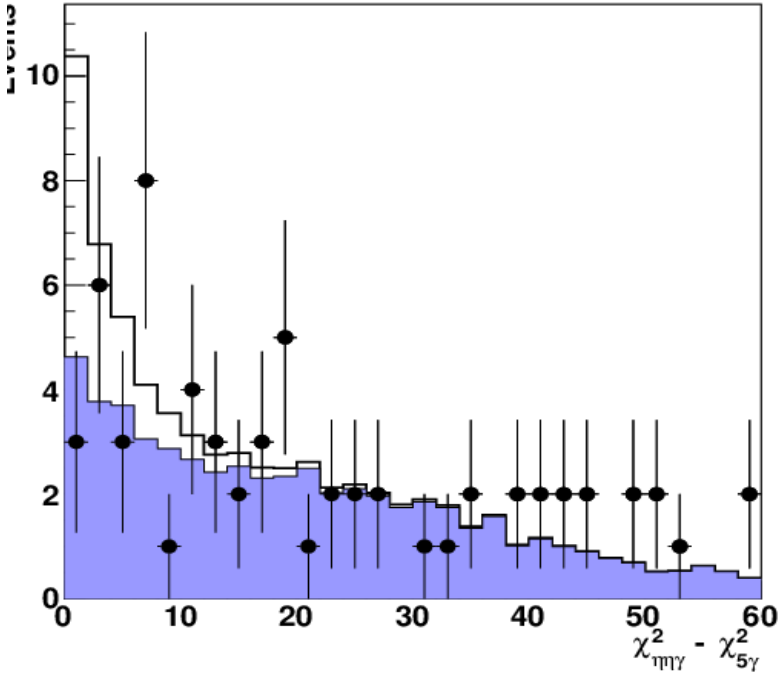
Cross section

E, GeV	syst. error
1.0 — 1.5	3.0 — 4.0 %
1.5 — 2.0	4.0 — 14.3 %

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



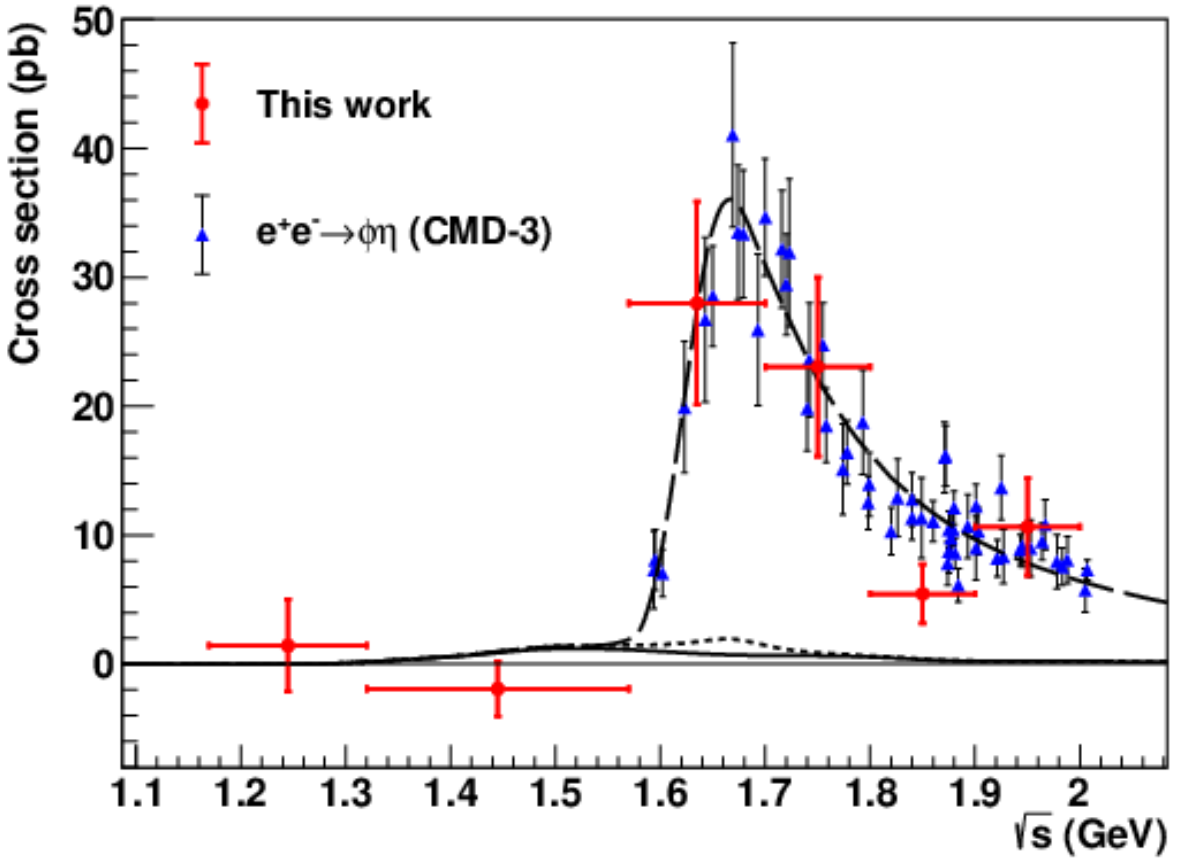
$\chi^2_{\eta\eta\gamma}$-$\chi^2_{5\gamma}$ for selected events



$\chi^2_{\eta\eta\gamma}$-$\chi^2_{5\gamma}$ with additional cut $\chi^2_{\eta\phi}$-$\chi^2_{5\gamma}$>20

- $\chi^2_{\eta\eta\gamma}$-$\chi^2_{5\gamma}$ fit is used for event number calculation
- Effect is described by MC in $e^+e^- \to (\phi\eta, \rho\eta, \omega\eta) \to \eta\eta\gamma$ model
- Background by MC of $\pi^0\pi^0\gamma$, $\eta\pi^0\gamma$, $\pi^0\pi^0\pi^0\gamma$, $\eta\pi^0\pi^0\gamma$, QED 4γ (with fake photons), 5γ
- Data with suppressed φη events are described by background processes - no significant mechanism other then φη, ρη, ωη.

