Study of the e^+e^- annihilation into hadrons with the SND detector at the VEPP-2000 collider
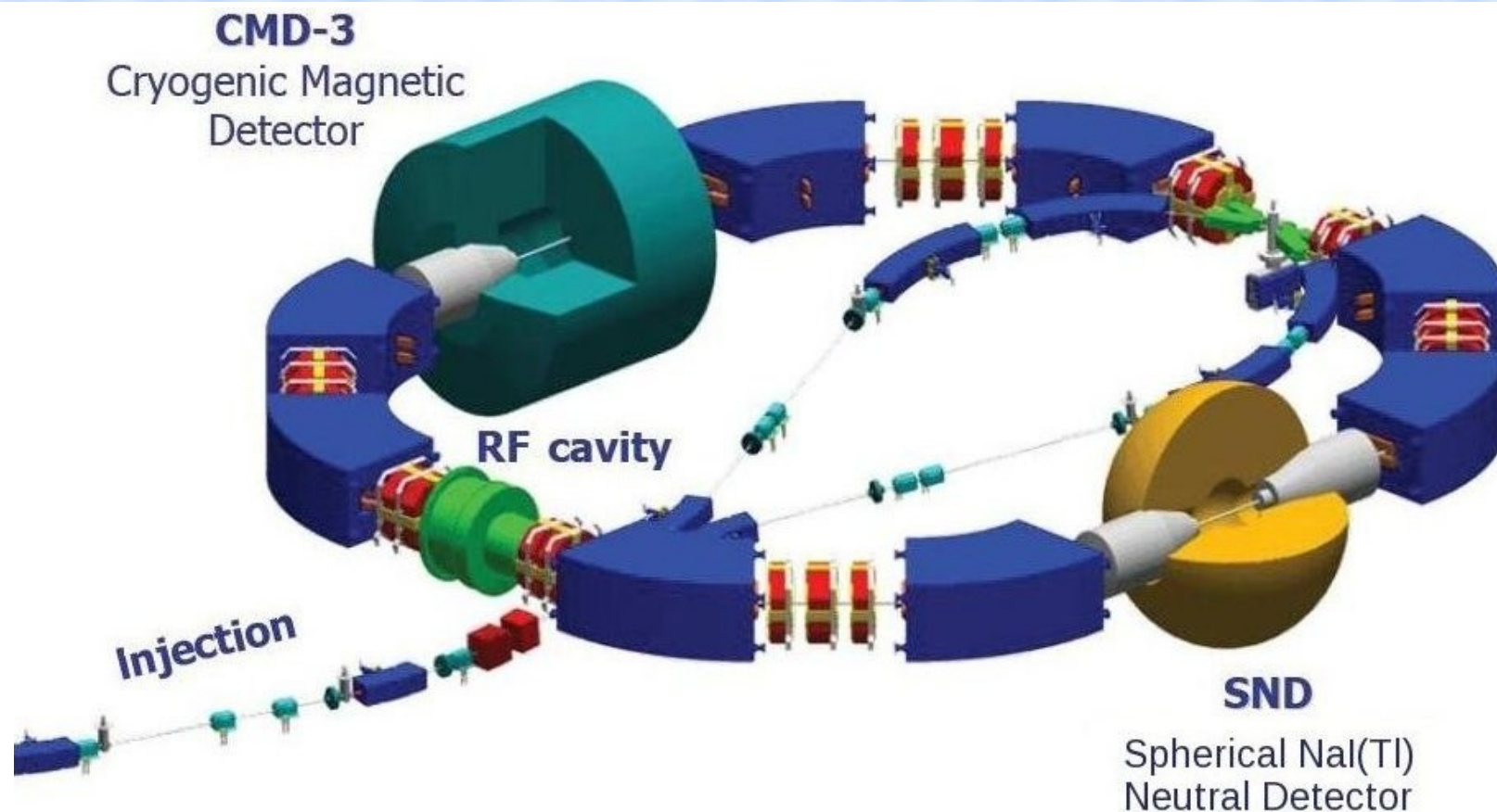
Alexander A. Botov
On behalf of SND Collaboration

Budker Intstitute of Nuclear Physics

CMD-3
Cryogenic Magnetic
Detector

RF cavity

Injection

SND
Spherical NaI(Tl)
Neutral Detector

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
  - 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 — 790 pb⁻¹ (not processed)

Since 2013 — beam energy measurements with laser Compton backscattering

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Since 2013 — beam energy measurements with laser Compton backscattering

- Measurement of total hadronic cross section below 2 GeV for calculation hadronic vacuum polarization contribution into $(g-2)_\mu$.
- Study of hadron production dynamics, i.e. separation between different intermediate states, for example, $\omega\eta$, $\varphi\eta$, 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 C-even resonances production: $e^+e^-\rightarrow\eta$, η', f_1, f_2, a_2, etc.
- Using the radiative return technique as alternative method for measurement of hadronic cross sections.
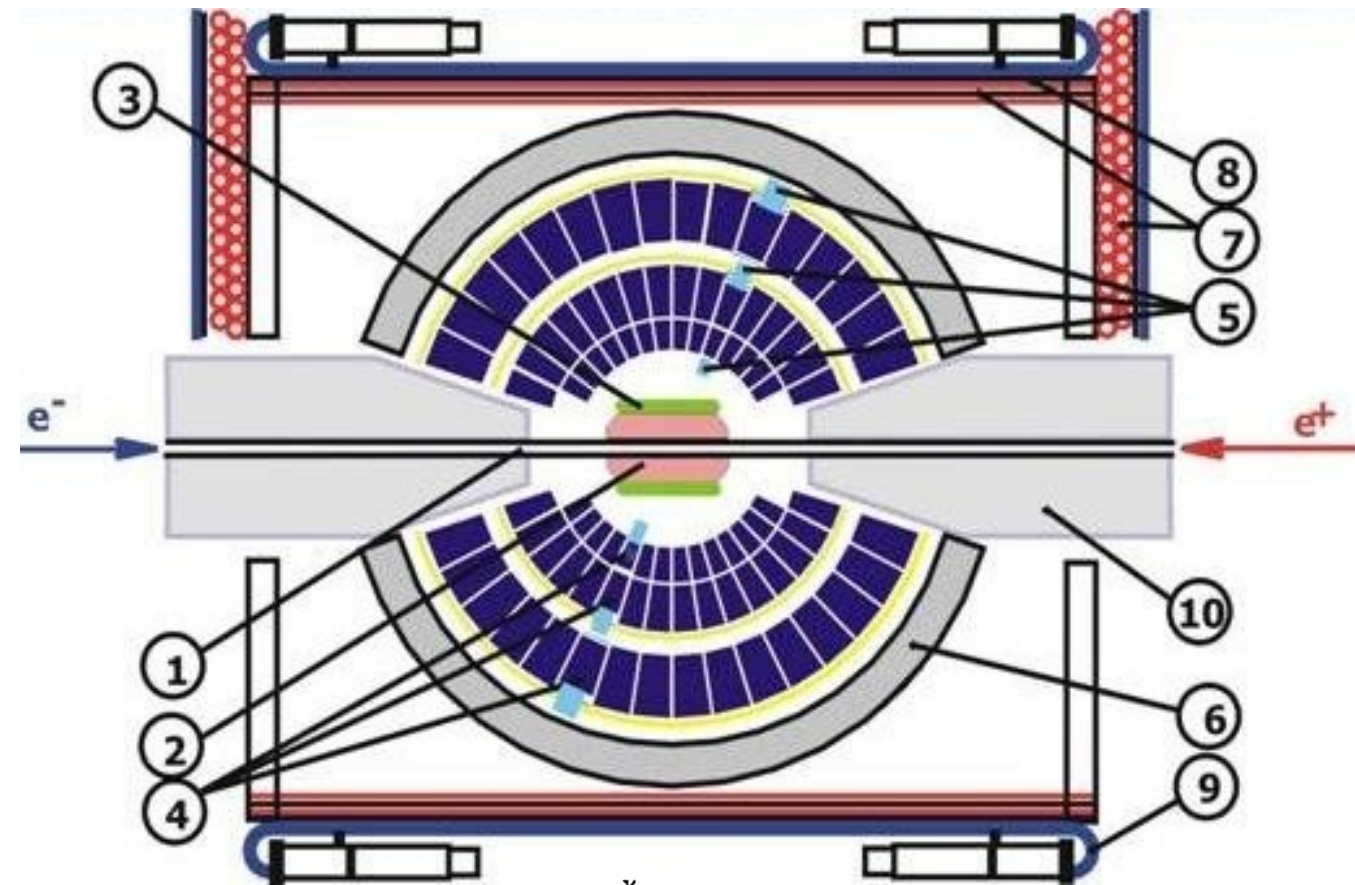
1 — beam pipe
2 — tracking system
3 — aerogel Cherenkov
    counter
4 — NaI(Tl) crystals
5 — phototriodes
6 — iron absorber
7 — muon tubes
8 — iron plates
9 — scintillation counters
10 — focusing solenoids
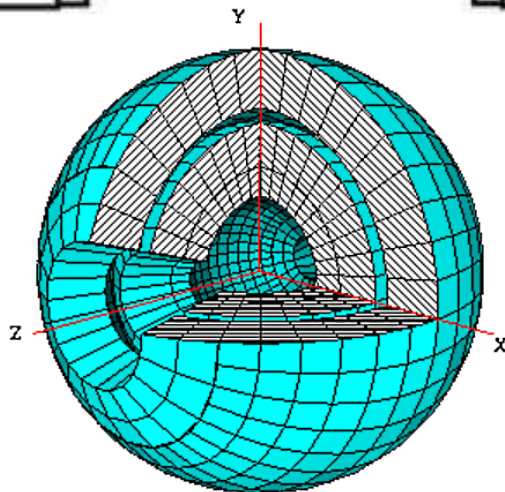
Solid angle — $0.95 \cdot 4\pi$

