Физика Частиц при Средних и Высоких Энергиях 2026

«Физика частиц при средних и высоких энергиях»

2-5 июня 2026 г. Протвино

Обзор последних результатов детектора СНД на ВЭПП2000

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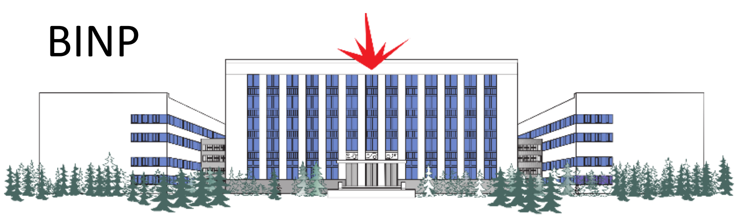
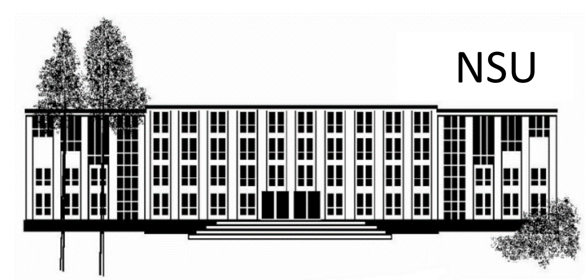
BINP





Physics tasks of SND at VEPP2000

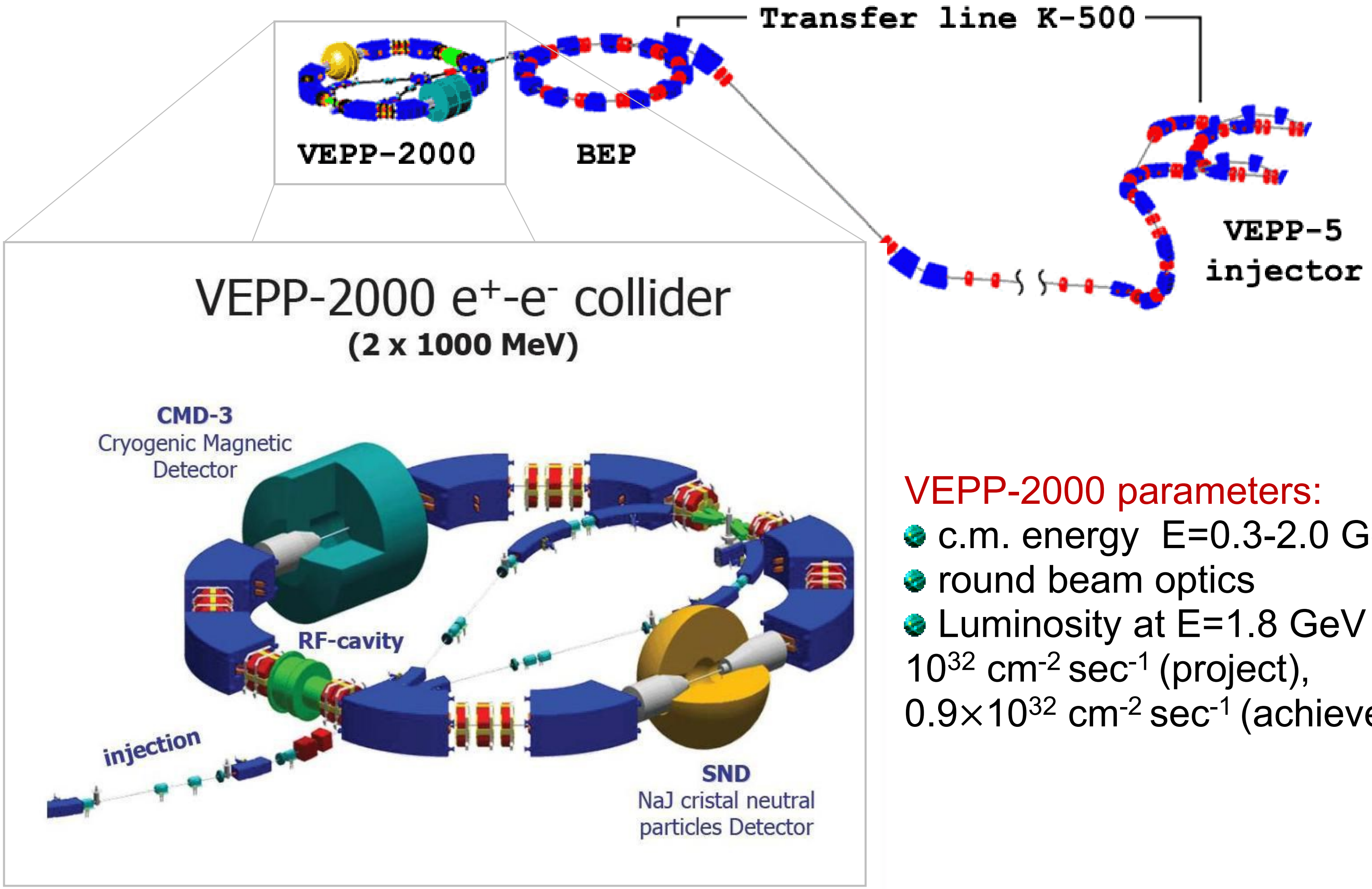
The main goal of experiments at VEPP-2000:

- *a measurement of the total and exclusive cross sections of* $e^+e^- \rightarrow hadrons$ *with high precision*
- *a study of spectroscopy of light vector mesons and their excitations*
- *investigation of mesons with various* J^{PC}
- *production of* $p\bar{p}$ *and* $n\bar{n}$ *pairs near threshold*
- *two-photon physics*

Implications of high-precision measurements of low energy cross sections:

- *muon anomalous magnetic moment,* a_μ
- *the running* α
- $m_{u(d)}$ *and quark/gluon condensates from QCD sum rules*
- *tests of CVC by comparing* e^+e^- *and* τ
- *searches for various exotics*

VEPP-2000 e^+e^- complex

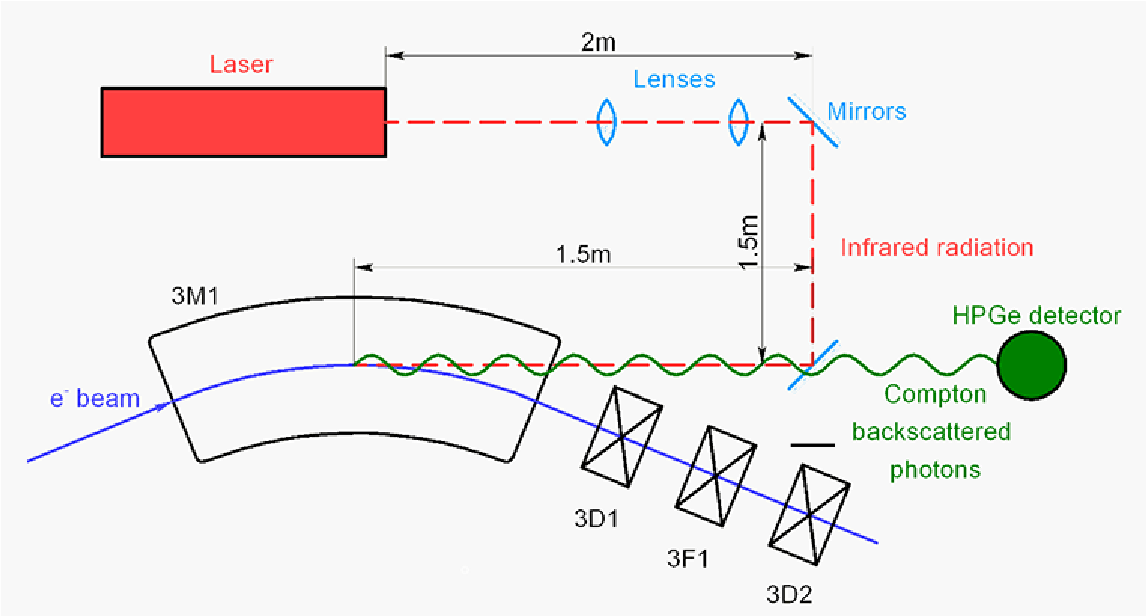


VEPP-2000 parameters:

- c.m. energy E=0.3-2.0 GeV
- round beam optics
- Luminosity at E=1.8 GeV

10^{32} cm^{-2} sec^{-1} (project),
0.9×10^{32} cm^{-2} sec^{-1} (achieved)