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



E, GeV	syst. error
<1.32	21 %
1.32 — 1.57	23 %
>1.57	12

- Solid curve — ηρ cross section
- Dotted curve — ηρ+ωρ cross section
- Dashed curve — ηφ+ηρ+ωρ cross section

Published in Eur. Phys. J. C (2022) 82:168

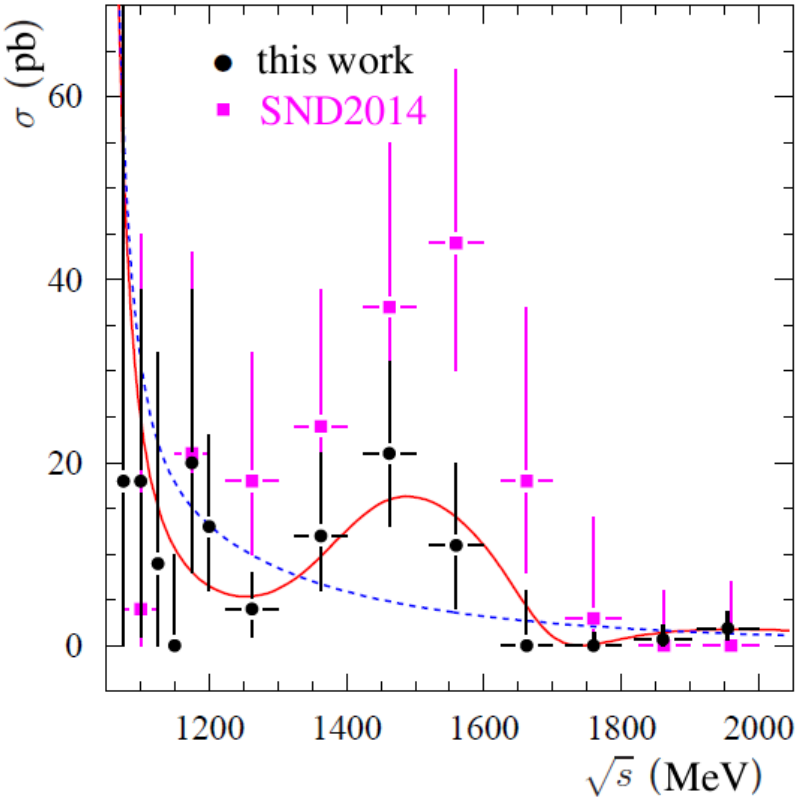
$e^+e^- \to \eta\gamma$

$$\sigma_{\eta\gamma}(\sqrt{s}) = \left(\frac{k_\gamma(\sqrt{s})}{\sqrt{s}}\right)^3 \left| \sum_{V=\rho,\ \omega,\ \phi,\ldots} A_V(\sqrt{s}) \right|^2$$

$$A_V(\sqrt{s}) = \frac{m_V \Gamma_V(m_V) e^{i\varphi_V}}{D_V(\sqrt{s})} \sqrt{\frac{m_V^3}{k_\gamma(m_V)^3} \sigma_{V\eta\gamma}}$$

$$D_V(\sqrt{s}) = m_V^2 - s - i\sqrt{s}\Gamma_V(\sqrt{s})$$

$$k_\gamma(\sqrt{s}) = \frac{\sqrt{s}}{2}\left(1 - \frac{m_\eta^2}{s}\right)$$



Dashed curve — only ρ, ω, φ
Solide curve includes aslo ρ′ and φ′.

$\sigma_{\rho'\eta\gamma} = 16^{+15}_{-10} \pm 2$ pb

$\sigma_{\phi'\eta\gamma} = 14^{+14}_{-10} \pm 2$ pb

Quark model prediction[1] is

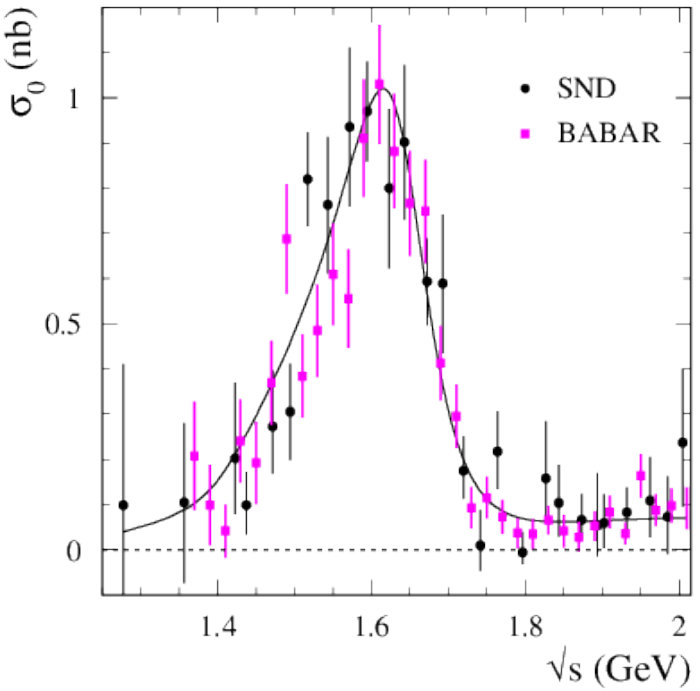
$\sigma_{\rho'\eta\gamma} \approx 15$ pb , $\sigma_{\phi'\eta\gamma} \approx 10$ pb