Energy $E \geq 1.075$ GeV
$L = 746$ pb^{-1} (2010−2024 scans)
$\eta' \to 2\pi^0\eta \to 7\gamma$ mode

$N_{\eta'\gamma} = 25.4^{+8.4}_{-7.6}$
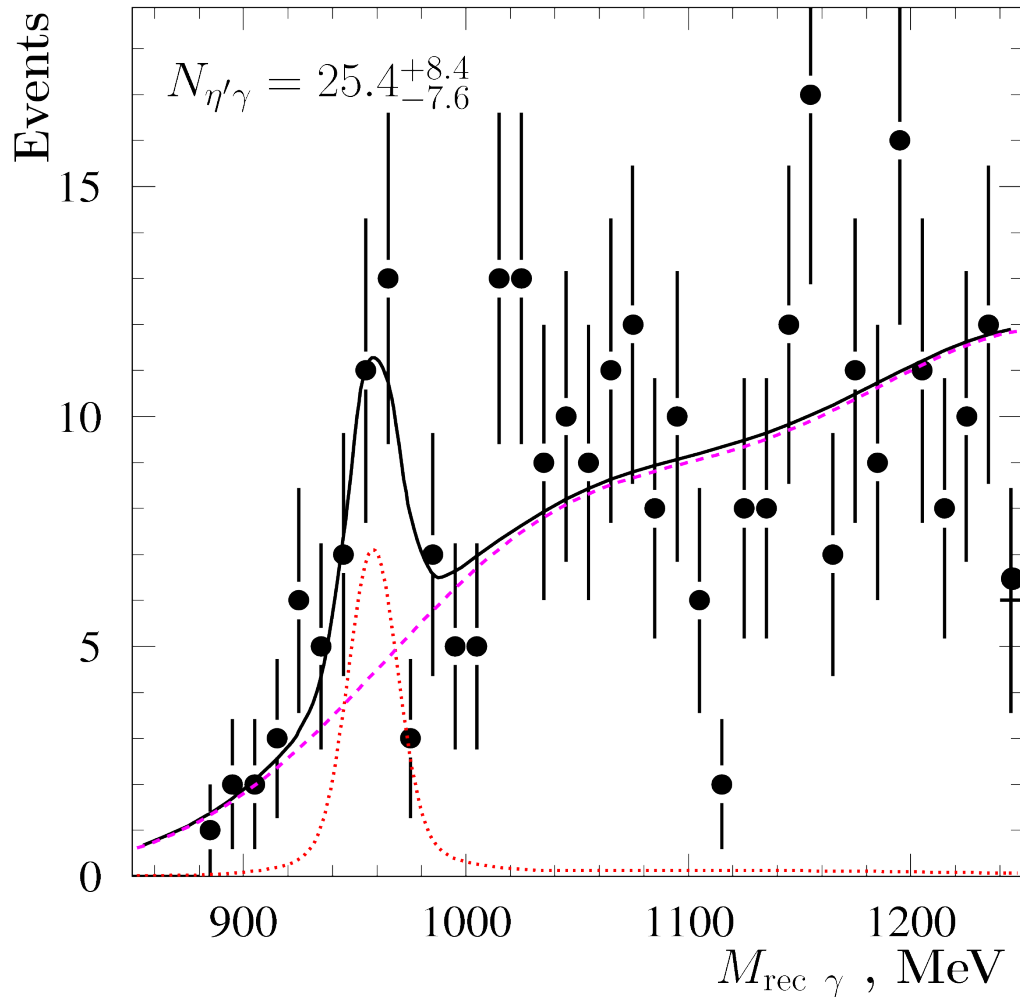
Selection conditions

- $N_{charged} = 0$
- $N_\gamma = 7$
- $E_\gamma > 20$ MeV
- Muon system veto
- $0.7 < E_{tot}/E < 1.2$
- $P_{tot}/E < 0.3$
- $E_{tot}/E - P_{tot}/E > 0.7$
- $\chi^2(2\pi^0\eta\gamma) < 50$
- 7γ hypothesis:
  - no 3 photon pairs with $|M_{\gamma\gamma} - M_{\pi0}| < 35$ MeV
  - no 3 photons with $|M_{3\gamma} - M_\omega| < 35$ MeV $|M_{\gamma\gamma} - M_{\pi0}| < 35$ MeV

M_γ^{rec} spectra fit

- $e^+e^- \to \eta'\gamma$ simulation (without radiative corrections)
- Background simulation — α_{bkg}

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

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

$$x = 2E_\gamma/E \qquad x_{max} = 1 - m_{\eta'}^2/E^2$$

$$\sigma(E) = \left(\frac{k_\gamma(E)}{E}\right)^3 \left| \frac{m_V\Gamma_V}{D_V(E)}\sqrt{\frac{m_V^3}{k_\gamma^3(m_V)}}\sigma_{V\eta'\gamma}\right|^2$$

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

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

For systematics on $\delta(E)$:

V = $\phi(1680)$
$\phi(2170)$

Total signal evidence is 4σ

σ < 13 pb⁻¹ at the 90% CL

σ < 7.5 pb⁻¹ at the 90% CL in ρ(1450) region

(quark model prediction)

Submitted to Phys. Rev. D
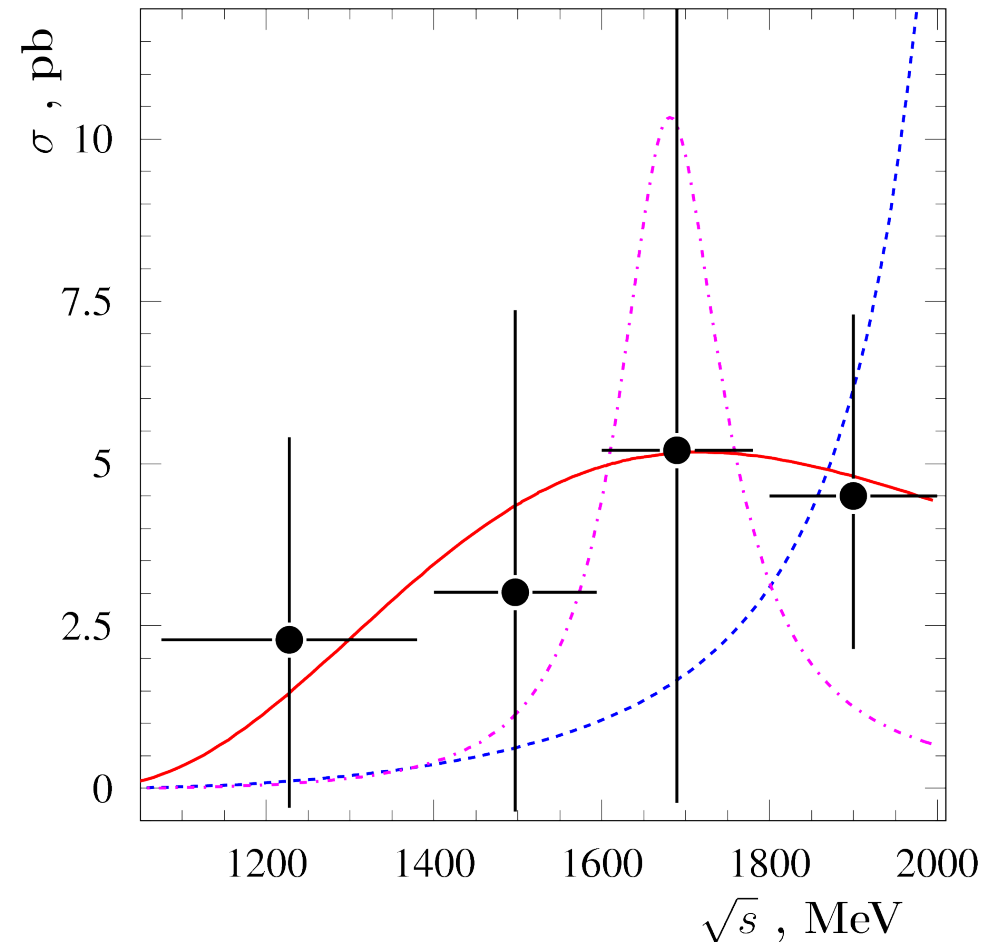
Energy $1.00 \leq E \leq 1.10$ GeV
$L = 20$ pb^{-1} (2019 scan)
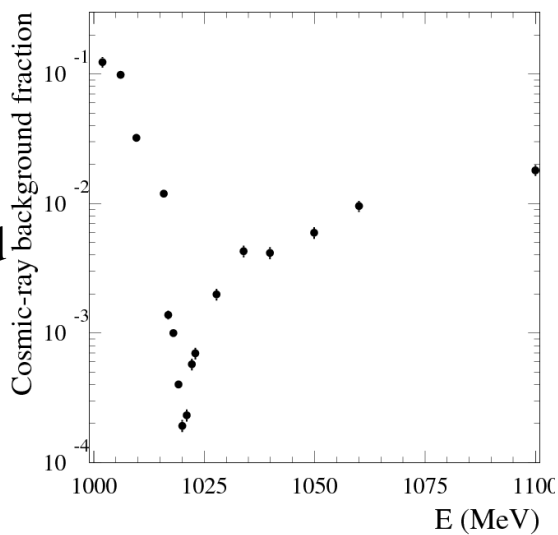## $K_S \rightarrow 2\pi^0 \rightarrow 4\gamma$ mode
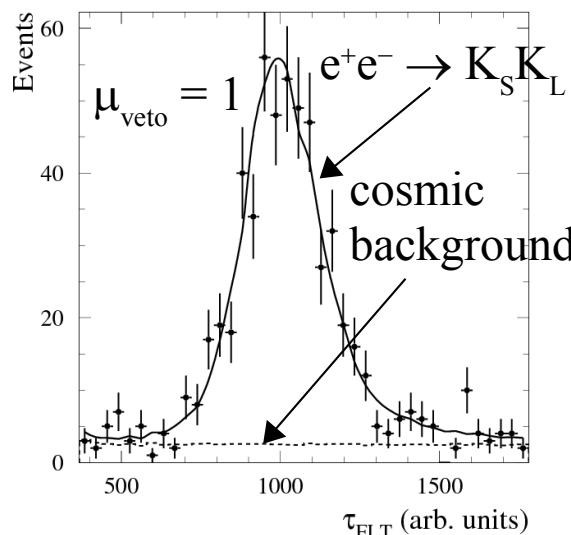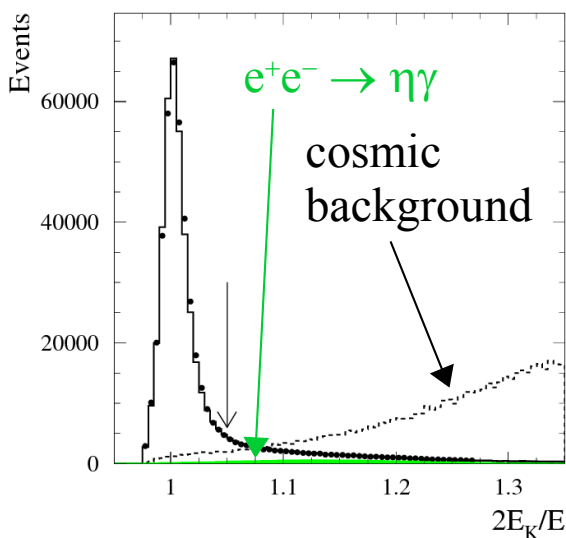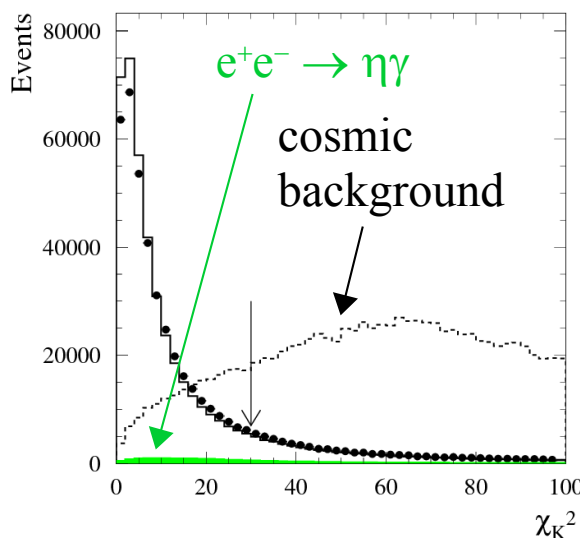

