

**TWENTY-FIRST LOMONOSOV
CONFERENCE** August, 24-30, 2023
ON ELEMENTARY PARTICLE PHYSICS
MOSCOW STATE UNIVERSITY

Study of the e^+e^- annihilation into hadrons with the SND detector at the VEPP-2000 collider

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On behalf of SND Collaboration

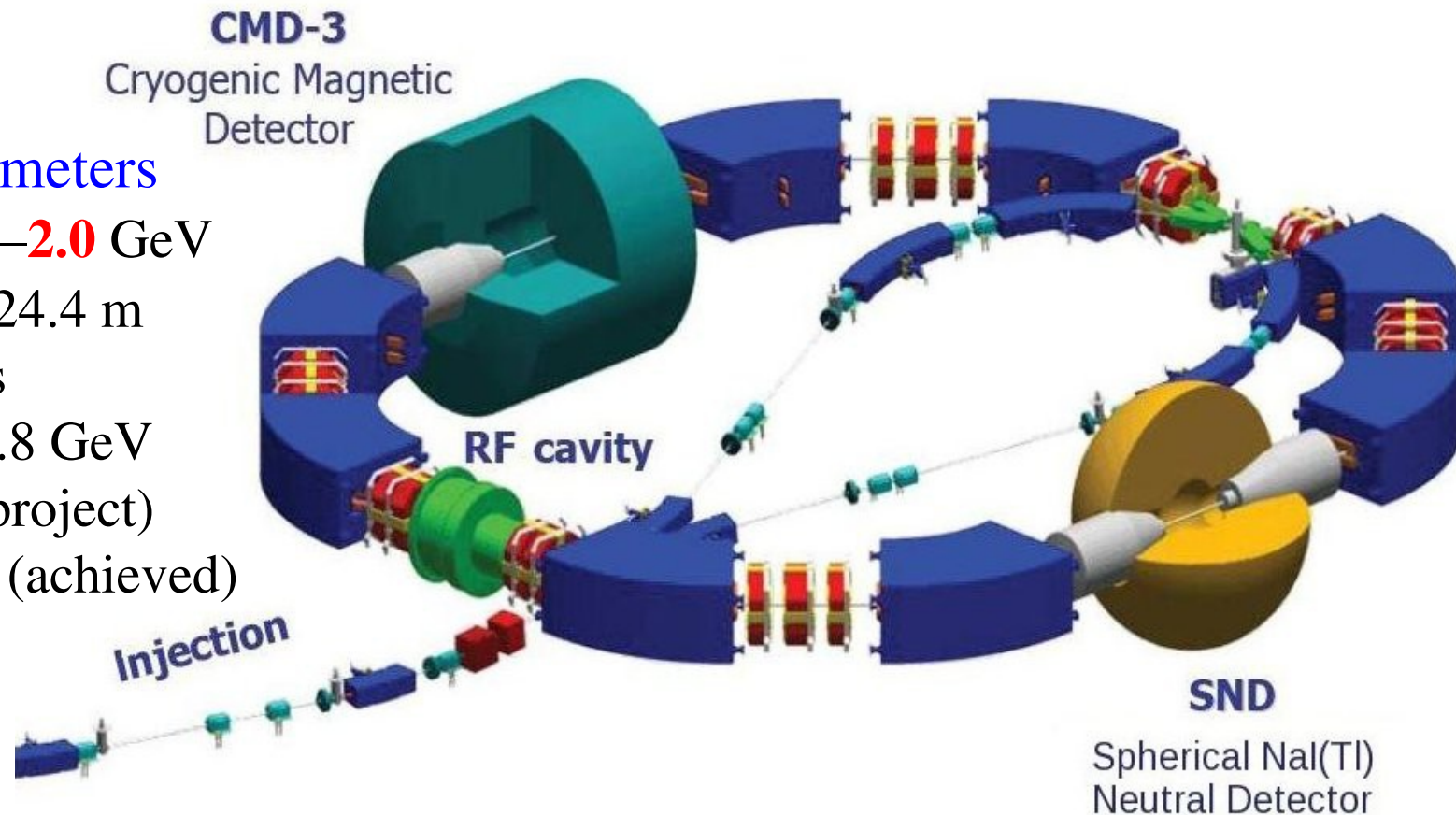
Budker Institute of Nuclear Physics



VEPP-2000 e^+e^- collider (2 x 1000 MeV)