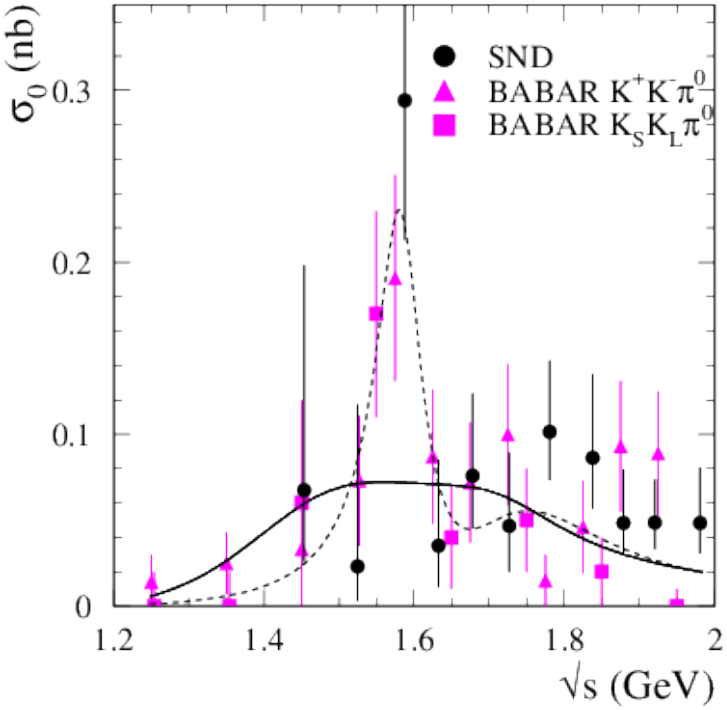
Published in arXiv:2306.12734

[1] F. E. Close, A. Donnachie and Y. S. Kalashnikova, Phys. Rev. D 65, 092003 (2002).

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

$e^+e^- \to K^+K^-\pi^0$ without $\varphi\pi^0$ events ($m_{rec}^{\gamma\gamma} > 1.05$ GeV/c^2)





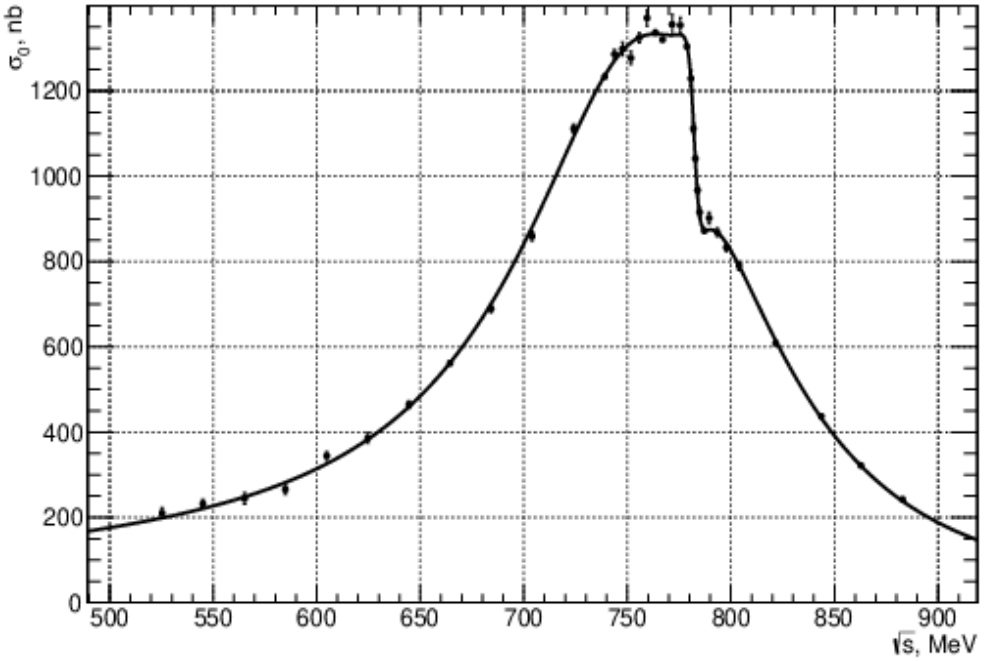
Two models:

1. ρ(1450) and ρ(1700) with masses fixed on PDG values (solid line, χ2/ndf=50/28).
2. Fixed ρ(1700) and free resonance (dashed line), gives M=1585±15 MeV and Γ=75±30 MeV for free resonance, χ2/ndf=38/26. Such vector resonance is not known