Selection conditions

Preselection

- $N_{charged} = 0$
- $N_\gamma \geq 4$

After $K_S \rightarrow 2\pi^0$ kinematic reconstruction

- $\chi^2_K < 30$
- $2E_K / E < 1.05$ GeV

Background subtraction

- Cosmic background: FLT time (τ_{FLT}) fit
  - $\mu_{veto} = 1$: at each energy point
  - $\mu_{veto} = 0$: $N^{cosm}_i = N^{cosm}_0 \, t_i / t_{0,}$ N^{cosm}_0 at $E = 910$–930 MeV
- $e^+e^- \rightarrow \eta\gamma$ and $e^+e^- \rightarrow 2\pi^0\gamma$ background
  - from simulation
  - $e^+e^- \rightarrow \eta\gamma$ (main background)
    - checked for $100 < \chi^2_K < 30$
    - accuracy is 5%

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

$$\sigma^{exp}(E_i) = \frac{\sigma_{vis}^{exp}(E_i)}{1+\delta(E_i)} \quad x = 2E_\gamma/E \quad x_{max} = 1 - 4m_{K^0}^2/E^2$$

Vector meson Dominance Model (VDM):

$$\sigma(E) = \frac{12\pi}{E^3} \frac{P_K^3(E)}{P_K^3(m_\phi)} \frac{m_\phi^2}{E^2} \Gamma(\phi \to K_S K_L) \left| \frac{\sqrt{m_\phi^3 \Gamma(\phi \to e^+e^-)}}{D_\phi} e^{i\varphi_\phi} - \right.$$

$$\left. -k_{SU3} \left[\frac{\sqrt{m_\omega^3 \Gamma(\omega \to e^+e^-)}}{\sqrt{2}D_\omega} - \frac{\sqrt{m_\rho^3 \Gamma(\rho \to e^+e^-)}}{\sqrt{2}D_\rho} \right] + A_0 \right|^2$$

$$P_K(E) = \sqrt{E^2/4 - m_{K_S}}$$

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

$$A_0 = a_0/(1 - E^2/m_{\rho'}^2)$$

SU3 symmetry:

$$g_{\rho K_S K_L} = -g_{\omega K_S K_L} = g_{\phi K_S K_L}/\sqrt{2}$$

χ^2 / ndf (18) = 23.6 / 14
χ^2 / ndf (15) = 14.2 / 11
χ^2 / ndf (FSI) = 13.7 / 14

FSI — final state
       interaction factor

Fit parameters

Fixed
- $\varphi_\phi = 180º$
- $k_{SU3} = 1$

Free
- m_ϕ, Γ_ϕ, a_0
- $R = B(\phi \to K_S K_L)B(\phi \to e^+e^-)$ / $[B(\phi \to K_S K_L)B(\phi \to e^+e^-)]_{PDG}$
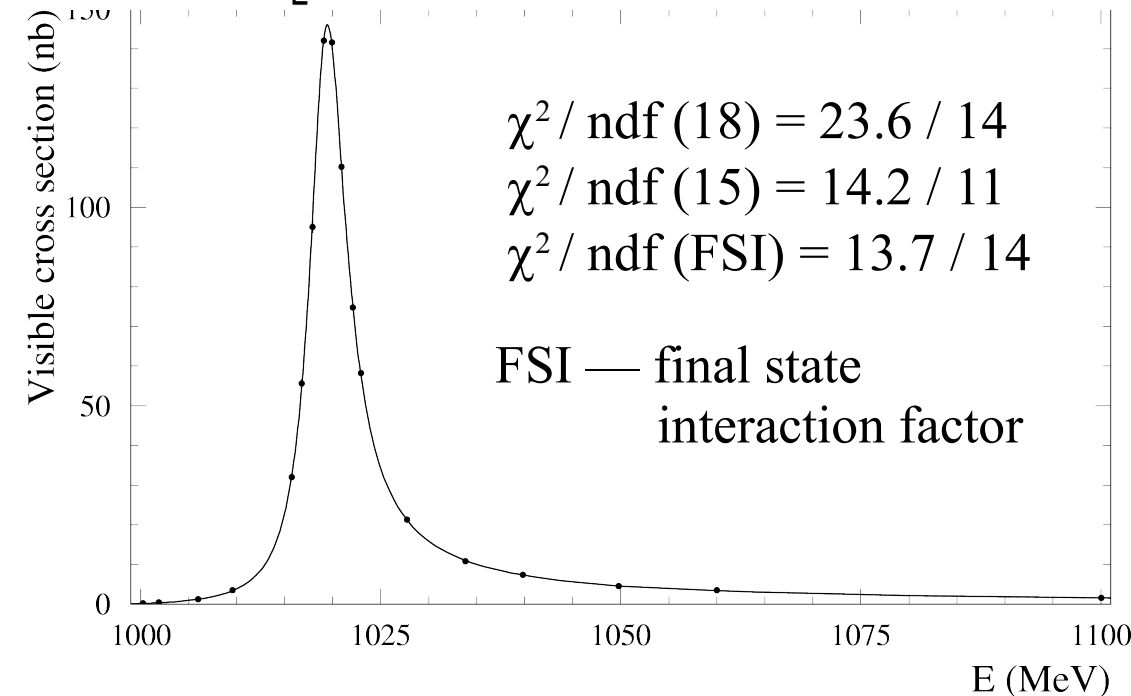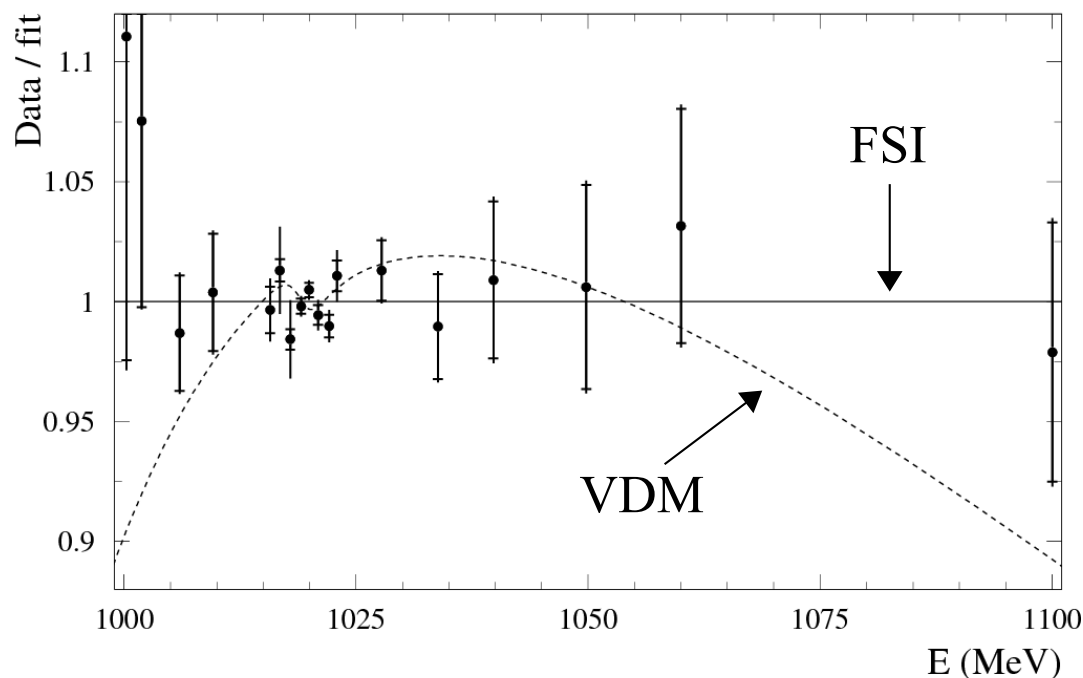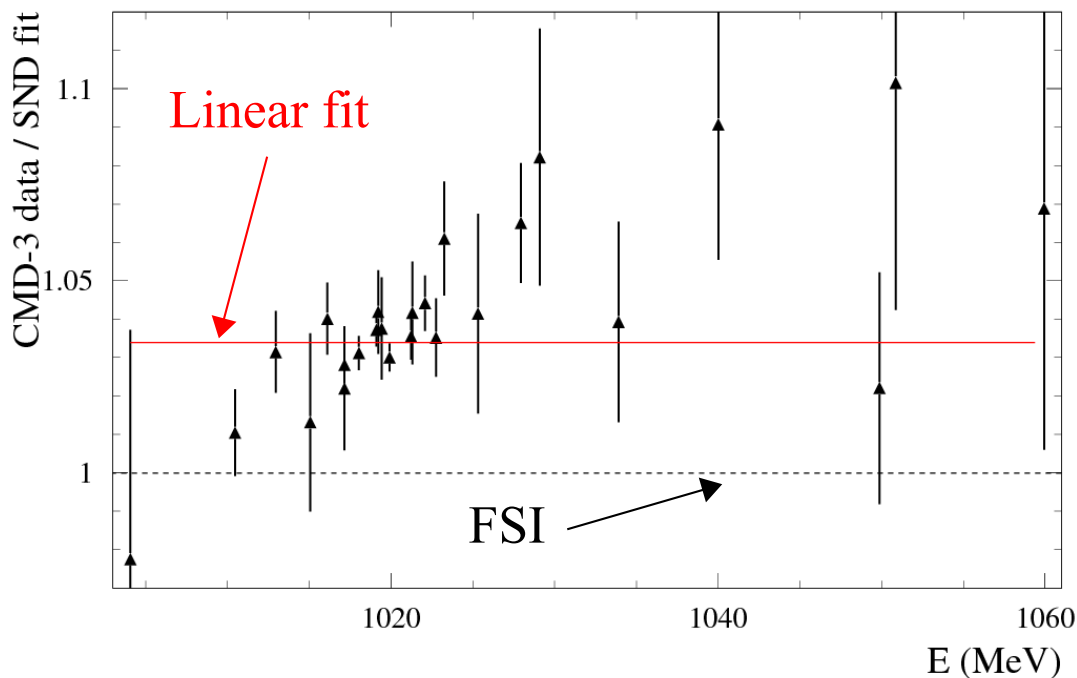
ϕ-meson parameters (VDM)