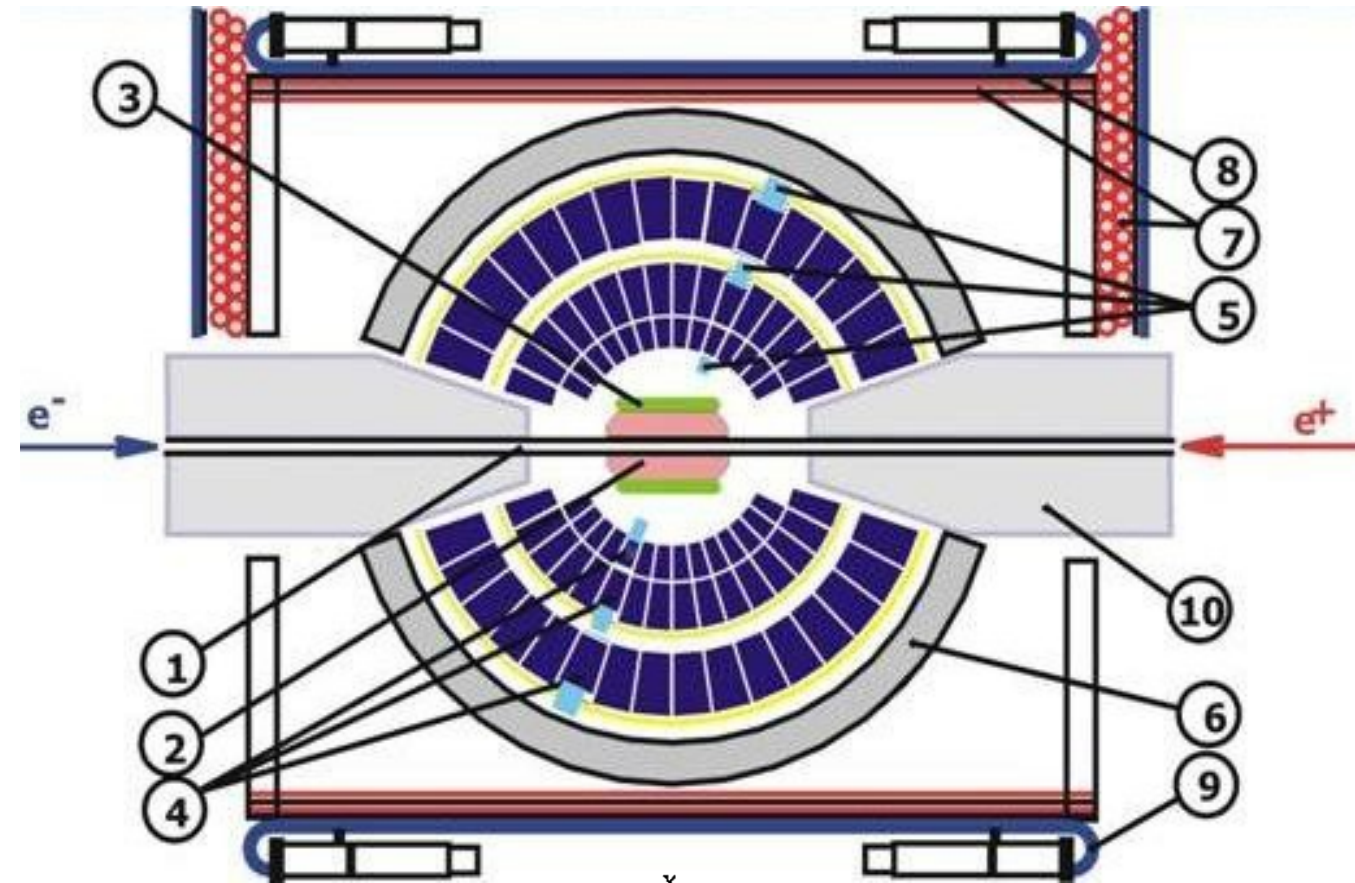
VEPP-2000 parameters

- C.m. energy $E=0.3\text{--}2.0$ GeV
- Circumference — 24.4 m
- Round beam optics
- Luminosity at $E=1.8$ GeV
 - 10^{32} cm⁻²sec⁻¹ (project)
 - $7 \cdot 10^{31}$ cm⁻²sec⁻¹ (achieved)

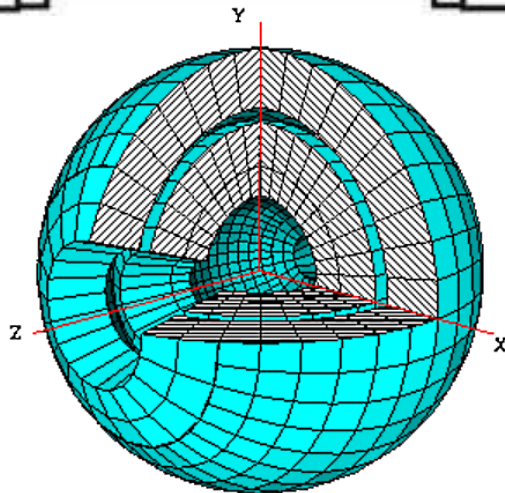


- 2010–2013 — 70 pb⁻¹
- 2013–2016 — upgrade, new injector
- 2016–2021 — 300 pb⁻¹
- 2022–now — 585 pb⁻¹ (not processed)

Since 2013 — beam energy measurements with laser Compton backscattering

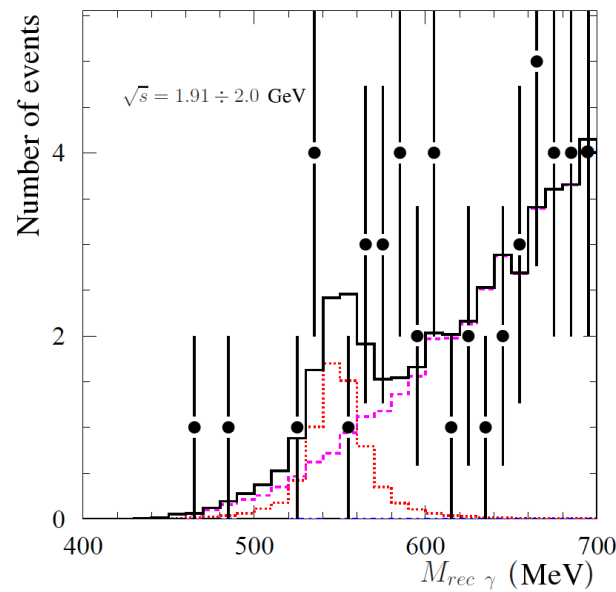
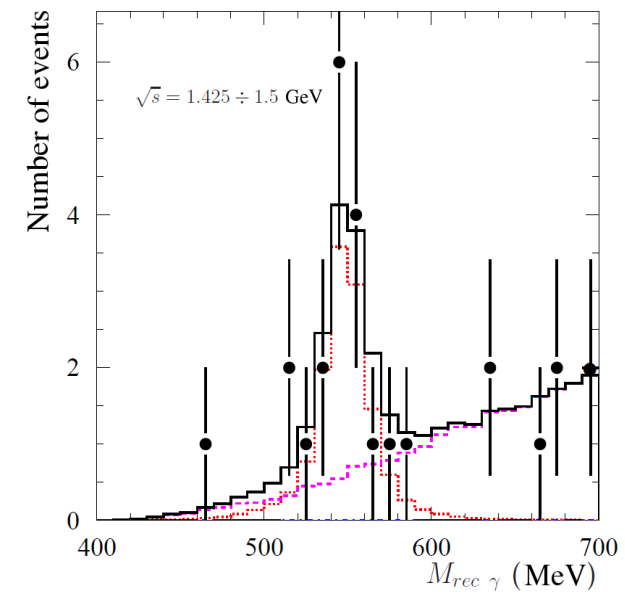
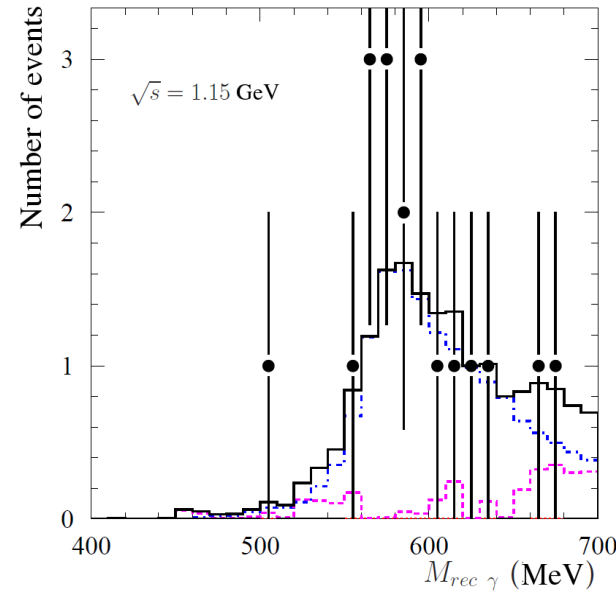
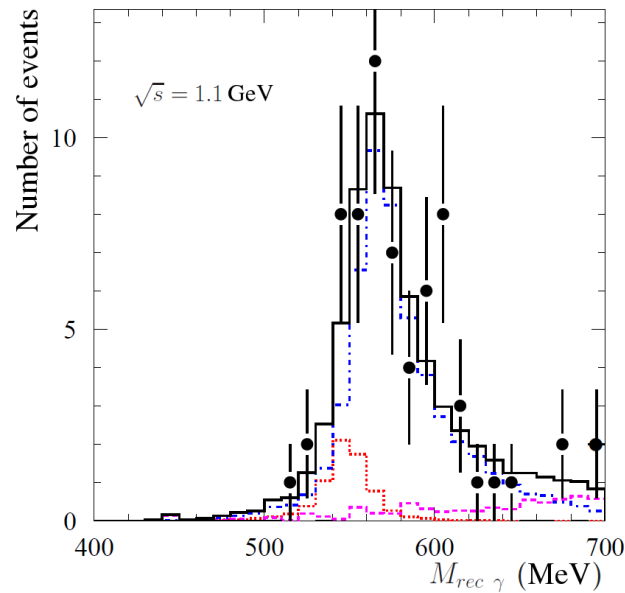