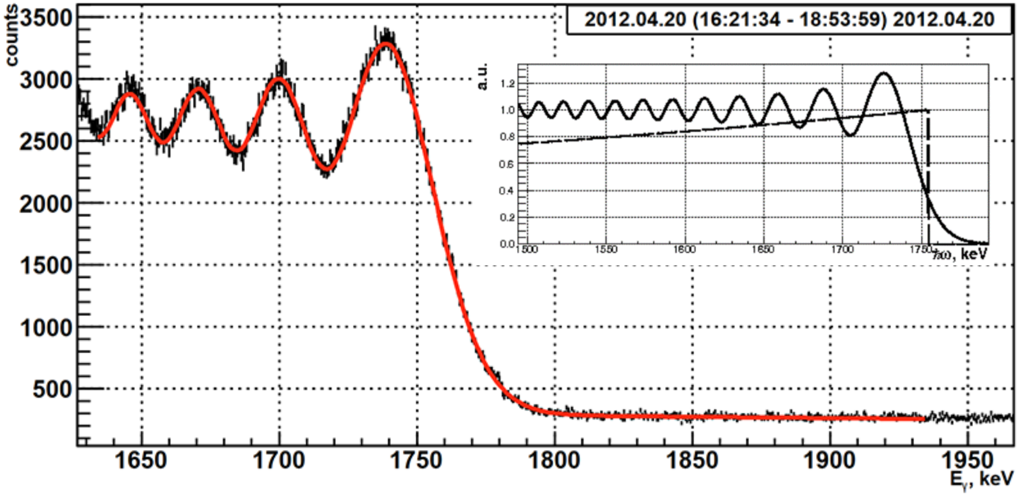
Beam energy measurements: CBS system



The systematic error of the beam energy determination is tested by comparison with a measurement using the resonance depolarization method:

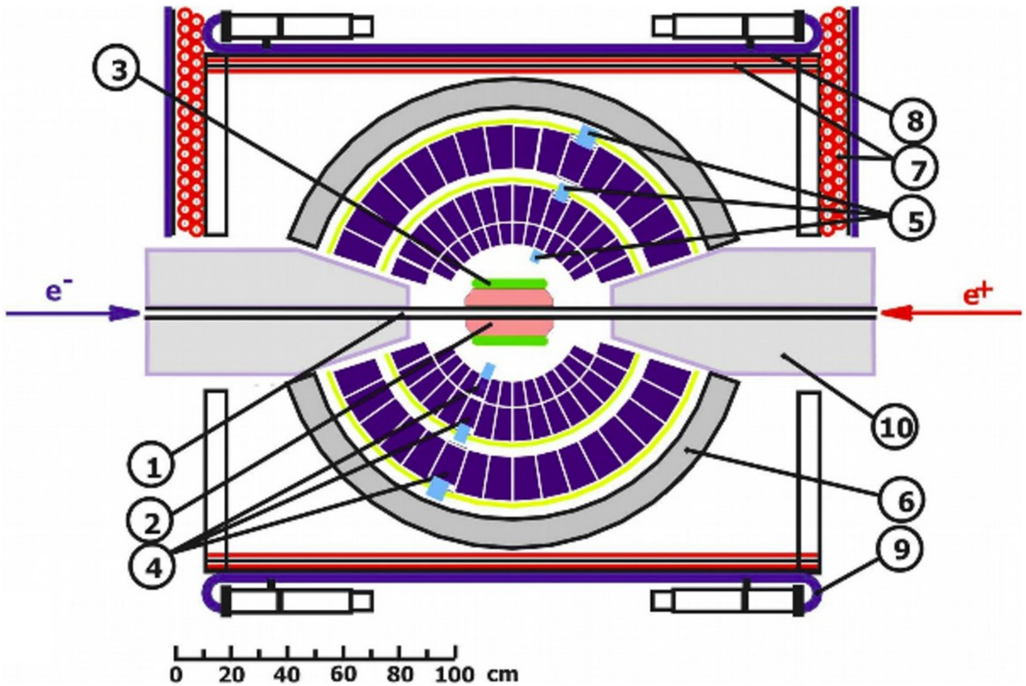
$$\frac{\Delta E}{E} \leq 6 \cdot 10^{-5}$$

E = 993.662 ± 0.016 MeV



The high accuracy of collider beam energy determination is crucial for a lot of physical studies. For example, in order to measure the cross section of the process $e^+e^-\to\pi^+\pi^-$ with accuracy better than 1%.

Spherical ***N****eutral* ***D****etector*



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*.

Calorimeter

Thickness	$13.5\ X_0$
Acceptance	$0.95 \times 4\pi$
Energy resolution	$\frac{\sigma_E}{E} = \frac{0.042}{\sqrt[4]{E[GeV]}}$
Angular resolution	$\sigma_{\phi,\theta} = \frac{0.82^{\circ}}{\sqrt[4]{E[GeV]}} \oplus 0.63^{\circ}$