- $B(\phi \rightarrow K_S K_L)B(\phi \rightarrow e^+e^-) =$
  $(9.85 \pm 0.03 \pm 0.10) \times 10^{-5}$
  PDG: $(10.11 \pm 0.12) \times 10^{-5}$ (1.6σ)
- $M_\phi = 1019.443 \pm 0.010 \pm 0.060$ MeV
- $\Gamma_\phi = 4.21 \pm 0.20 \pm 0.13$ MeV
  PDG: 4.25 ± 0.13 MeV (1.8σ)

Cross section

- $k_{CMD\text{-}3} = 1.034 \pm 0.002 \pm 0.018$
- Most precise measurement: systematic error is **0.9%** at ϕ-resonance maximum
- FSI significance is **3.2σ**

Ready to submittion

Energy E ≥ 1.075 GeV
L = 70 pb^{-1} (2019 scan)

E = 1.282 GeV

Selection conditions

Preselection

- $N_{charged} = 2$
  - R < 0.5 cm
  - |z| < 10 cm
  - Δz < 1.5 cm
- $N_\gamma = 2$ ($E_\gamma > 50$ MeV)
  - $30° < \theta < 150°$
  - $0.3 < E_{tot} / E < 0.8$
- $E_{tot}^{charged} / E < 0.6$

- $E_{tot}^{outer} < 70$ MeV
- $\tau_{cal} < 5$ ns

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

- $30° < \theta_\pi < 150°$
- $|180°-|\varphi_{\pi 1}-\varphi_{\pi 2}|| > 10°$
- $\chi_R^2 < 200$
- $\chi_E^2 < 30$

E = 1.282 GeV

M$_{\gamma\gamma}$ spectra fit

- Signal: $e^+e^- \rightarrow 3\pi$ simulation ($\rho\pi+\omega\pi^0+\rho'\pi$)
  $\rho \equiv \rho(770)$ $\rho' \equiv \rho(1450)$
- Background: simulation of
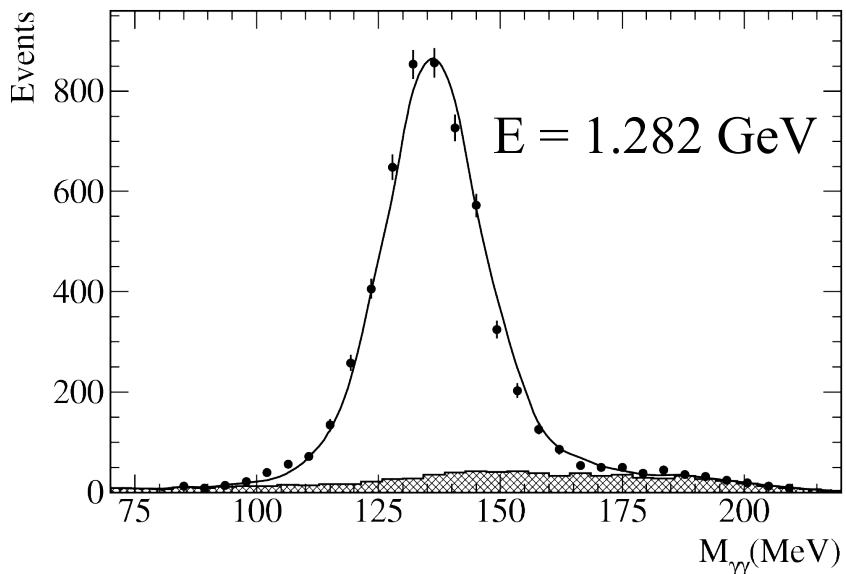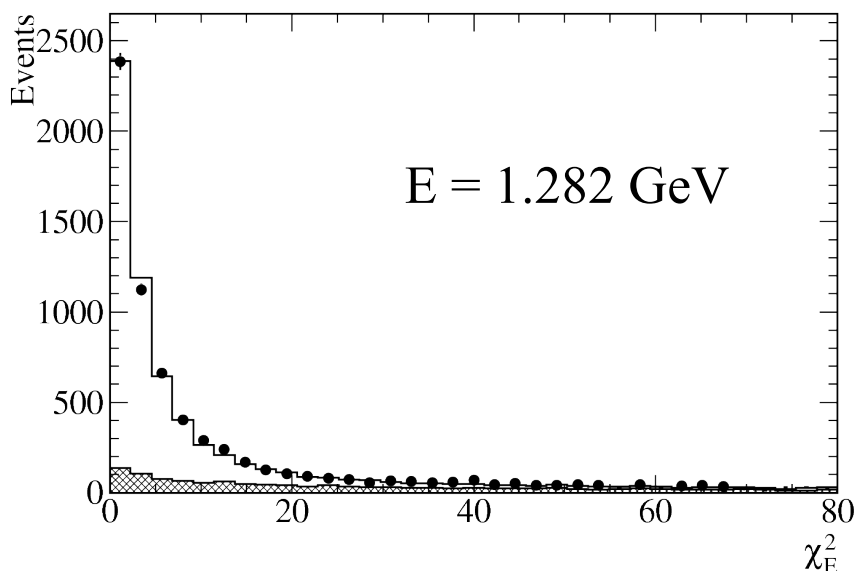 - $2(\pi^+\pi^-)\pi^0$
  - $\pi^+\pi^-\gamma$
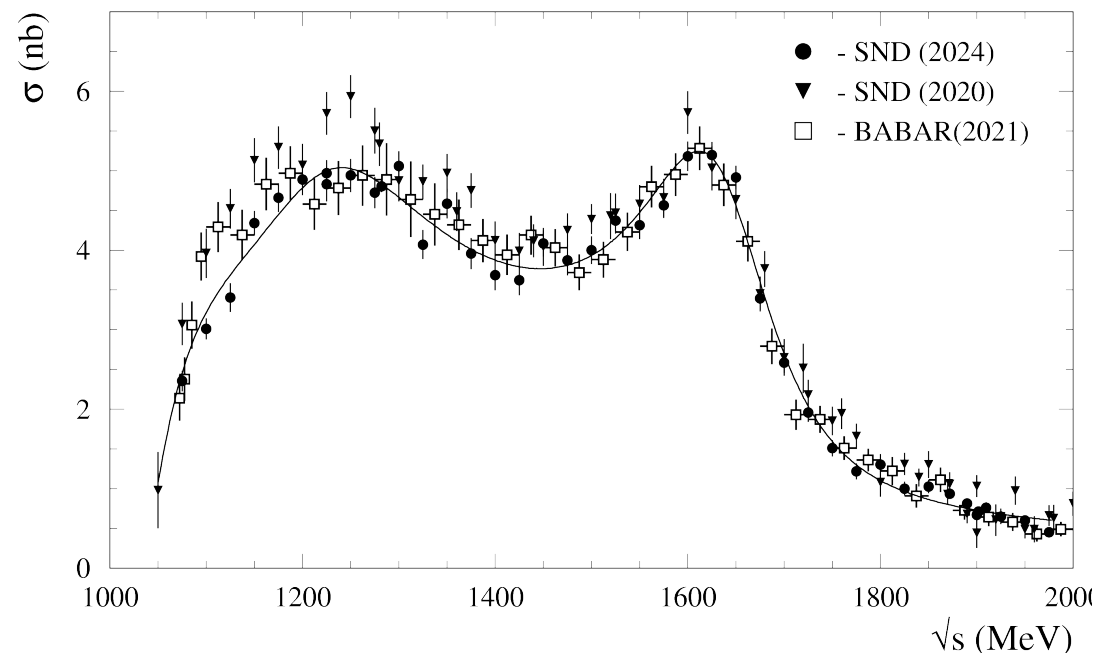 - $\mu^+\mu^-\gamma$
  - $K_S K_L$ (E < 1.14 GeV)
  - $K^+K^-\pi^0$ (E > 1.7 GeV)
  - $K_{S(L)}K^\pm\pi^{-+}$ (E > 1.7 GeV)