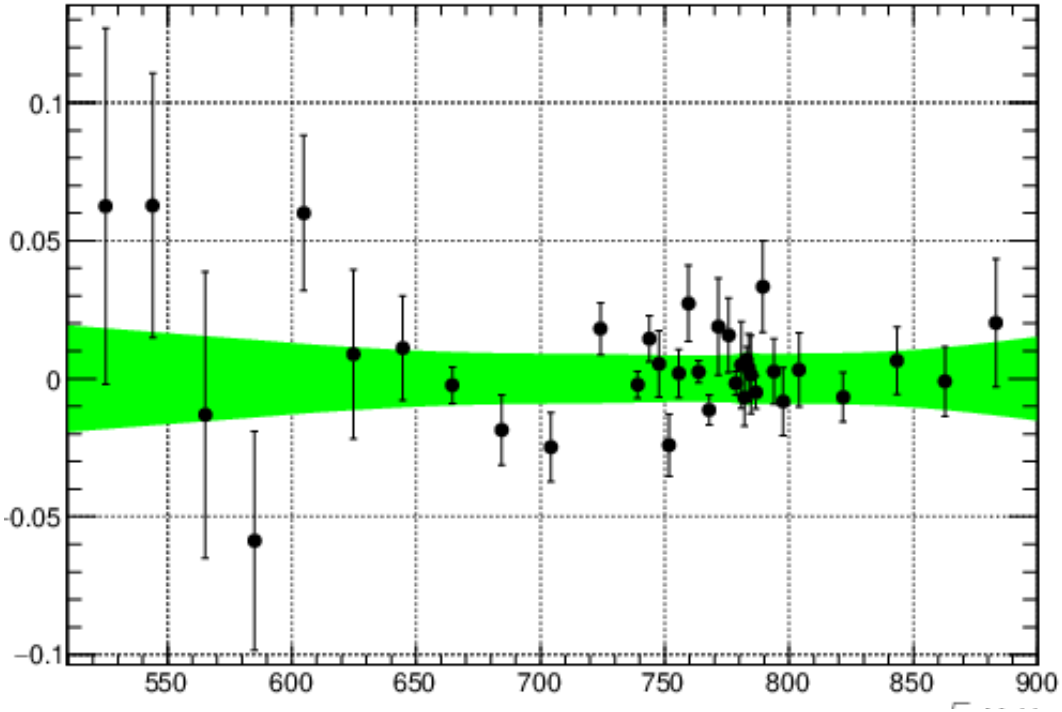
$e^+e^- \to \varphi\pi^0 \to K^+K^-\pi^0$ ($m_{rec}^{\gamma\gamma} < 1.11$ GeV/c^2)

Published in Physics of Atomic Nuclei, 2021, Vol. 84, No. 1, pp. 59–62.

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



Born cross section



Fit - data difference for cross section

Model for fit includes ρ and ω

M_ρ, MeV	775.3±0.5±0.6	
Γ_ρ, MeV	145.6±0.6±0.8	
$\varphi_{\rho\omega}$, deg	110.7±1.1±1.0	
$B_{\rho\to e^+e^-}B_{\rho\to\pi^+\pi^-}$	$(4.889\pm0.015\pm0.039)10^{-5}$	
$B_{\omega\to e^+e^-}B_{\omega\to\pi^+\pi^-}$	$(1.318\pm0.051\pm0.021)10^{-6}$	

E, MeV	syst. error
525 — 600	0.9 — 1.2 %
600 — 883	0.8 %

Published in JHEP01(2021)113

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

Total cross section:

$$\sigma(e^+e^- \to B\bar{B}) = \frac{4\pi\alpha^2\beta C}{3m^2}\left(|G_M|^2 + \frac{2m_B^2}{m^2}|G_E|^2\right)$$

Effective form factor

$$|F|^2 = \frac{|G_M|^2 + |G_E|^2/2\tau}{1+1/2\tau}, \quad \tau = \frac{m^2}{4m_B^2}$$

$m^2=s$ Two measurable values:

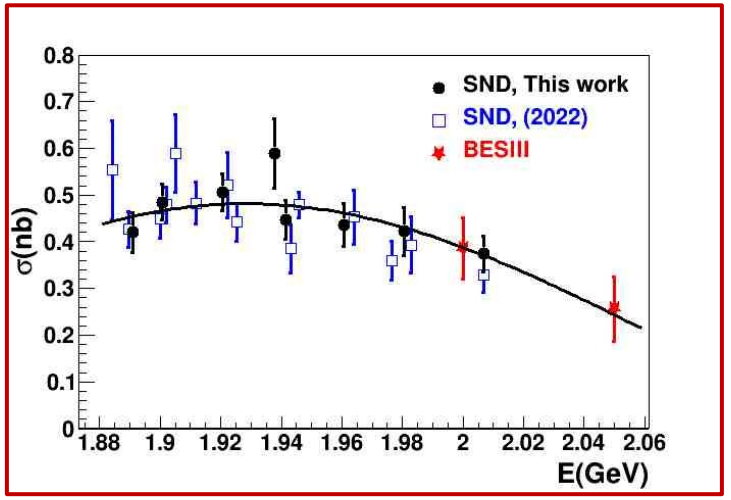
1 - effective FF,

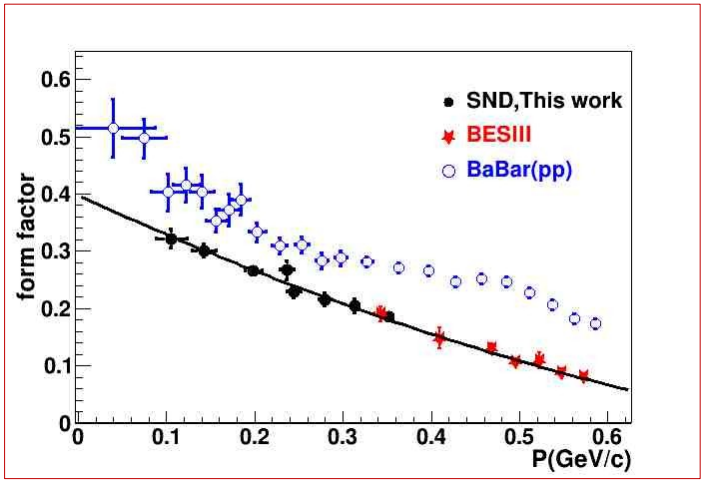
2 - G_E/G_M

C=1 for neutrons

At threshold : $s=4m_B^2 \longrightarrow |G_E| = |G_M| = |F|$

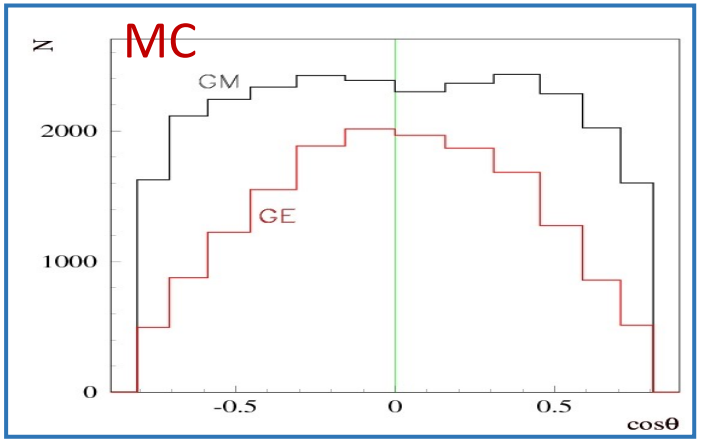
Asymptotic prediction: $F_n = - F_p / 2$

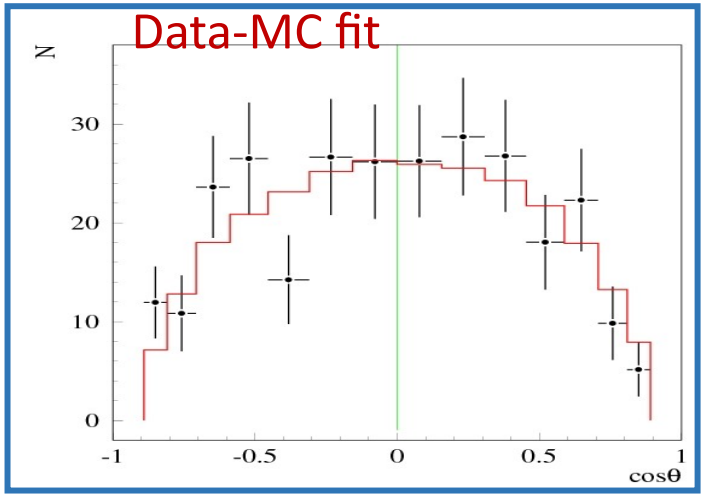


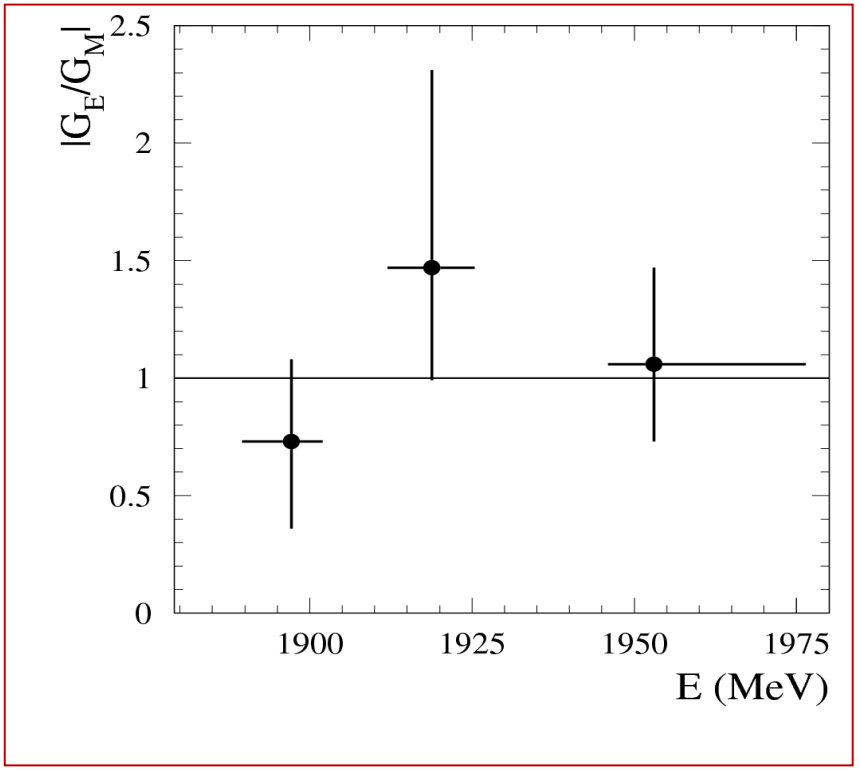


$|G_E|/|G_M|$ measurement

$$d\sigma(e^+e^- \to B\bar{B}) = \frac{\alpha^2 \beta C^2}{4m^2}\left(|G_M|^2(1+\cos^2\theta) + \frac{4m_B^2}{m^2}|G_E|^2(1-\cos^2\theta)\right)d\Omega$$