Tracking system

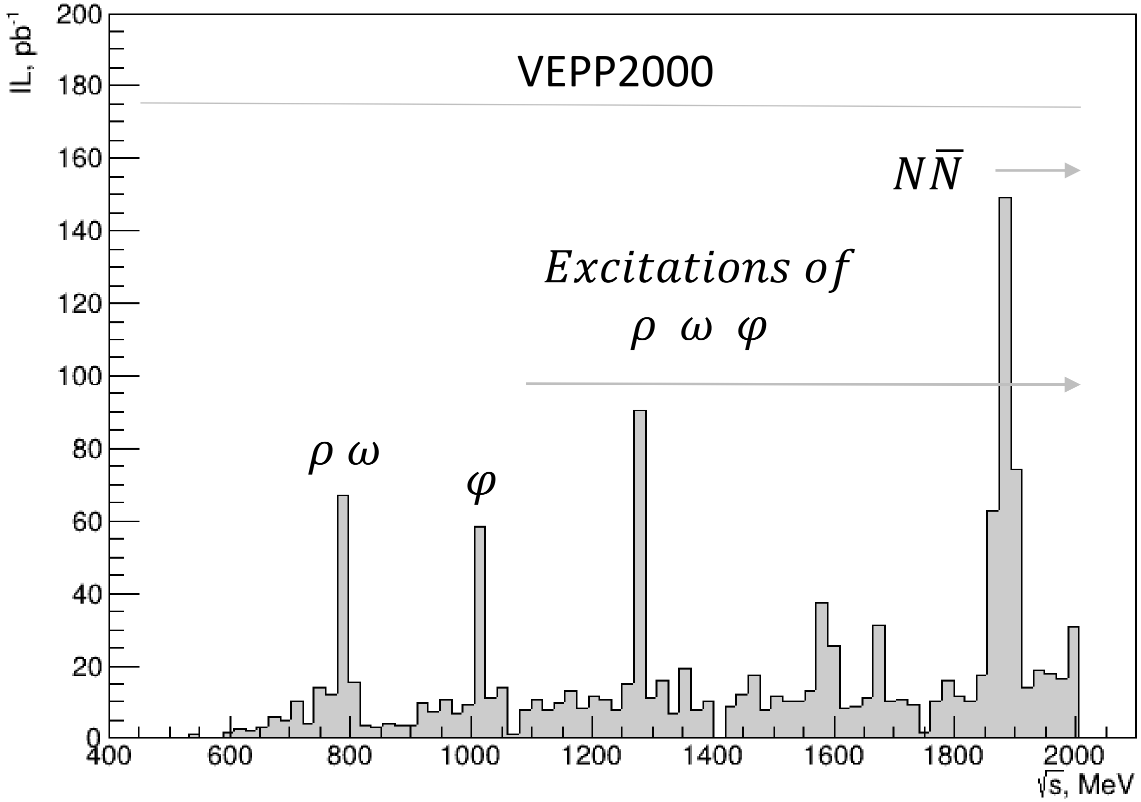
Acceptance (9 layers)	$0.94 \times 4\pi$
Angular resolution	$\sigma_\phi = 0.55^{\circ}, \sigma_\theta = 1.2^{\circ}$
Vertex resolution	$\sigma_R = 0.12cm, \sigma_Z = 0.45cm$

Aerogel counters

K/π separation	E < 1 GeV

No magnetic field!

SND data 2010-2025



Luminocity:

- ρ region: 200 pb^{-1}
- φ region: 80 pb^{-1}
- Excitations: 970 pb^{-1}
- $N\bar{N}$ region: 300 pb^{-1}
- Total: 1250 pb^{-1}

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

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

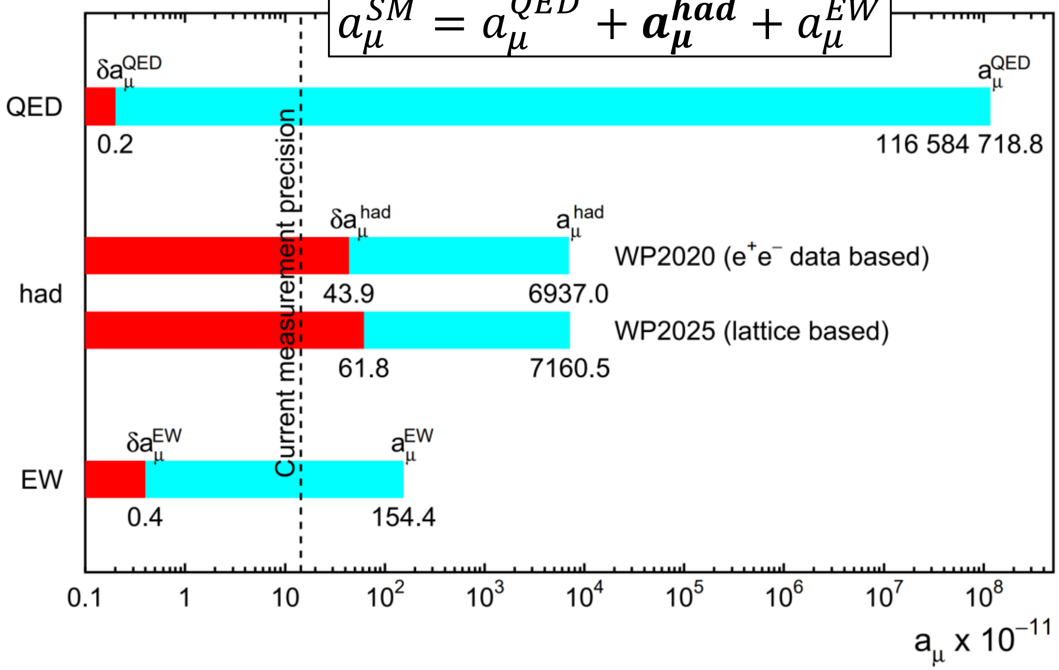
$e^+e^- \to \eta\gamma,\quad e^+e^- \to \pi^o\gamma$