$\alpha_{bkg} = 1.14 \pm 0.03$

Cross section

$$\sigma^{exp}(E_i) = \frac{\sigma_{det}^{exp}(E_i)}{\varepsilon_0(E_i)(1 + \delta(E_i))}$$

- σ^{exp}_{det} fit:
  - amplitude: ω, ϕ, $\omega(1420)$, $\omega(1650)$ and complex constant
  - phase space: $\rho\pi$ only

- Systematic uncertainty:
  - 10% for E = 1.075 GeV
  - 3.4% for E = 1.1 GeV
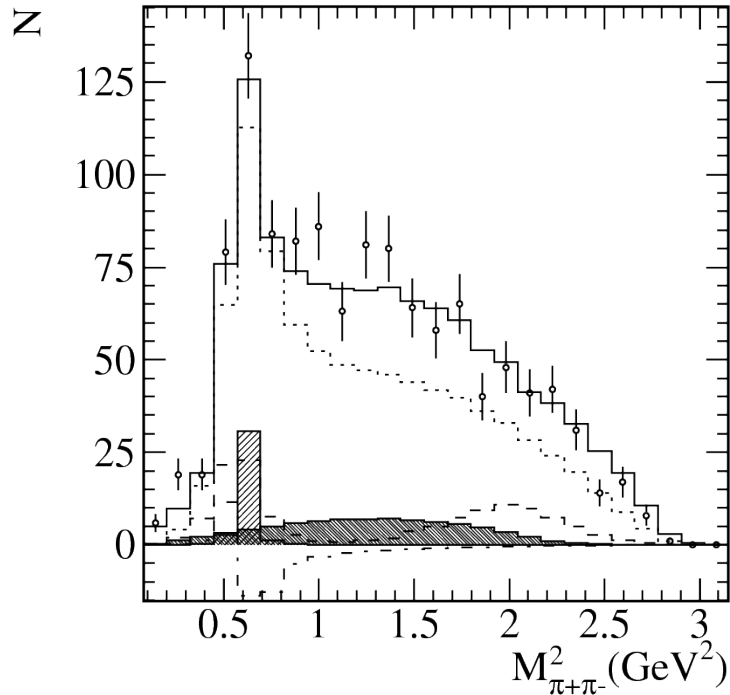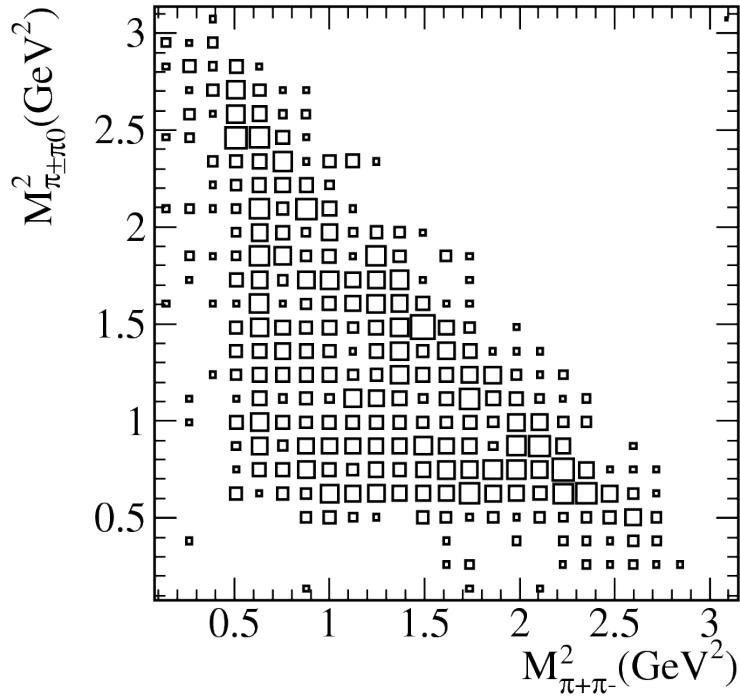 - 2.8% for E > 1.1 GeV

Intermediate states determination

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

- 42 energy points are combined (by 3) into 14 ranges
- additional conditions
  - $\chi_E^2 < 20$
  - $110 < M_{\gamma\gamma} < 170$ MeV
- 25×25 bins

Fit model

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

- $\rho'\pi$ also inlcudes $\rho(1700)\pi$ and $\rho_3(1690)\pi$
- fit parameters: α, β, γ, $\varphi_{\rho\pi-\rho'\pi}$, $\varphi_{\rho\pi-\omega\pi}$
- γ ($\omega\pi^0$) varies nearby value calculated from PDG within its error

$$A_{\rho^{(')}\pi} \sim \sum_{k=+,-,0} \frac{m^2_{\rho_k^{(')}}}{q_k^2 - m^2_{\rho_k^{(')}} + iq_k\Gamma_{\rho_k^{(')}}(q_k^2)}$$

$$\Gamma_{\rho_k^{(')}}(q_k^2) = \Gamma_{\rho_k^{(')}} \frac{m^2_{\rho_k^{(')}}}{q_k^2} \left[\frac{p_\pi(q_k^2)}{p_\pi(m^2_{\rho_k^{(')}})} \right]^3$$

$$A_{\omega\pi} \sim \frac{m^2_\omega}{q_0^2 - m^2_\omega + im_\omega\Gamma_\omega}$$

$$D(M^2_{\pi^\pm\pi^0}, M^2_{\pi^+\pi^-}) = |\alpha|^2 H_{\rho\pi} + |\beta|^2 H_{\rho'\pi} + |\gamma|^2 H_{\omega\pi}$$

$$+2|\alpha||\beta|\cos(\phi_1)R_{\rho\pi-\rho'\pi} + 2|\alpha||\beta|\sin(\phi_1)I_{\rho\pi-\rho'\pi}$$

$$+2|\alpha||\gamma|\cos(\phi_2)R_{\rho\pi-\omega\pi} + 2|\alpha||\gamma|\sin(\phi_2)I_{\rho\pi-\omega\pi}$$