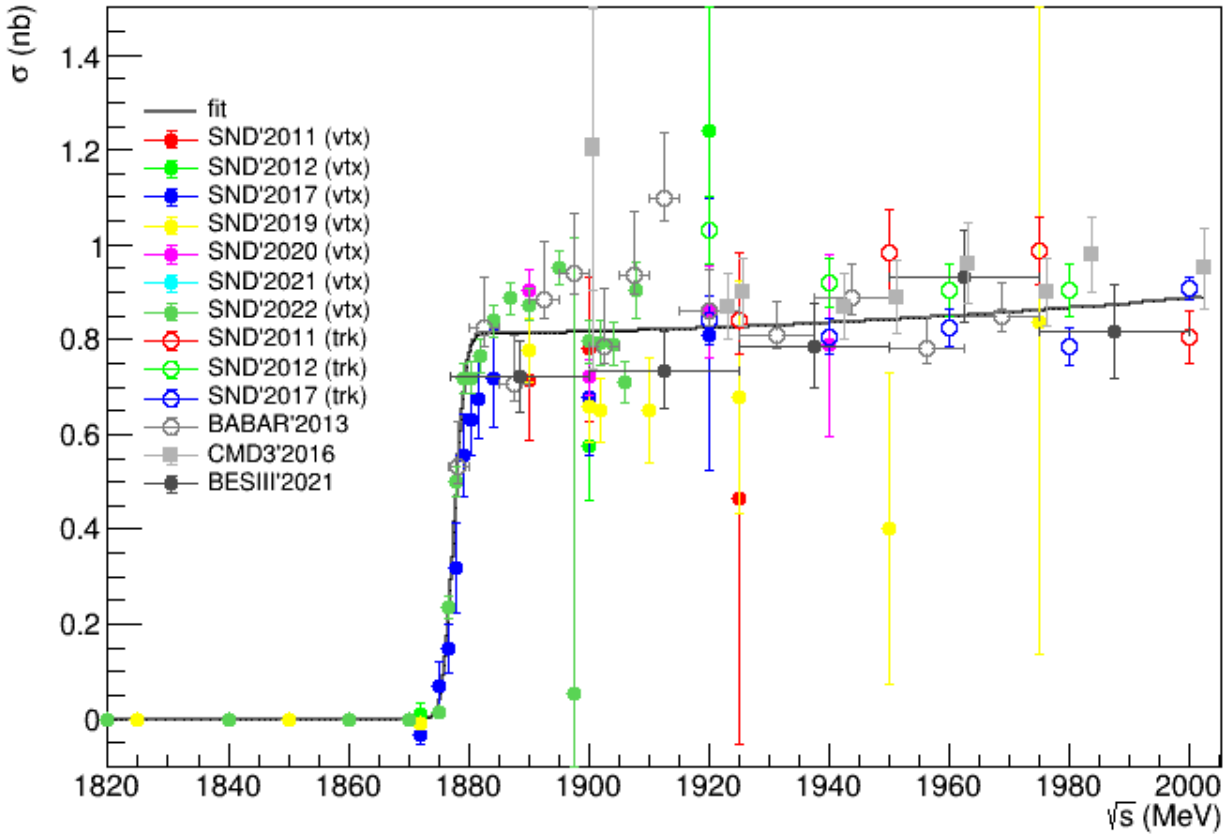




- More then 2500 $n\bar{n}$ pairs detected.
- Effective form-factor was measured, consistent with BESIII results for greater momentum
- $|G_E|/|G_M|$ is consistent with 1 near threshold

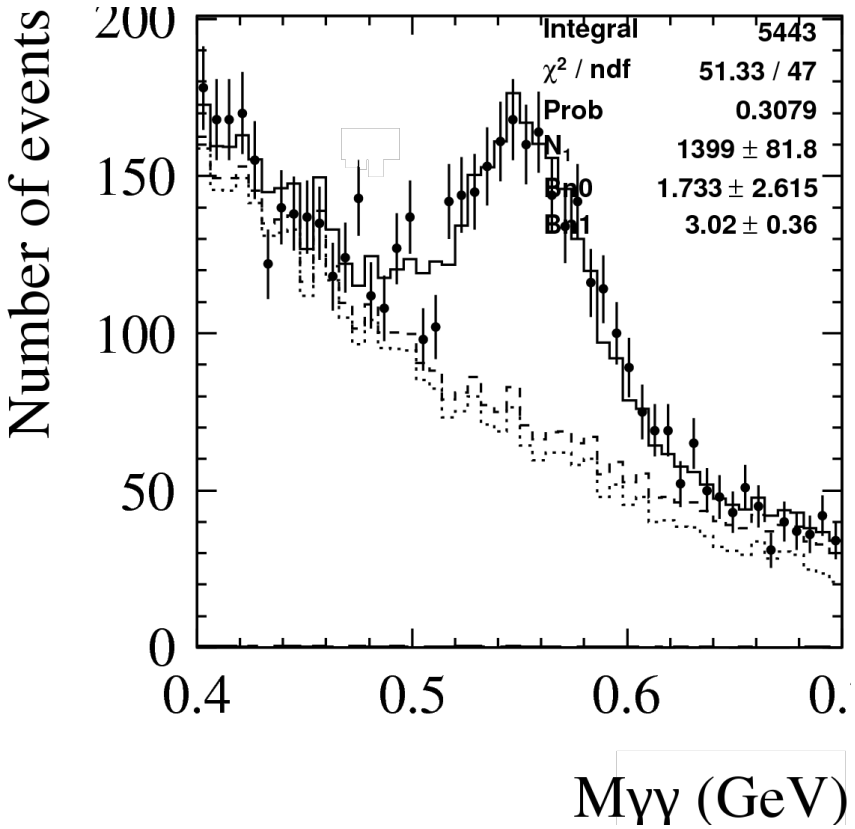
Published in Eur.Phys.J.C 82 (2022) 8, 761