$e^+e^- \to \pi^o\gamma,\quad e^+e^- \to \omega\pi^o$

$e^+e^- \to hadrons$

Motivation

$$a_\mu^{SM} = a_\mu^{QED} + \boldsymbol{a_\mu^{had}} + a_\mu^{EW}$$

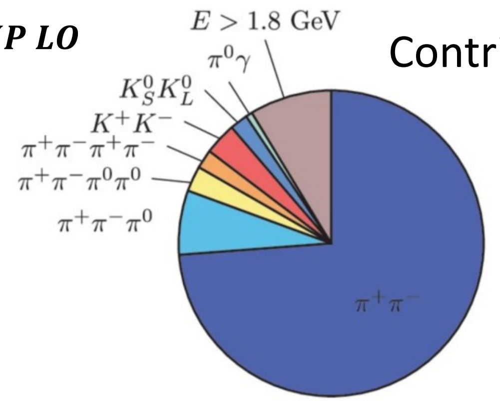


$$a_\mu^{had} = \boldsymbol{a_\mu^{HVP\ LO}} + a_\mu^{HVP\ HO} + a_\mu^{HLbL}$$

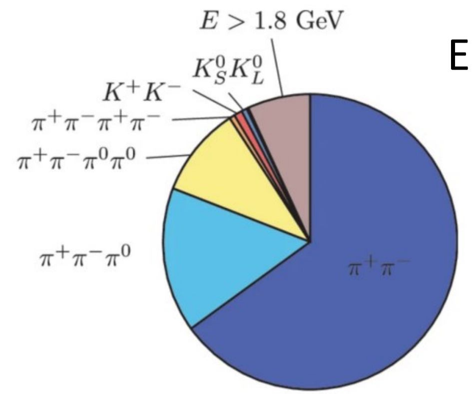
had	HVP LO	HVP HO	HLbL
	$a_\mu[10^{-11}]$ (uncertainty)		
WP2020	6931 (40)	−85.9(0.7)	92 (18)
WP2025	7132 (61)	−87.2(1.3)	115.5 (9.9)