- 1 — beam pipe
- 2 — tracking system
- 3 — aerogel Cherenkov counter
- 4 — NaI(Tl) crystals
- 5 — phototriodes
- 6 — iron absorber
- 7 — muon tubes
- 8 — iron plates
- 9 — scintillation counters
- 10 — focusing solenoids



Solid angle — $0.95 \cdot 4\pi$

Energy $E \geq 1.075$ GeV 2010–2021 scans



Selection conditions

- $N_{\text{charged}} = 0$
- $N_{\gamma} > 6$
- Muon system veto
- $0.7 < E_{\text{tot}} / E < 1.2$
- $P_{\text{cal}} / E < 0.3$
- $E_{\text{tot}} / E - P_{\text{cal}} / E > 0.7$
- $\chi^2(\pi^0\pi^0\gamma) > 20$
- $\chi^2(3\pi^0\gamma) < 50$
- γ — maximal energy photon

M_{γ}^{rec} spectra fit

- $e^+e^- \rightarrow \eta\gamma$ simulation with M_{γ}^{rec}
 - < 1.03 GeV ($\phi\gamma$ channel)
 - fixed
 - other masses (signal) — $N_{\eta\gamma}$
- Background simulation — α_{bkg}

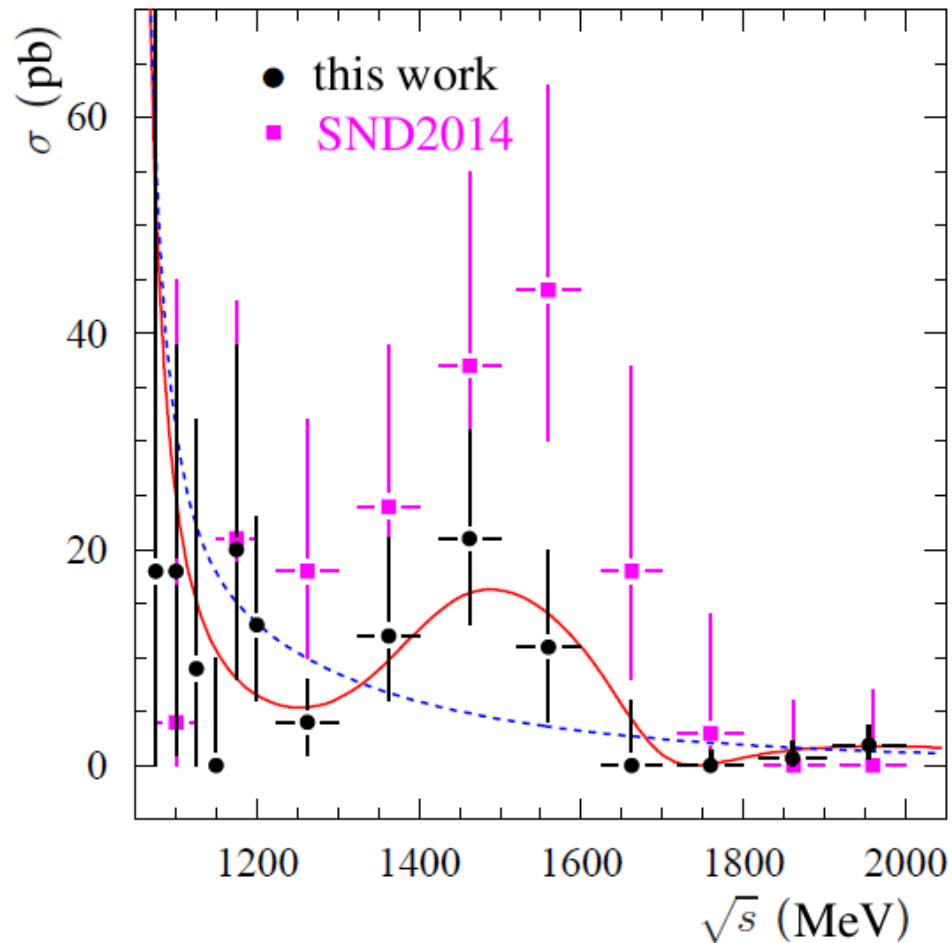


$e^+e^- \rightarrow \eta\gamma \rightarrow 3\pi^0\gamma$ (2)

$$\sigma_{det}^{exp}(E_i) = \frac{N_i}{L_i} \quad \sigma_{det}(E) = \int_0^{x_{max}} \varepsilon(E, xE) F(x, E) \sigma(E\sqrt{1-x}) dx \equiv \sigma(E) \varepsilon_0(E) (1 + \delta(E))$$

$$\sigma^{exp}(E_i) = \frac{\sigma_{det}^{exp}(E_i)}{\varepsilon_0(E_i) (1 + \delta(E_i))} \quad \varepsilon(E, xE) = \varepsilon_0(E) \varepsilon_\gamma(E, xE), \quad \varepsilon_\gamma(E, 0) = 1$$

$$x = 2E_\gamma/E \quad x_{max} : E\sqrt{1-x} > 1.03 \text{ GeV}$$



$$\sigma(E) = \left(\frac{k_\gamma(E)}{E} \right)^3 \left| \sum_{V=\rho, \omega, \phi, \dots} A_V(E) \right|^2$$

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

$$D_V(E) = m_V^2 - E^2 - iE\Gamma_V$$

$$k_\gamma(E) = E/2(1 - m_\eta^2/E^2)$$

$$\sigma_{\rho'\eta\gamma} = 16_{-10}^{+15} \pm 2 \text{ pb (15 pb)} \quad \text{(Quark model prediction)}$$

$$\sigma_{\phi'\eta\gamma} = 14_{-10}^{+14} \pm 2 \text{ pb (10 pb)} \quad \text{(Quark model prediction)}$$

$$\chi^2 / \text{ndf} = 4.7/10$$

$$V = \rho, \omega, \phi$$

$$\chi^2 / \text{ndf} = 11.4/14$$

Energy $E \geq 1.075$ GeV

2019 scan

Selection conditions

Preselection

- $N_{\text{charged}} = 2$
 - $R < 0.5$ cm
 - $z < 10$ cm
 - $\Delta z < 1.5$ cm
- $N_\gamma = 2$ ($E_\gamma > 30$ MeV)
- $0.3 < E_{\text{tot}} / E < 0.8$