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

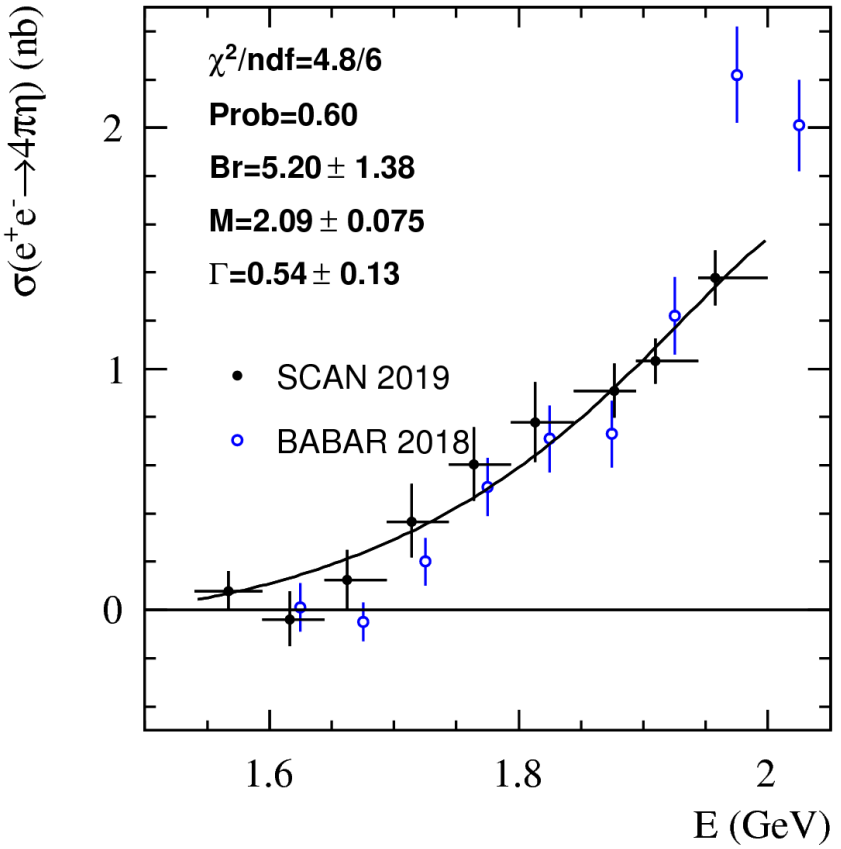


Preliminary

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



Background subtraction using $M_{\gamma\gamma}$



Fit is done in a model
$e^+e^- \to \varphi(2170) \to \eta\pi^+\pi^-\pi^0\pi^0$

Preliminary

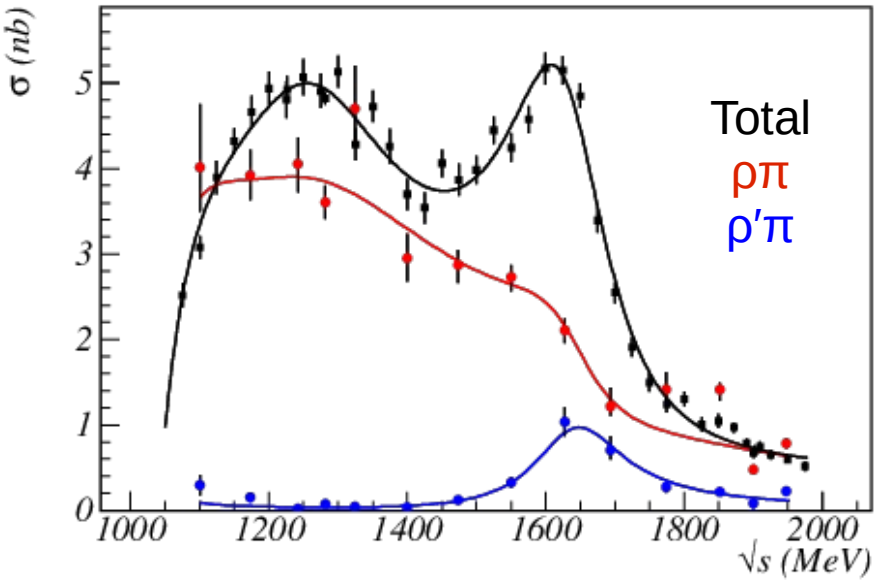
Summary

- In experiment SND at VEPP2000 the following processes are studied:
- $e^+e^- \to \pi^+\pi^-\pi^0$
- $e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$
- $e^+e^- \to \eta\eta\gamma$
- $e^+e^- \to \eta\gamma$
- $e^+e^- \to K^+K^-\pi^0$
- $e^+e^- \to \pi^+\pi^-$
- $e^+e^- \to n\bar{n}$
- $e^+e^- \to p\bar{p}$
- $e^+e^- \to \eta\pi^+\pi^-\pi^0\pi^0$

- For the most of the processes cross sections are compatible with the previous but has better accuracy
- This results are using statistics of VEPP-2000 until 2021 (including), IL=300 pb^{-1}.
- Results using 2022 and 2023 statistics are coming soon, IL=585 pb^{-1}.