$$+2|\beta||\gamma|\cos(\phi_2 - \phi_1)R_{\rho'\pi-\omega\pi}$$

$$+ 2|\beta||\gamma|\sin(\phi_2 - \phi_1)I_{\rho'\pi-\omega\pi}$$

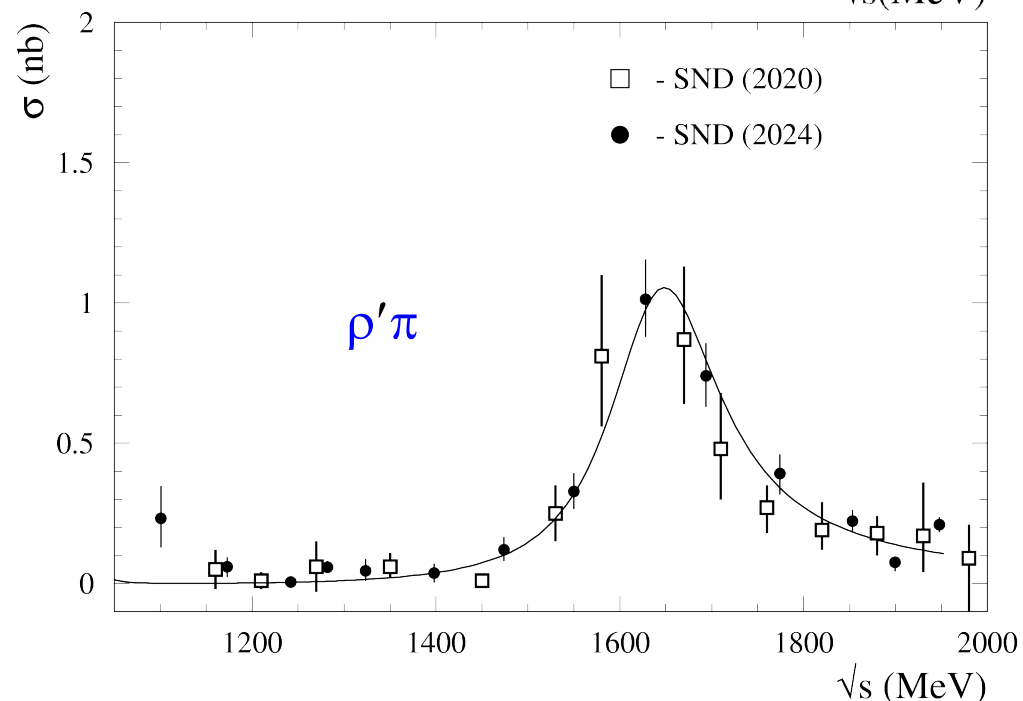$$2R_{\rho\pi-\rho'\pi} = H_{\rho\pi+\rho'\pi} - H_{\rho\pi} - H_{\rho'\pi}$$
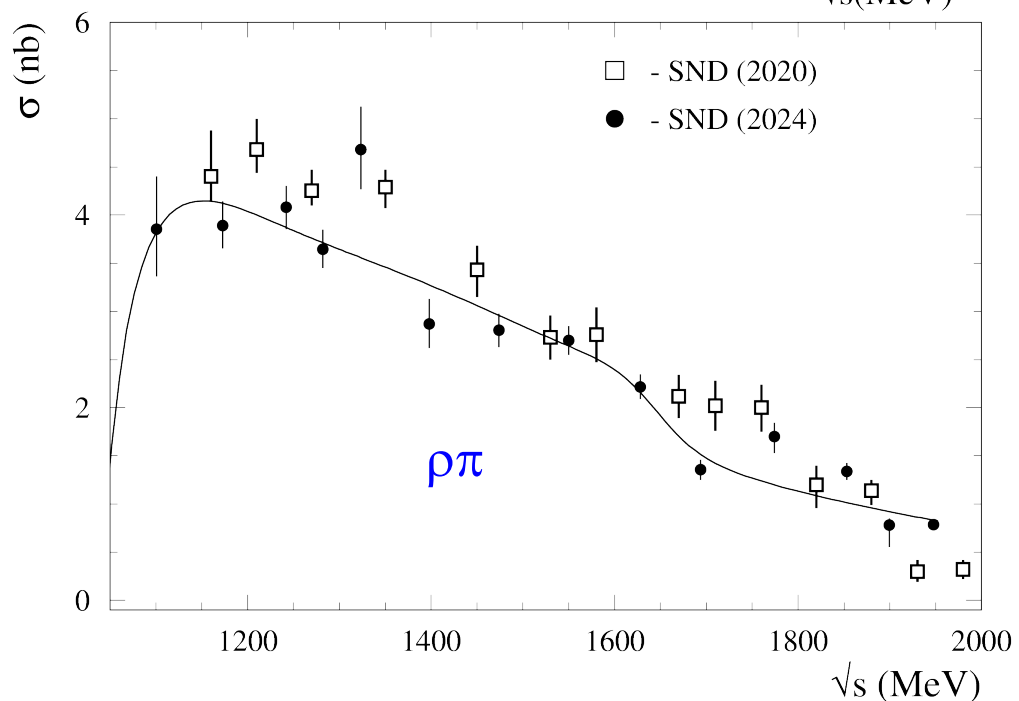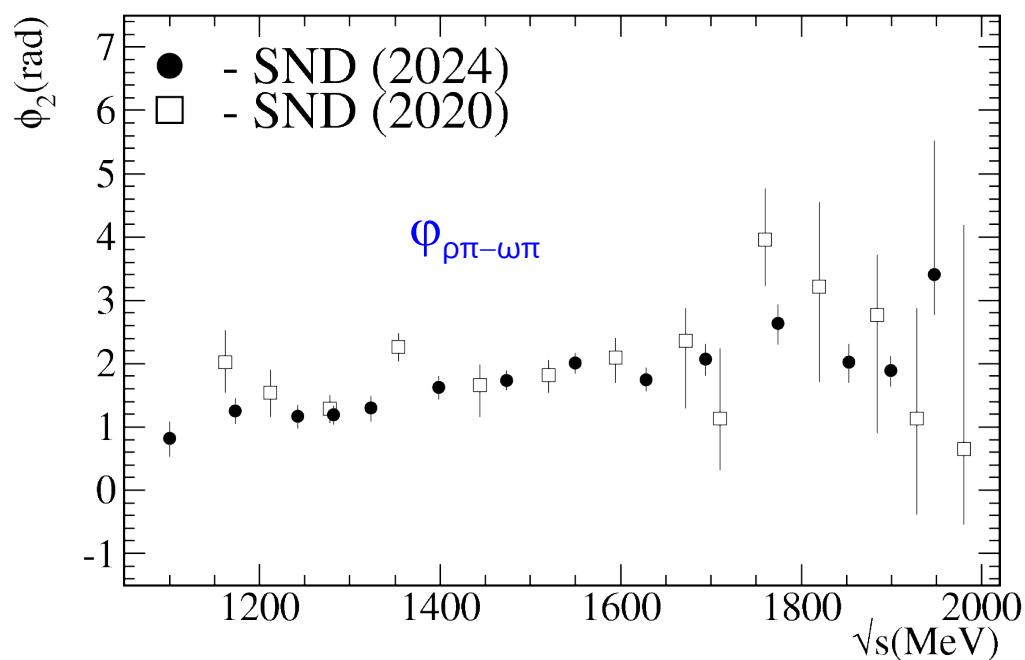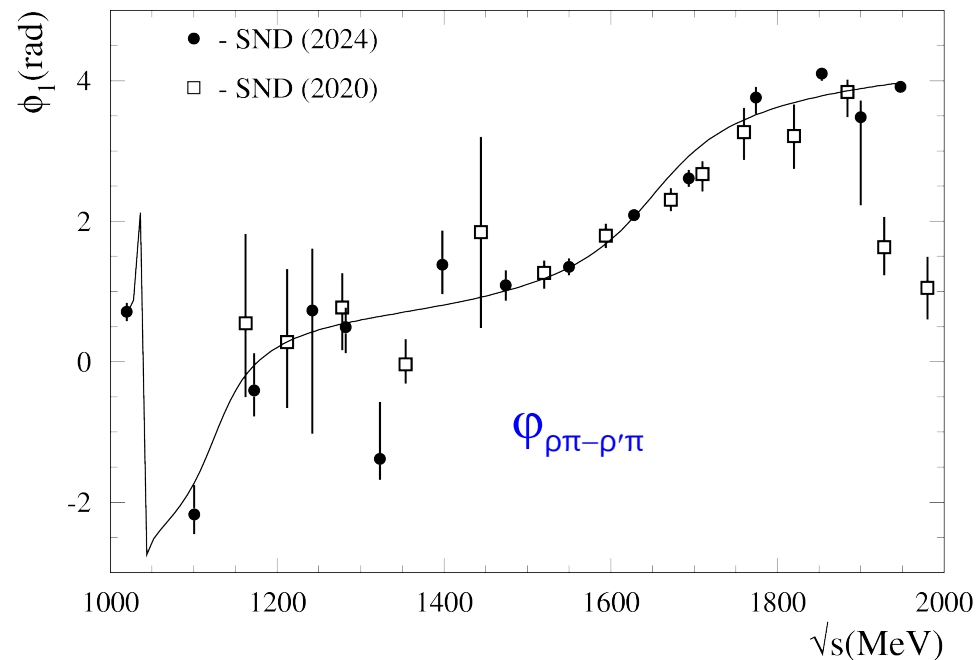
$$2I_{\rho\pi-\rho'\pi} = H_{\rho\pi+i\rho'\pi} - H_{\rho\pi} - H_{\rho'\pi}$$

$$\sigma_{\omega\pi}(s_i) = |\gamma(s_i)|^2 \int |A_{\omega\pi}(s_i)|^2 d\Gamma = \sigma_{\pi^0\pi^0\gamma}(s_i)\frac{B(\omega \to \pi^+\pi^-)}{B(\omega \to \pi^0\gamma)}$$

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

$e^+e^- \rightarrow \pi^+\pi^-\pi^0$ (4)

**Energy E ≥ 1.55 GeV
L = 146 pb^{-1} (2011−2021 scans)
$\eta \to 2\gamma$ mode
Selection conditions**

Background

- $\pi^+\pi^-2\pi^0$, $\pi^+\pi^-3\pi^0$, $\pi^+\pi^-4\pi^0$, $K^+K_s\pi^-\pi^0$
- $\chi^2_{\pi^+\pi^-3\pi0} > 100$