After $\pi^+\pi^-2\gamma$ kinematic reconstruction

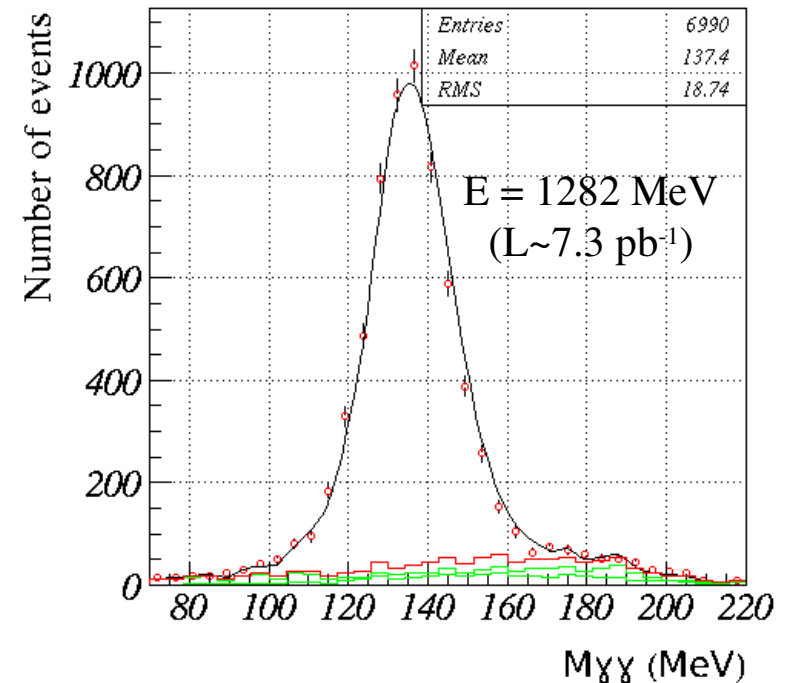
- $\chi^2 < 30$
- $z_{\text{vertex}} < 10$ cm
- $30^\circ < \theta_{\pi, \gamma} < 150^\circ$
- $\Delta\phi_\pi > 10^\circ$
- $E_{\text{tot}}^{\text{charged}} < 0.6 E$
- $E_{\text{tot}}^{\text{outer}} < 70$ MeV
- $E_\gamma > 50$ MeV

$M_{\gamma\gamma}$ spectra fit

to obtain cross section

- Signal: $e^+e^- \rightarrow 3\pi$ simulation
- **Background**: simulation of
 - fixed: $\pi^+\pi^-2\pi^0, 2(\pi^+\pi^-)\pi^0$
 $K_S K_L, K^+K^-\pi^0, K_{S(L)} K^\pm \pi^\mp$
 - fitted: $\pi^+\pi^-\gamma$

Preliminary



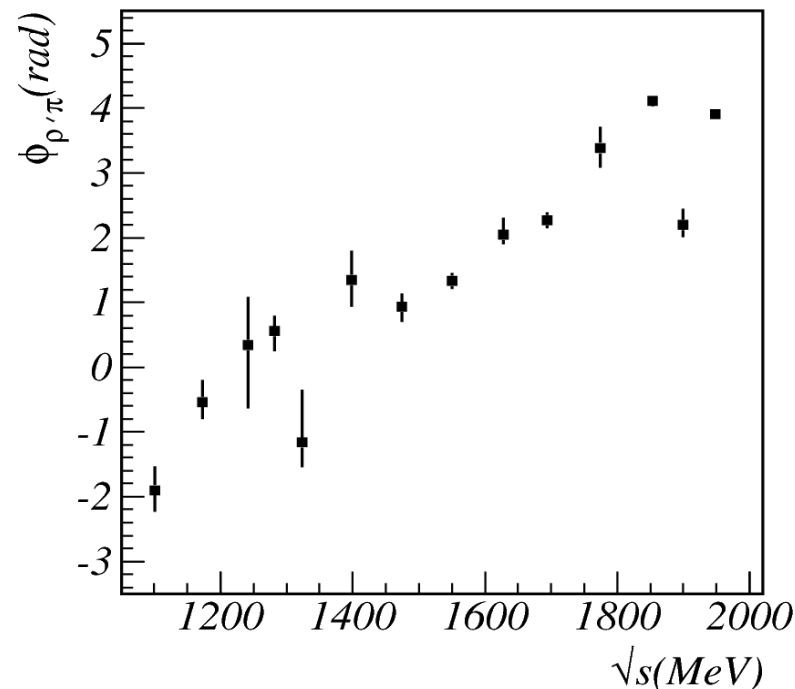
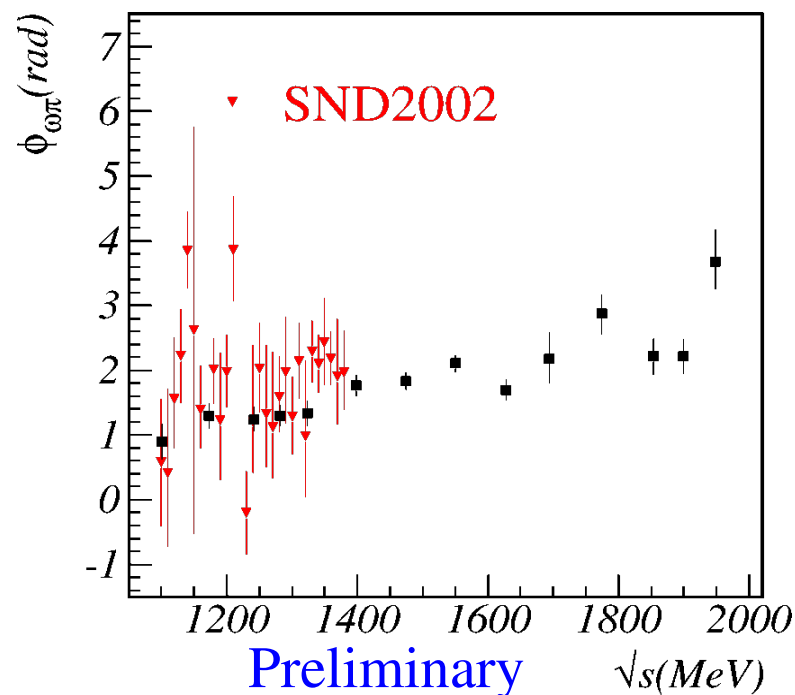
Intermediate states

Fractions of $\rho\pi$, $\rho'\pi$ and $\omega\pi^0$ are measured by the fit of Dalitz-plot $(M_{\pi^+\pi^0})^2$ vs $(M_{\pi^+\pi^-})^2$ using model

$$\frac{d\sigma}{d\Gamma} = |\alpha A_{\rho\pi} + \beta A_{\rho'\pi} + \gamma A_{\omega\pi^0}|^2$$

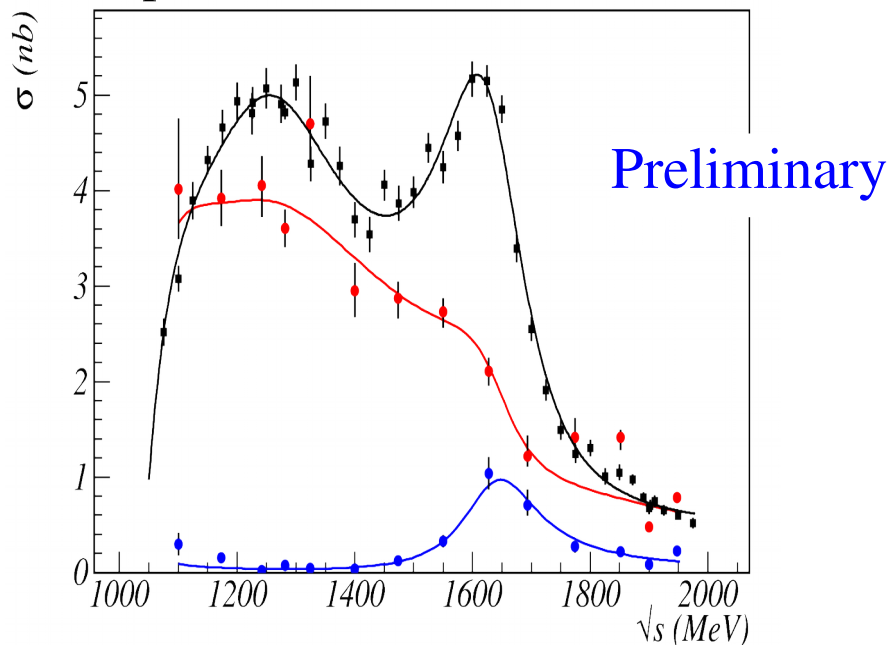
- fit parameters: α , β , γ , $\phi_{\rho\pi-\omega\pi^0}$, $\phi_{\rho\pi-\rho'\pi}$
 - γ ($\omega\pi^0$) varies nearby value calculated from PDG within its error
- Dalitz-plots
 - 42 energy points are combined (by 3) into 14 ranges
 - additional conditions
 - ▶ $\chi^2 < 20$
 - ▶ $110 < M_{\gamma} < 170$ MeV