BACKUP

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



Model includes mechanisms:

$e^+e^- \to (\omega, \varphi, \omega', \omega'') \to \rho\pi \to \pi^+\pi^-\pi^0$

$e^+e^- \to (\varphi, \omega', \omega'') \to \rho'\pi \to \pi^+\pi^-\pi^0$

$M(\omega') = 1190 \pm (45/38)$ (1450 ± 60)

$\Gamma(\omega') = 380 \pm (42/31)$ (450 ± 300)

$\sigma(\omega' \to \rho\pi) = 6.62 \pm (0.48/0.70)$ nb

$\sigma(\omega' \to \rho'\pi) = 0.068 \pm (0.018/0.016)$ nb

$M(\omega'') = 1640.7 \pm (7.1/7.8)$ (1670 ± 150)

$\Gamma(\omega'') = 159 \pm (15/14)$ (300 ± 200)

$\sigma(\omega'' \to \rho\pi) = 0.126 \pm (0.052/0.040)$

$\sigma(\omega'' \to \rho'\pi) = 1.31 \pm (0.15/0.14)$

Фазы: для ρπ:

$\varphi_{\omega\omega'} = 176° \pm (12/14)$

$\varphi_{\omega\omega''} = -40° \pm (15/18)$

Фаза для ρ′π:

$\varphi_{\varphi\omega'} = 173° \pm (11/14)$

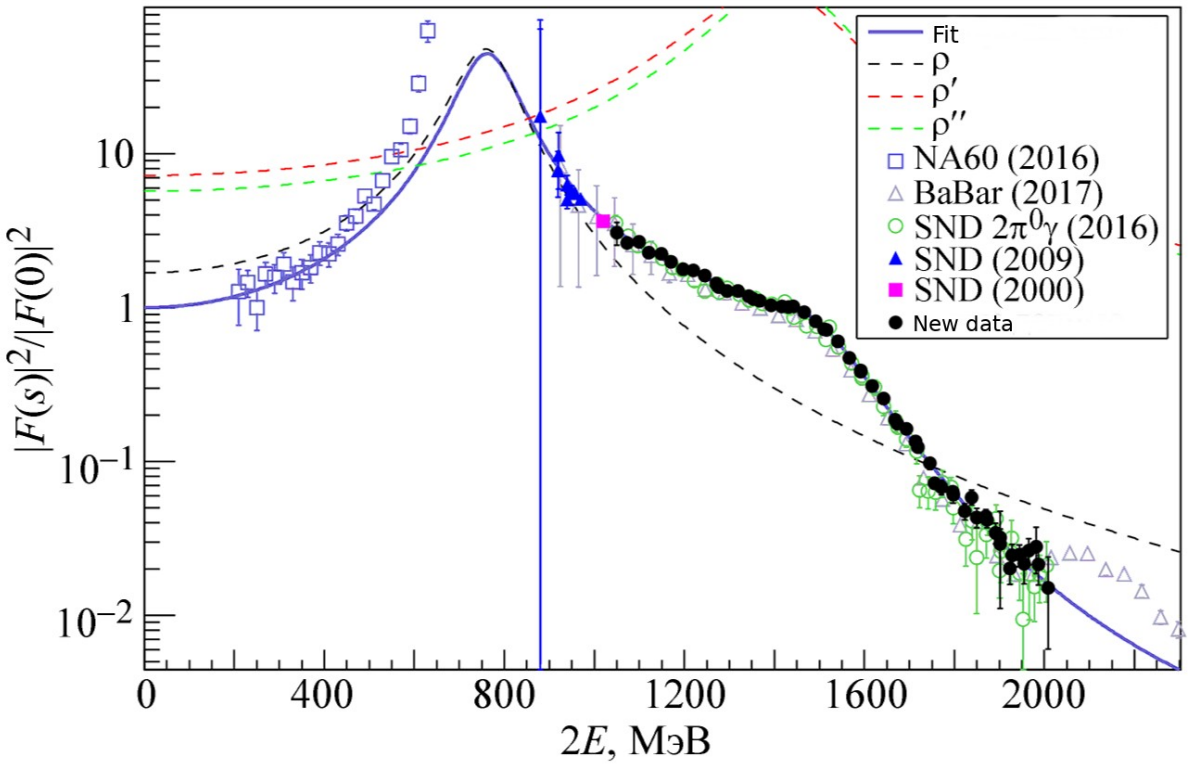
$\varphi_{\varphi\omega''} = 30° \pm (15/19)$

Phase for ρπ is measured relatively to ω, for ρ′π - relatively φ.

Input of ρ′π on φ mass taken from KLOE data and was fixed

$\sigma(\varphi \to \rho'\pi) = 47 \pm 14$ (40±15)

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



Form-factor

$$\sigma_{\text{born}}(E) = \frac{4\pi\alpha^2}{E^3} \left|F_{\gamma\omega\pi}(E)\right|^2 P_f(E)$$