$\boldsymbol{a_\mu^{HVP\ LO}}$

Contribution



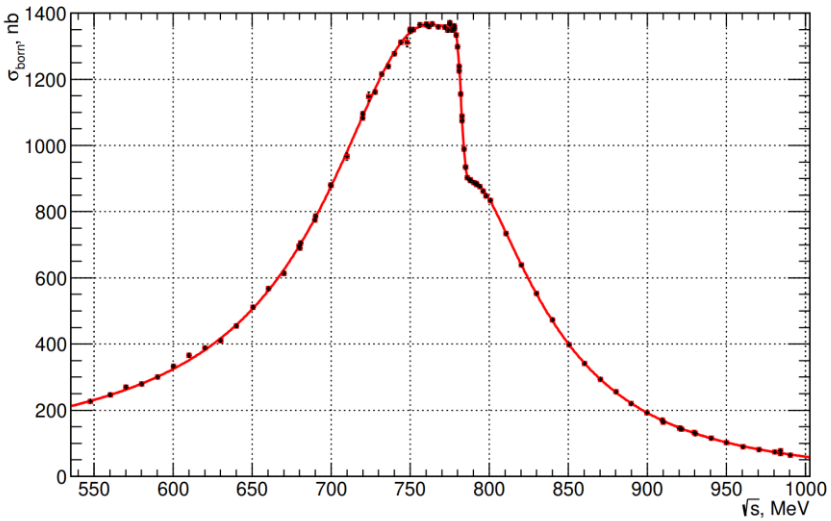
Error²

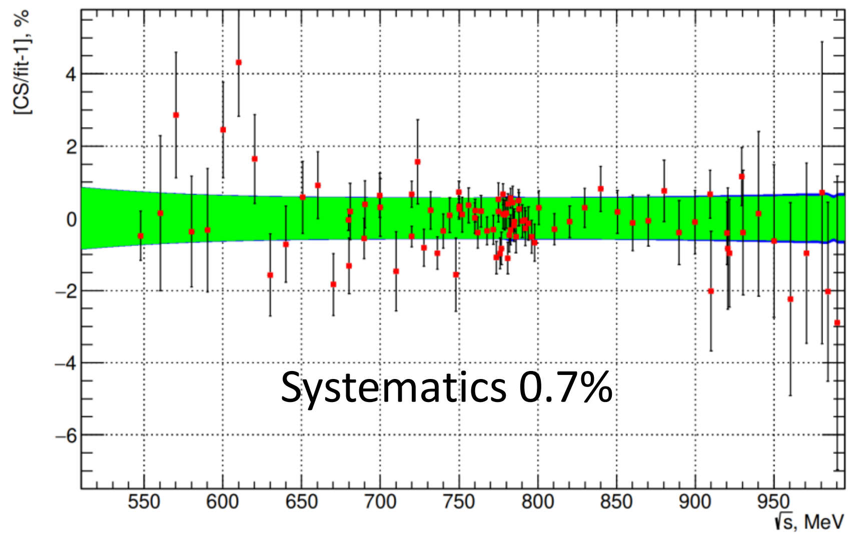


I. There is no tension: $a_\mu^{exp} - a_\mu^{SM} = 38(63) \cdot 10^{-11}$
II. The theoretical error is ~5 times greater than the experimental error
III. SM error is determined by the hadronic contribution a_μ^{had}
IV. The main contribution to a_μ^{had} is $a_\mu^{HVP\ LO}$
V. Finally, the main contribution to the magnitude and error of $a_\mu^{HVP\ LO}$ is given by $\pi^+\pi^-$ and $\pi^+\pi^-\pi^o$

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

Data from 2017-2018, 100 points, luminosity 65 pb^{-1}





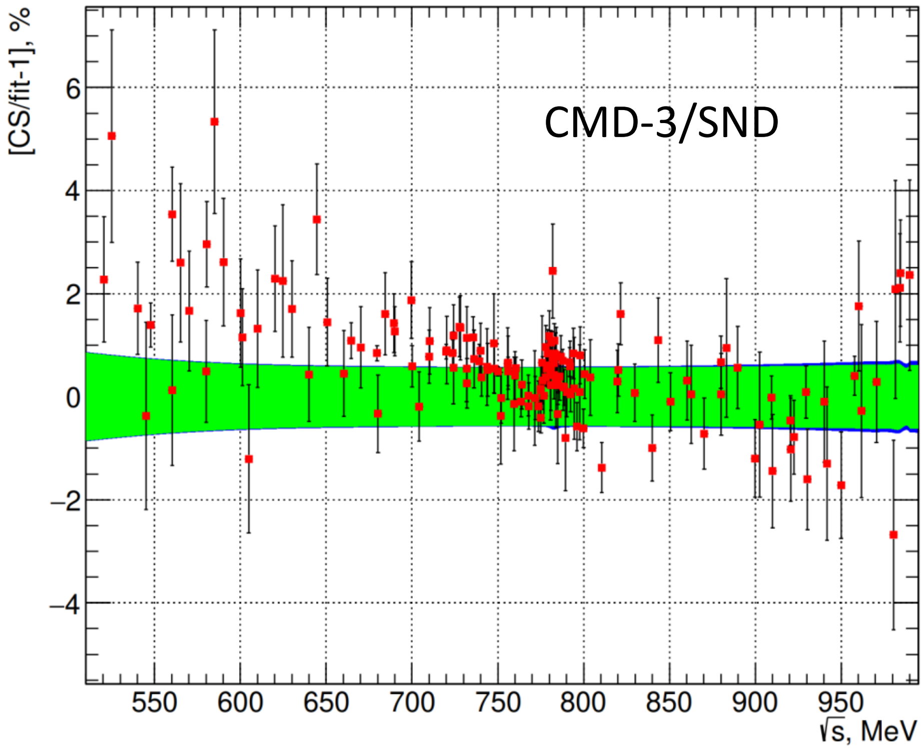
$$\sigma_{\pi^+\pi^-} = \frac{\pi\alpha^2}{3s}\beta_\pi^3 |F_\pi(s)|^2$$