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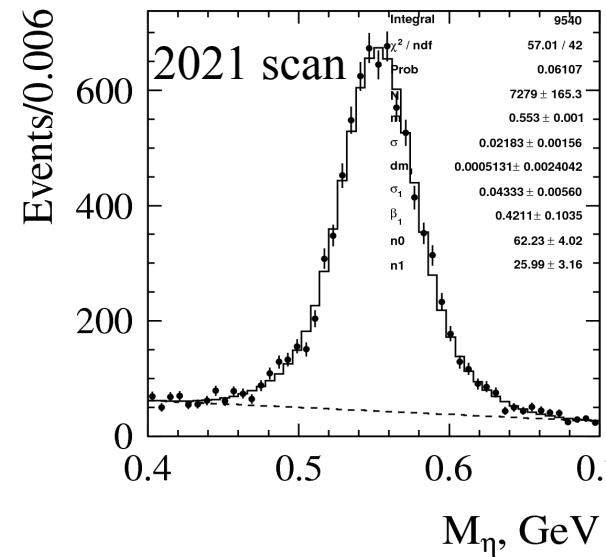
- $N_{charged}$ = 2 or 3
  - R < 1 cm
  - z < 15 cm
- $N_\gamma \geq 6$
  - $E_\gamma > 20$ MeV
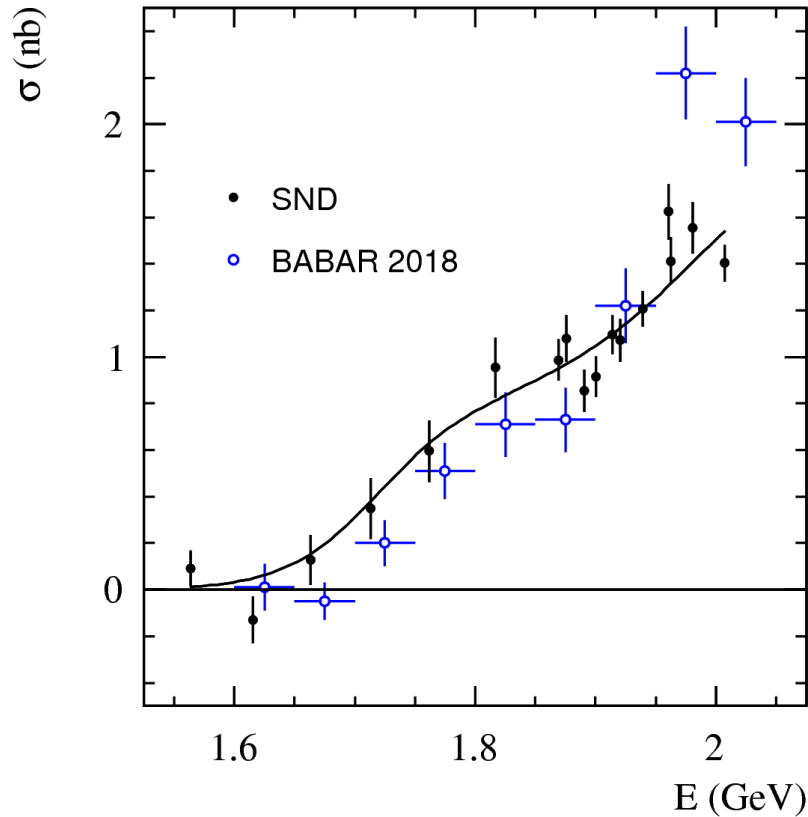 - 10 most energetic are used
- $E_{tot} > 0.3$ GeV

$\pi^+\pi^-2\pi^0\gamma\gamma$ kinematic reconstruction

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

σ (nb)

E (GeV)
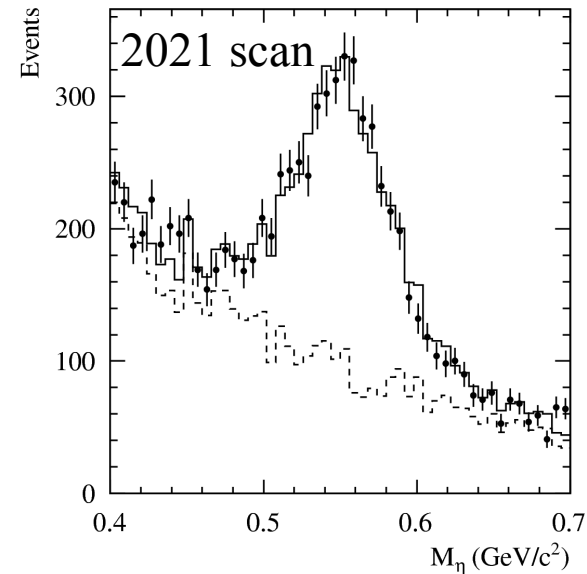
Cross section

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

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

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

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

Fit parameters
$B_{\rho''}$, $B_{\rho'''}$ and φ

$$\sigma(s) = \frac{12\pi}{s^{3/2}} \left| \sqrt{\frac{B_{\rho''}}{P_f(m_{\rho''}^2)}} \frac{m_{\rho''}^{3/2}\Gamma_{\rho''}}{D_{\rho''}} + \sqrt{\frac{B_{\rho'''}}{P_f(m_{\rho'''}^2)}} \frac{m_{\rho'''}^{3/2}\Gamma_{\rho'''}}{D_{\rho'''}} e^{i\varphi} \right|^2 P_f(s),$$

$$\rho'' \equiv \rho(1700), \quad \rho''' \equiv \rho(2150)$$

$$P_f(s) = \frac{1}{3}q_f \cdot \frac{2}{3} = \frac{2}{9} \int_{(m_\eta + m_\pi)^2}^{(\sqrt{s} - m_\omega)^2} \frac{dm^2}{\pi} \frac{m\Gamma_{a_0}q(s, m, m_\omega)}{(m^2 - m_{a_0}^2)^2 + (m\Gamma_{a_0}))^2},$$

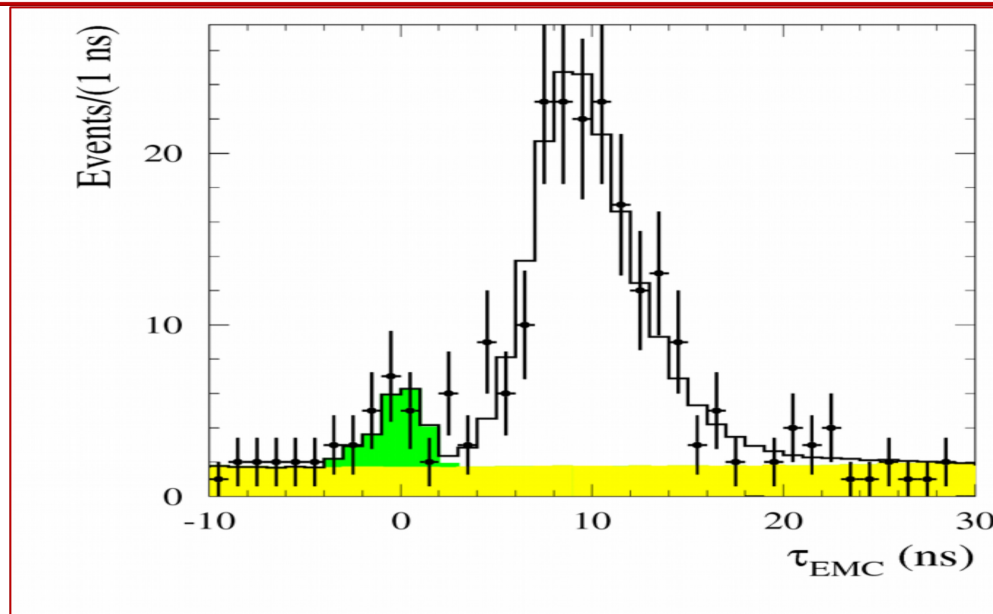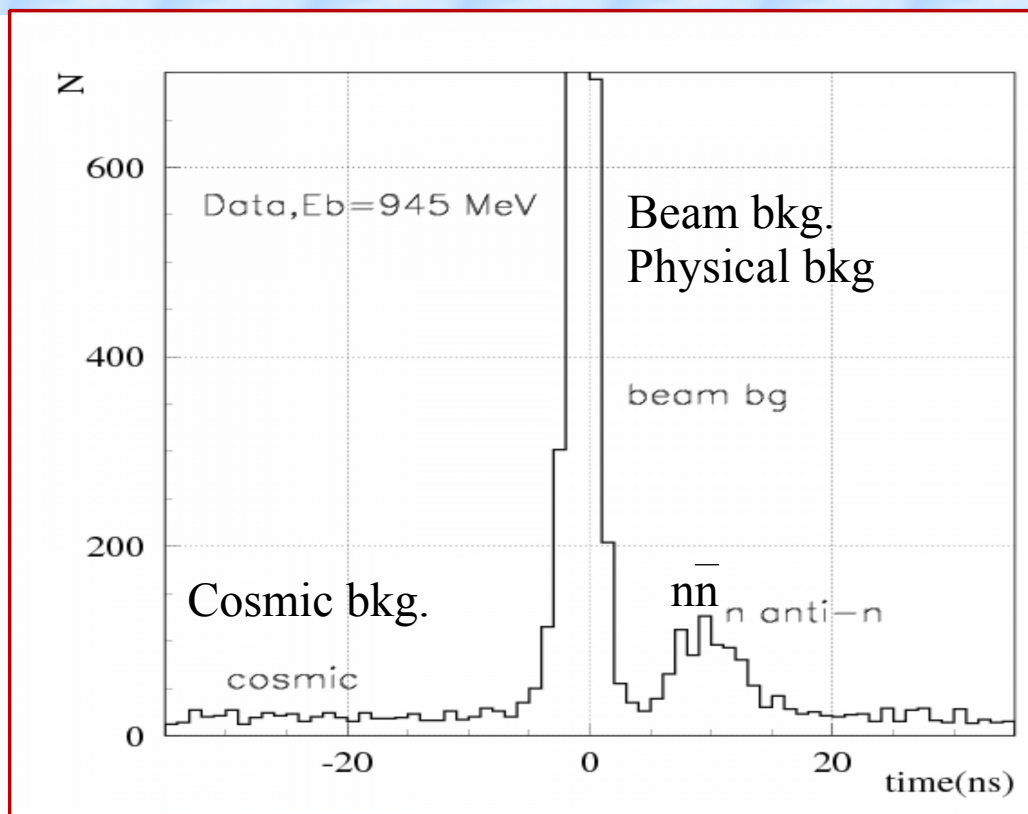$$q(s, m, m_\omega) = \frac{1}{2\sqrt{s}}\sqrt{(s - (m - m_\omega)^2)(s - (m + m_\omega)^2)}$$

- SND
- BABAR 2018

Energy E ≤ 1.91 GeV
L = 106 pb^{-1}
(+64 pb^{-1} under threshold)
(2022 scan)