SND2002: M.N. Achasov et al. (SND Collaboration),
Phys. Rev. D 66, 032001 (2002)



Cross sections

- $\pi^+\pi^-\pi^0$: ω , ϕ , ω' and constant inputs
- $\rho\pi$ and $\rho'\pi$
 - ➔ $\pi^+\pi^-\pi^0$ cross section for points is averaged within energy ranges
 - ➔ multiplied on measured fractions
 - ➔ combined fit is done
 - ▶ $\rho\pi$: ω , ϕ , ω' , ω''
 - ▶ $\rho'\pi$: ϕ , ω' , ω''
 - ▶ interference with measured $\varphi_{\rho\pi-\rho'\pi}$ phase is accounted for



$$M(\omega') = 1190^{+45}_{-38} \quad (1450 \pm 60)$$

$$\Gamma(\omega') = 380^{+42}_{-31} \quad (450 \pm 300)$$

$$M(\omega'') = 1640.7^{+7.1}_{-7.8} \quad (1670 \pm 150)$$

$$\Gamma(\omega'') = 159^{+15}_{-14} \quad (300 \pm 200)$$

$\rho\pi$

$$\sigma(\omega' \rightarrow \rho\pi) = 6.62^{+0.48}_{-0.70}$$

$$\sigma(\omega'' \rightarrow \rho\pi) = 0.126^{+0.052}_{-0.040}$$

$$\varphi_{\omega\omega'} = (176^{+12}_{-14})^\circ$$

$$\varphi_{\omega\omega''} = (-40^{+15}_{-18})^\circ$$

phases are measured relatively to ω
 $\sigma(\phi \rightarrow \rho\pi)$ fixed from SND2002

$\rho'\pi$

$$\sigma(\omega' \rightarrow \rho'\pi) = 0.068^{+0.018}_{-0.016}$$

$$\sigma(\omega'' \rightarrow \rho'\pi) = 1.31^{+0.15}_{-0.14}$$

$$\varphi_{\phi\omega'} = (173^{+11}_{-14})^\circ$$

$$\varphi_{\phi\omega''} = (30^{+15}_{-19})^\circ$$

phases are measured relatively to ϕ
 $\sigma(\phi \rightarrow \rho'\pi) = 47 \pm 14 \quad (40 \pm 15)$

(calculated from KLOE data)

(values to bound fit parameters)

Systematic error estimate is 7.3%

Energy $E \geq 1.05$ GeV

2011-2012 scans

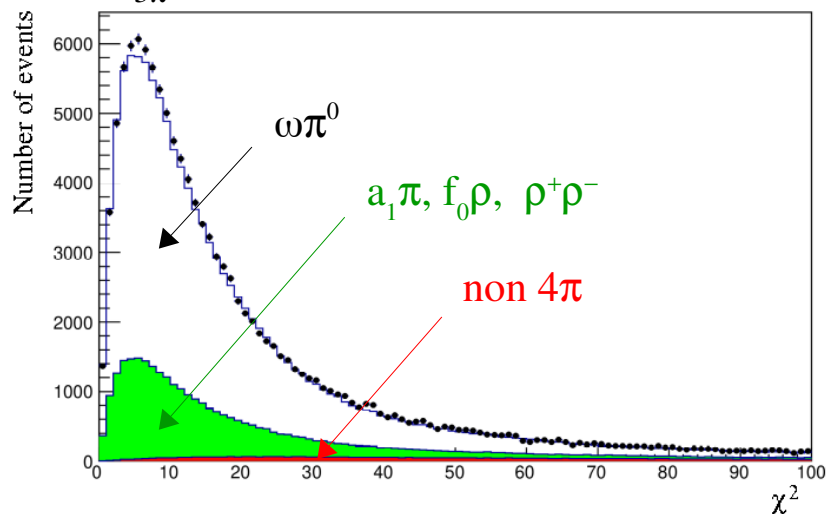
Selection conditions

Preselection

- $N_{\text{charged}} \geq 2$
 - $R < 1$ cm
 - $z < 15$ cm
 - $\Delta\alpha > 20^\circ$ (for $E \leq 1.1$ GeV)
- $N_\gamma \leq 5$ (for $E \geq 1.8$ GeV)

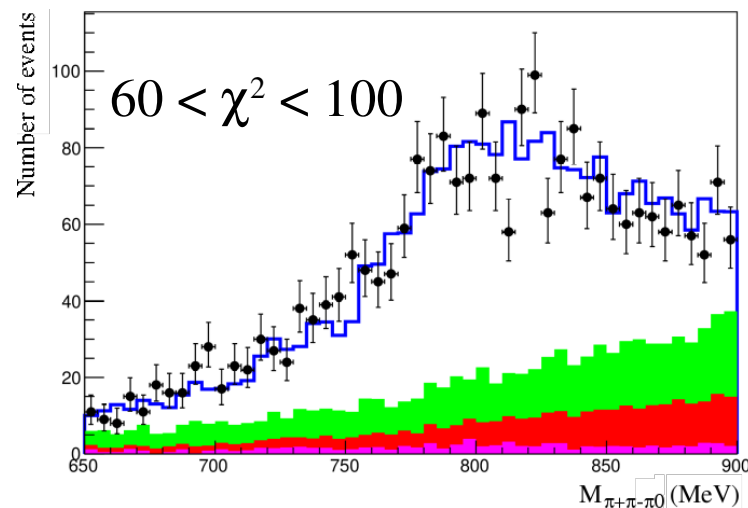
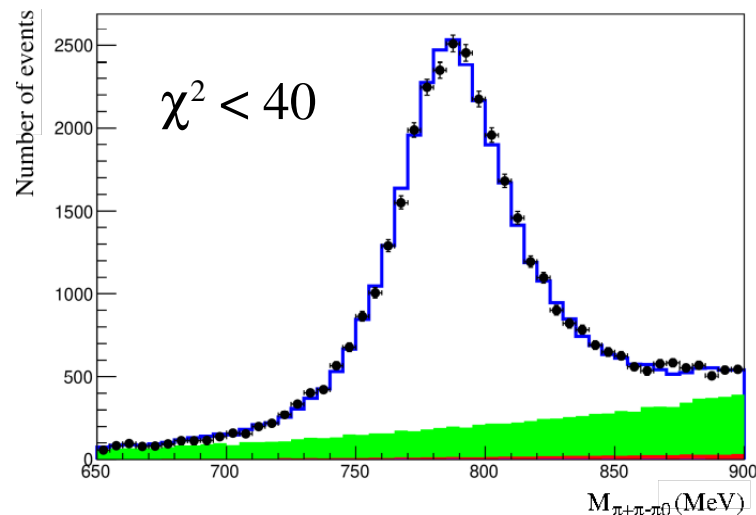
After $\pi^+\pi^-\pi^0$ kinematic reconstruction