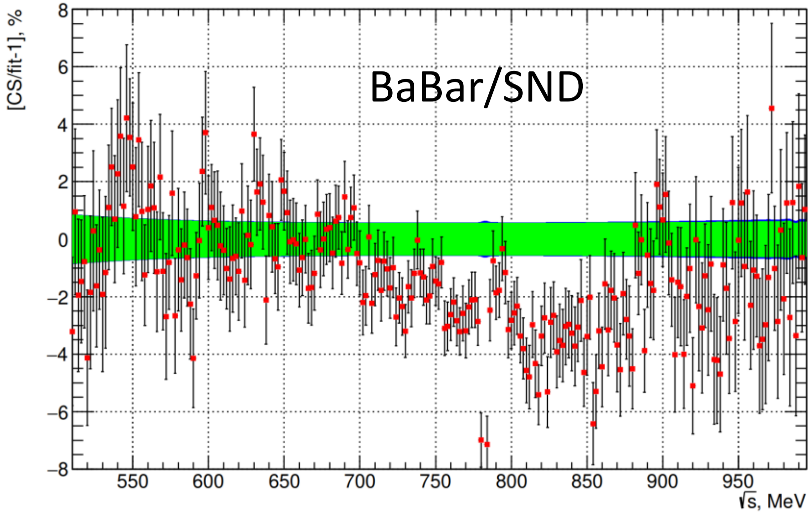
The pion FF model includes ω, ρ, ρ′ and ρ″ with GS energy dependence. The masses and widths for the excitations are fixed

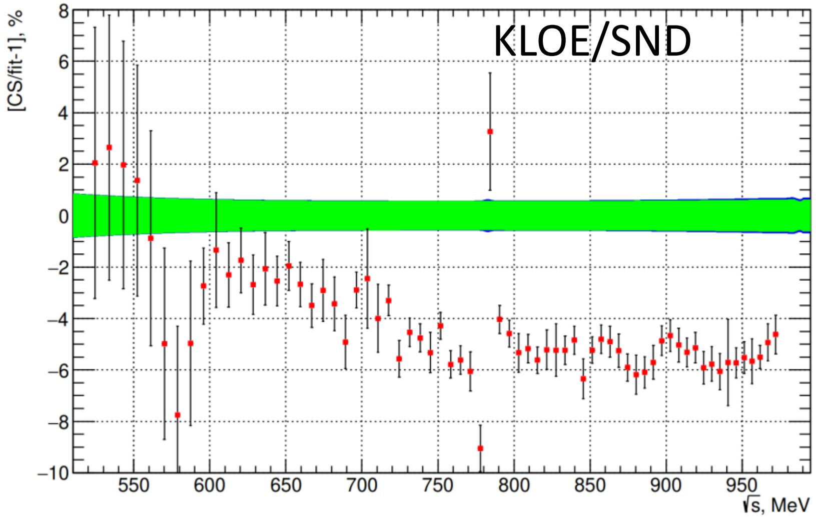
Parameter	This work	BaBar
m_ρ, MeV	775,556 ± 0,077 ± 0,05	774,998 ± 0,157
Γ_ρ, MeV	149,092 ± 0,215 ± 0,045	149,954 ± 0,358
m_ω, MeV	782,381 ± 0,06 ± 0,05	781,962 ± 0,191
Γ_ω, MeV	8,822 ± 0,132 ± 0,06	8,074 ± 0,372
$B(\omega \to \pi^+\pi^-)$	0,0169 ± 0,00028 ± 0,0005	0,01481 ± 0,00072
$\lvert\beta\rvert$	0,2445 ± 0,012 ± 0,0389	0,16283 ± 0,011
$\lvert\delta\rvert$	0,1974 ± 0,01 ± 0,0155	0,02946 ± 0,0076
$\phi_{\rho\omega}$, rad	0,1334 ± 0,013 ± 0,0039	0,02116 ± 0,0381
$\phi_{\rho\rho'}$, rad	4,283 ± 0,009 ± 0,13	3,7935 ± 0,0623
$\phi_{\rho\rho''}$, rad	1,8278 ± 0,0169 ± 0,33	1,408 ± 0,168
χ^2/ndf	108,6/83	257,8/260

Systematics without model error!

SND in comparison with other experiments







Good agreement with the KMD-3 result, significant discrepancy with the BABAR data ($\approx 2\sigma$). Complete disagreement with the KLOE

Contribution to g-2

The contribution of the $e^+e^- \to \pi^+\pi^-$ to the anomalous magnetic moment of the muon in the leading order of perturbation theory is expressed through the dispersion relation:

$$a_\mu(\pi\pi, \sqrt{s_{max}} \leq \sqrt{s} \leq \sqrt{s_{min}}) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{s_{min}}^{s_{max}} \frac{R(s)K(s)}{s^2} ds,$$

$$R(s) = \sigma_{\pi\pi}^{pol} \times \frac{3s}{4\pi\alpha^2} \quad \sigma_{\pi\pi}^{pol}(s) = \sigma_{\pi\pi}^0(s) \times |1 - \Pi(s)|^2 \times (1 + \frac{\alpha}{\pi} a(s))$$

The value of the anomalous magnetic moment according to the results of this work, BABAR and CMD3 calculated in the interval of $[548 - 990]$ Mev