Selection conditions

- $N_{charged} = 0$
- No cosmic tracks and showers in EMC
- Event momentum P > 0.1E
- $E_{tot} > E/2$
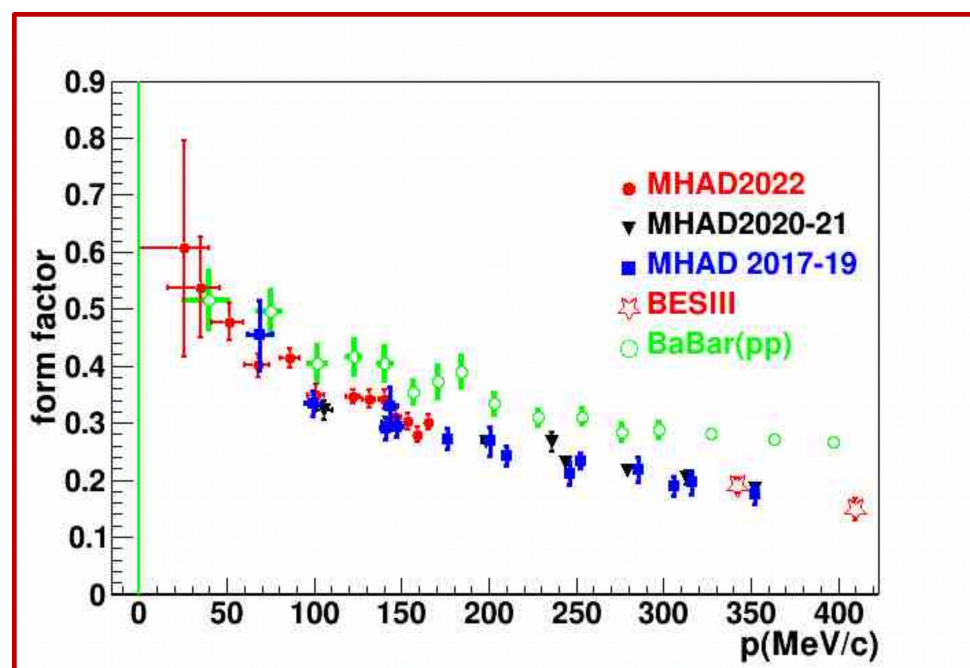- $\chi_\gamma > -2.5$
- Cherenkov counter is removed

(efficiency is ~20%)

Background

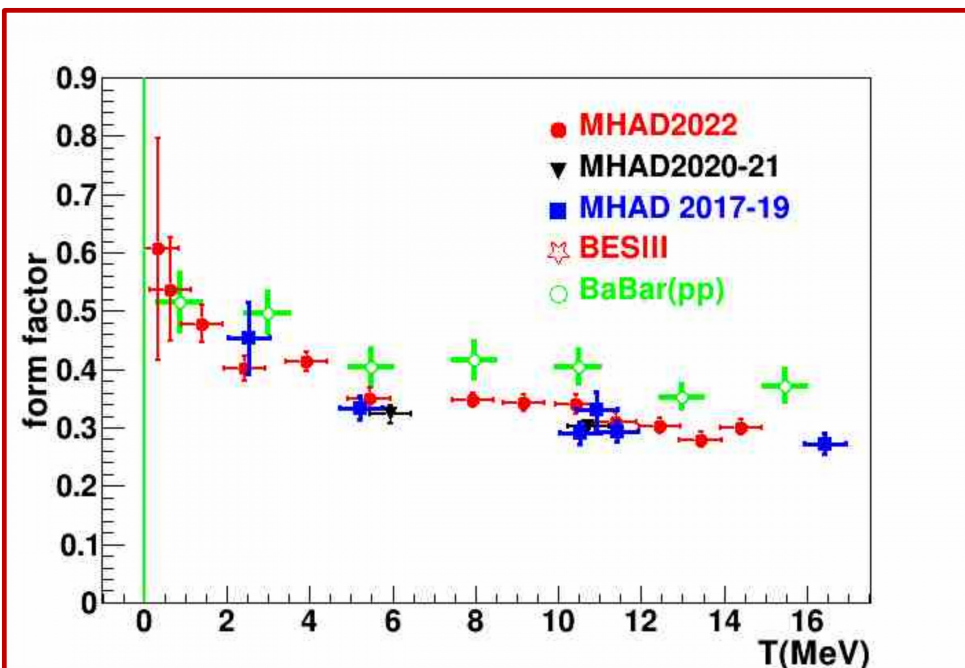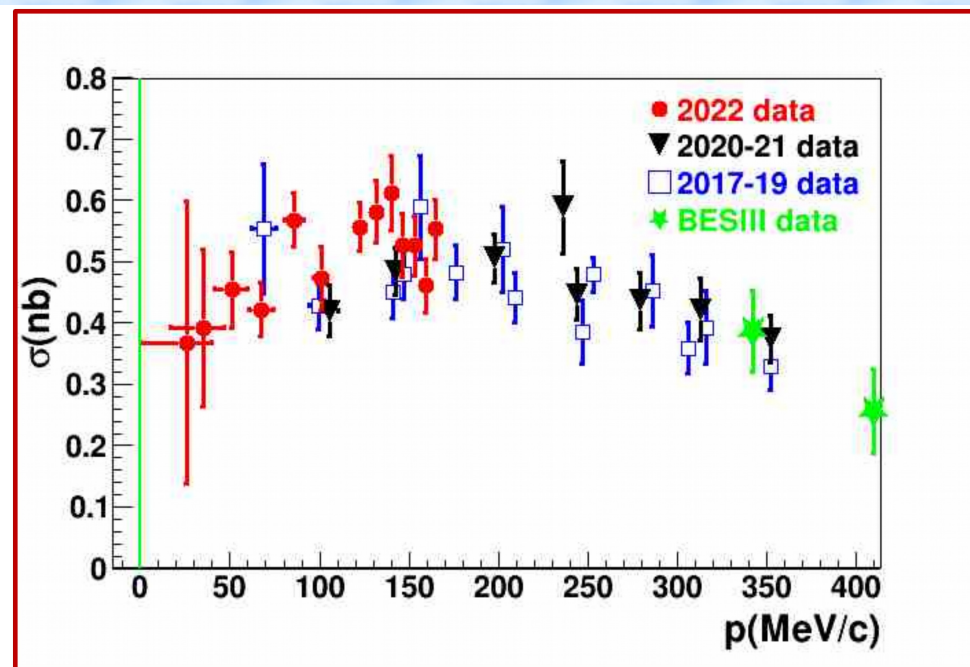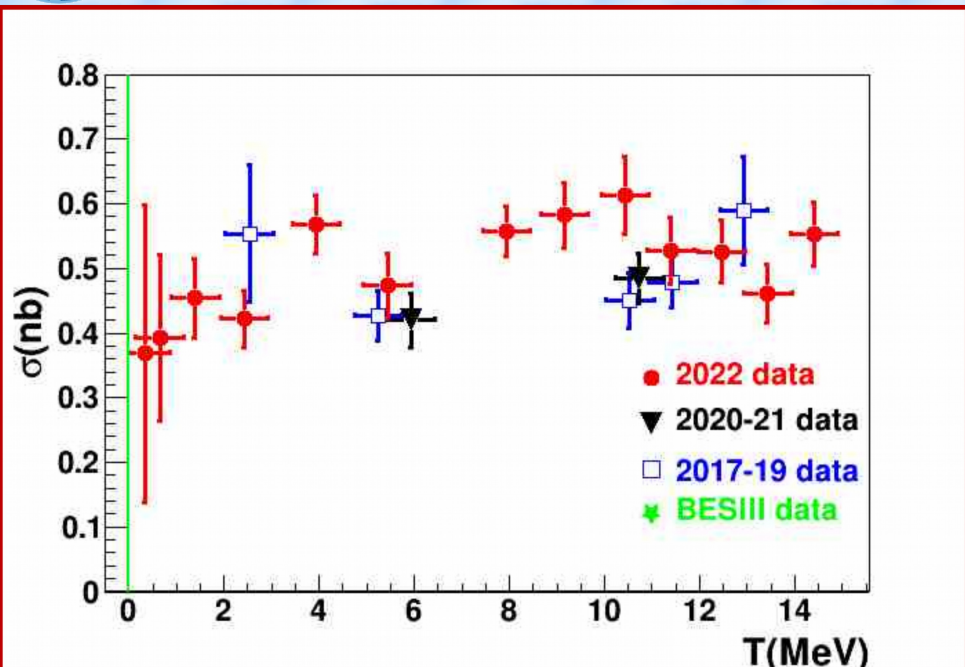- Cosmic: flat over time
- Beam: peaked at t = 0
- Physical:
  - not delayed: $e^+e^- \to N\gamma$ (QED), π^0, η etc.
  - delayed: $e^+e^- \to p\bar{p}$, K_L+X

$e^+e^- \to n\bar{n}$ (2)

Submitted to Physics of Atomic Nuclei

- The SND detector has been accumulated $IL \sim 1\ fb^{-1}$ of integrated luminosity (up to 2024) produced by VEPP-2000 collider in 0.3−2 GeV energy range
- The following processes are presented:
  - $e^+e^- \to \eta'\gamma, \eta' \to 2\pi^0\eta \to 7\gamma$: upper limit has been obtained for the cross section
  - $e^+e^- \to K_S K_L$ **nearby** $\phi(1020)$: the most precise measurement
  - $e^+e^- \to \pi^+\pi^-\pi^0$: process dynamics has been studied in 1.075−2 GeV energy range
  - $e^+e^- \to \pi^+\pi^-2\pi^0\eta$: cross section measurement has been measured in 1.075−2 GeV energy range
  - $e^+e^- \to n\bar{n}$: cross section and form factor have been measured
- Cross sections of the most of the processes are compatible with the previous results but has better accuracy
- Results on 2022−2024 statistics ($IL=790\ pb^{-1}$) are coming soon

BACKUP SLIDES

Background processes

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

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

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

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

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

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

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

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

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

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