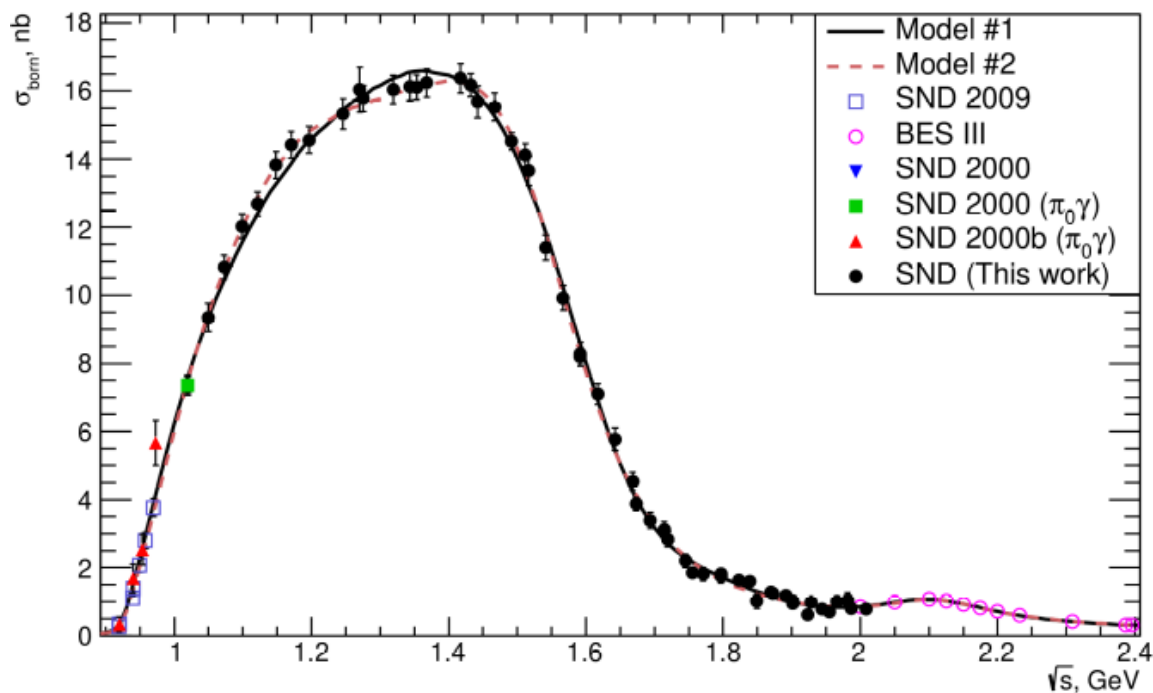
- $\chi^2 < 40$
- $M_{3\pi} < 0.9$ GeV



Background contribution

- Energy points are combined into ranges
- Combined fit of $M_{\pi^+\pi^-\pi^0}$ distributions for
 - $\chi^2 < 40$
 - $60 < \chi^2 < 100$





Cross section

$$\sigma_{vis}^{exp}(E_i) = \frac{N_i}{L_i \epsilon_i}$$

$$\sigma_{vis} = \int_0^{x_{max}} F(x, E) \sigma(E \sqrt{1-x}) dx$$

$$\equiv \sigma(E) (1 + \delta(E))$$

$$\sigma^{exp}(E_i) = \frac{\sigma_{vis}^{exp}(E_i)}{1 + \delta(E_i)}$$

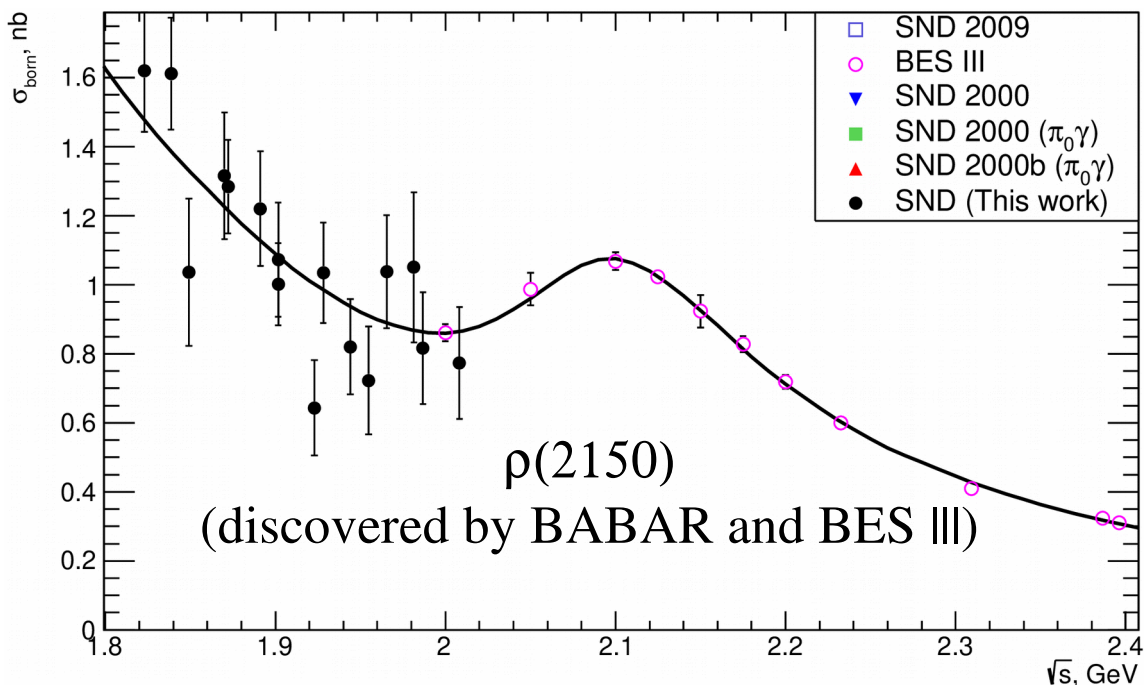
$$\sigma(E) = \frac{4\pi\alpha^2}{E^3} |F_{\gamma\omega\pi}(E)|^2 P_f(E)$$

$$F_{\gamma\omega\pi}(E) = \sum_V \frac{A_V M_V^2 e^{i\phi_V}}{M_V^2 - E_V^2 - iE\Gamma_V(E)}$$

$$V = \rho(770), \rho(1450), \rho(1700) \text{ and } \rho(2150)$$

E (GeV)	Systematic error (%)
1.0–1.5	3.0–4.0
1.5–2.0	4.0–14.3

Ready to be published in arXiv



Energy $E \geq 1.55$ GeV

2011-2021 scans

Selection conditions

Preselection

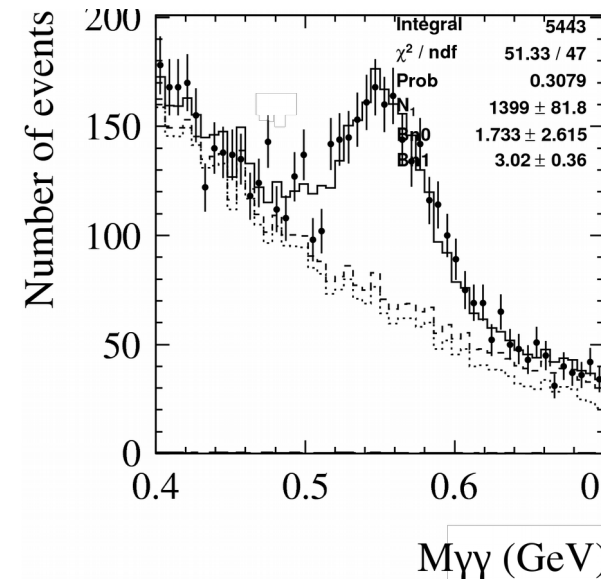
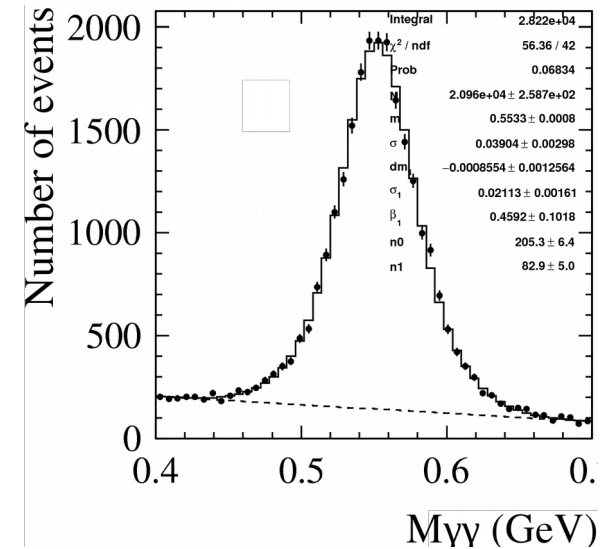
- $N_{\text{charged}} = 2$ or 3
 - ➔ $R < 1$ cm
 - ➔ $z < 15$ cm
- $N_{\gamma} \geq 6$
 - ➔ $E_{\gamma} > 20$ MeV
 - ➔ 10 most energetic are used
- $E_{\text{tot}} > 0.3$ GeV

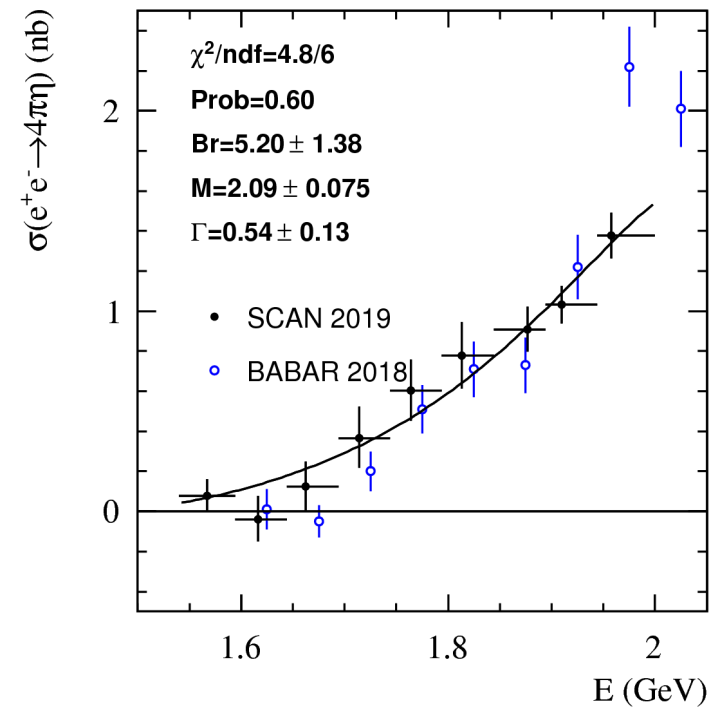
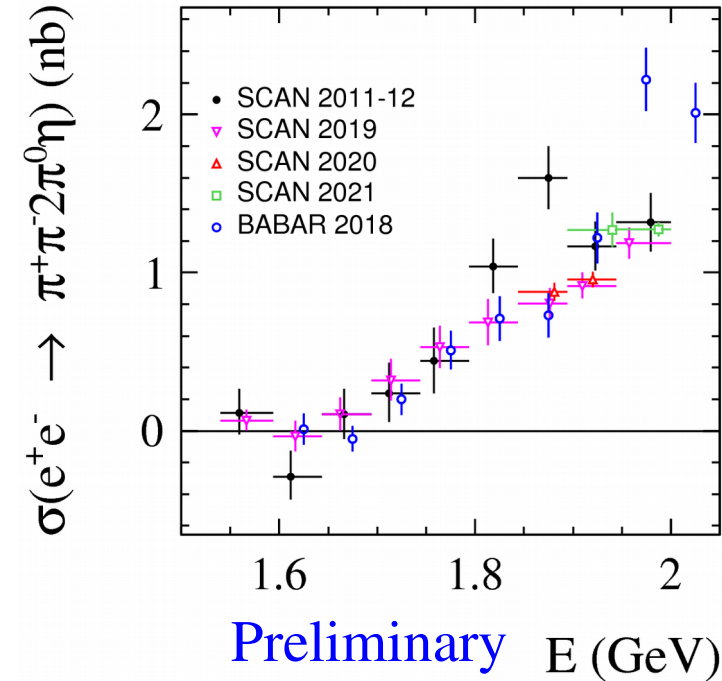
$\pi^+\pi^-\pi^0\gamma\gamma$ kinematic reconstruction

- before
 - ➔ 2 charged particles with best vertex fit
 - ➔ $100 < m_{12}, m_{34} < 170$ MeV
- after
 - ➔ $X^2 < 30$
 - ➔ $N_{\gamma} = 6$
 - ➔ $400 < m_{56} \equiv M_{\gamma\gamma} < 700$ MeV

Background

- $\pi^+\pi^-\pi^0, \pi^+\pi^-\pi^+\pi^-, \pi^+\pi^-\pi^+\pi^0,$
 $K^+K_s^-\pi^-\pi^0$
- $\chi^2_{\pi^+\pi^-\pi^0} > 100$





Cross section

$$\sigma_{vis}^{exp}(E_i) = \frac{N_i}{L_i \epsilon_i}$$

$$\sigma_{vis} = \int_0^{x_{max}} F(x, E) \sigma(E\sqrt{1-x}) dx$$

$$\equiv \sigma(E)(1 + \delta(E))$$

$$\sigma^{exp}(E_i) = \frac{\sigma_{vis}^{exp}(E_i)}{1 + \delta(E_i)}$$

Fit is done in

$$e^+e^- \rightarrow \phi(2170) \rightarrow \omega a_0 \rightarrow \pi^+\pi^-2\pi^0\eta$$

model

$$\sigma(E) = \frac{12\pi}{E^3} \left| \sqrt{\frac{B_V}{P_f(m_V^2)} \frac{m_V^{3/2} \Gamma_V}{D_V}} \right|^2 P_f(s), \quad V = \phi(2170)$$

$$P_f(s) = \frac{2}{9} \int_{(m_\eta+m_\pi)^2}^{(\sqrt{s}-m_\omega)^2} \frac{dm^2}{\pi} \frac{m \Gamma_{a_0} q(s, m, m_\omega)}{(m^2 - m_{a_0}^2)^2 + (m \Gamma_{a_0})^2}$$

- The SND detector has been accumulated $IL=300 \text{ pb}^{-1}$ of integrated luminosity (up to 2021) produced by VEPP-2000 collider in 0.3–2 GeV energy range
- The following processes are presented:
 - $e^+e^- \rightarrow \eta\gamma \rightarrow 3\pi^0\gamma$: new measurement supersedes previous one (is done more correctly)
 - $e^+e^- \rightarrow \pi^+\pi^-\pi^0$: process dynamics has been studied in 1.075–2 GeV energy range
 - $e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^+\pi^-2\pi^0$: the most precise measurement in 1.05–2 GeV energy range
 - $e^+e^- \rightarrow \pi^+\pi^-2\pi^0\eta$: preliminary cross section measurement has been done
- Cross sections of the most of the processes are compatible with the previous results but has better accuracy
- Results on 2022–2023 statistics ($IL=585 \text{ pb}^{-1}$) are coming soon,



BACKUP SLIDES

Background processes

$$e^+e^- \rightarrow \pi^0\pi^0\gamma$$

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

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

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

$$e^+e^- \rightarrow \omega\eta\pi^0$$

$$e^+e^- \rightarrow K_S K_L, K_S \rightarrow \pi^0\pi^0$$

$$e^+e^- \rightarrow K_S K_L, K_S \rightarrow \pi^0\pi^0$$

$$e^+e^- \rightarrow K_S K_L \pi^0\pi^0, K_S \rightarrow \pi^0\pi^0$$

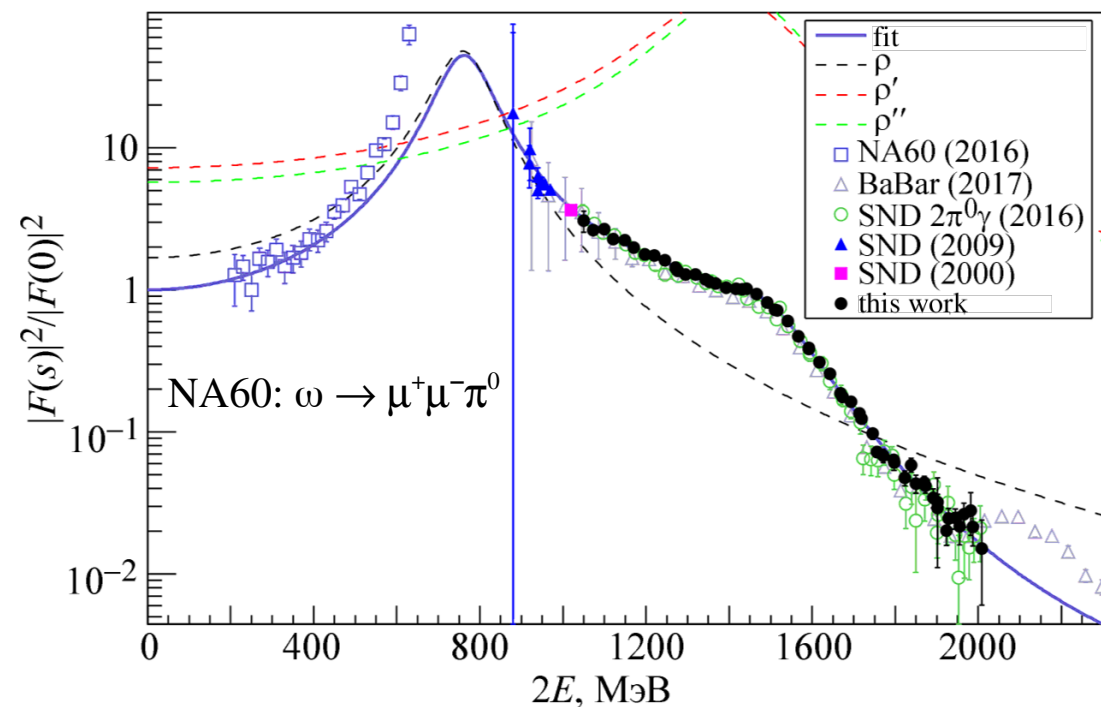
$$e^+e^- \rightarrow K_S K_L \eta, K_S \rightarrow \pi^0\pi^0$$

✓ Cross section is changed since 2014

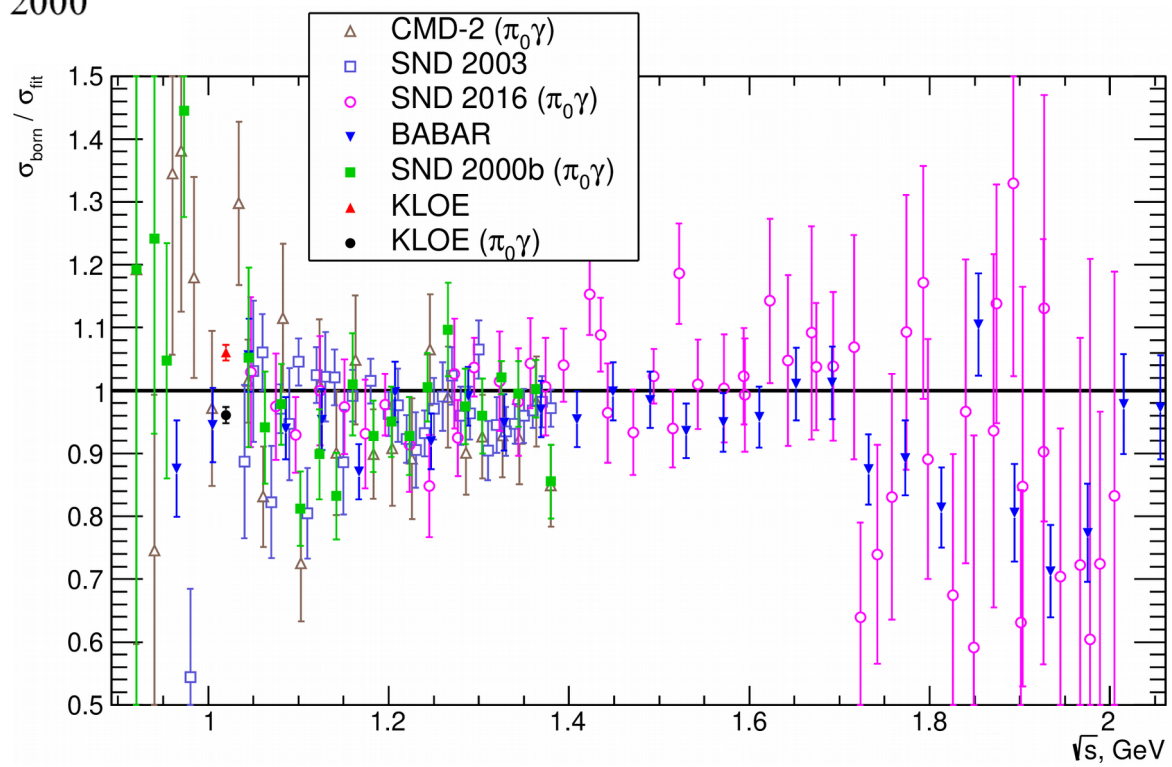
✓ New contributions relative to SND2014



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



Preliminary





$e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^+\pi^-\pi^0$ (2)