Experiment	$a_\mu(\pi\pi) \times 10^{10}$
This work	$430{,}15 \pm 0{,}49 \pm 2{,}94$
BABAR	$423{,}87 \pm 2{,}1 \pm 2{,}2$
CMD-3	$433{,}62 \pm 0{,}37 \pm 2{,}9$

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

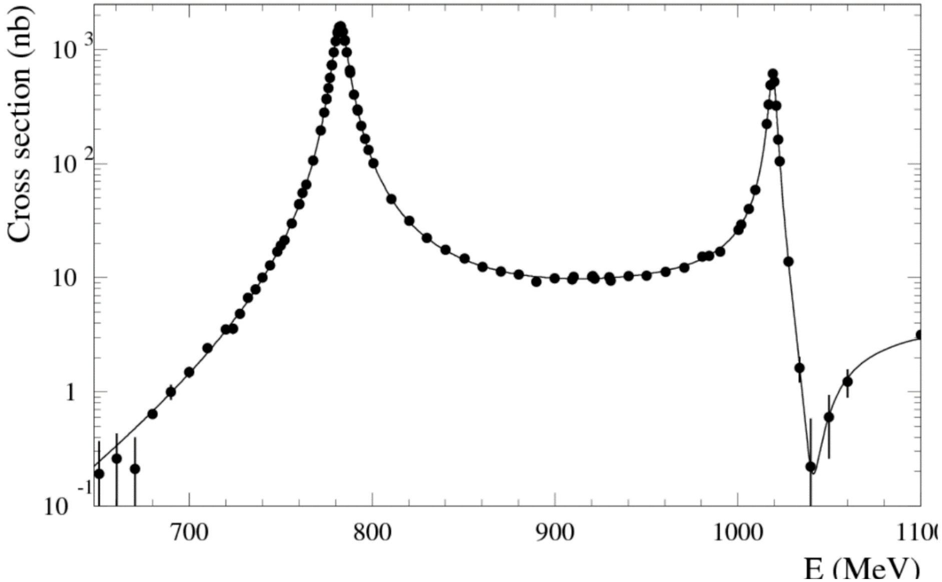
- The process $e^+e^- \to \pi^+\pi^-\pi^o$ makes the second largest contribution to $a_\mu^{HVP,LO}$
- Until 2021, the most accurate cross-section measurements were made at VEPP-2M with the SND and CMD2 detectors.
- In 2021, a measurement was made at the BaBar detector using the radiative return method. The accuracy near $\omega(782)$ and $\phi(1020)$ was 1.3%.
- In 2024, a measurement was made at the Belle-II detector using the radiative return method. The accuracy near $\omega(782)$ and $\phi(1020)$ was 2.2%. Contradiction with previous measurements

Эксперимент	$a_\mu^{3\pi} \times 10^{10}$	
До 2021	46.2 ± 0.6 ± 0.6	M. Hoferichter, B. L. Hoid and B. Kubis, JHEP 2019, 137 (2019)
BABAR	45.86 ± 0.14 ± 0.58	BABAR Collaboration, Phys. Rev. D 104, 112003 (2021)
Belle II	48.91 ± 0.23 ± 1.07	Belle II Collaboration, Phys. Rev. D 110, 112005 (2024)

The difference between Belle-II and BaBar – $(6.7 \pm 2.7)\%$

Cross section

Data from 2018, 102 points, luminosity 66 pb^{-1}



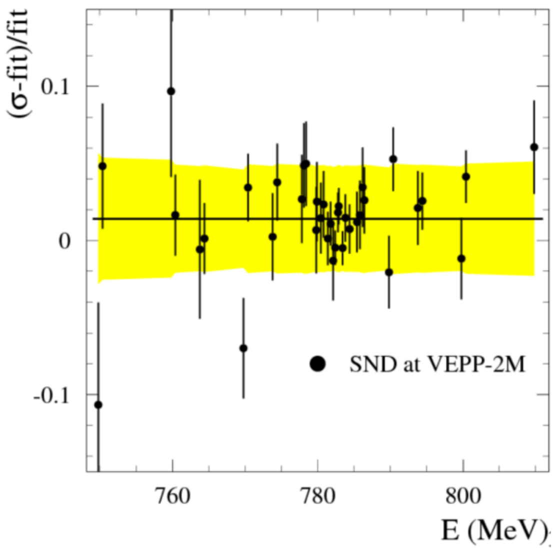
Fit model:

- VDM: $\omega(782) + \rho(770) + \phi(1020) + \omega(1420)$
- The phase $\omega(1420)$ relative to $\omega(782)$ is fixed at 180°
- To the statistical error in the number of $\pi^+\pi^-\pi^o$ events, an additional spread of about $\sim 0.6\%$ was added

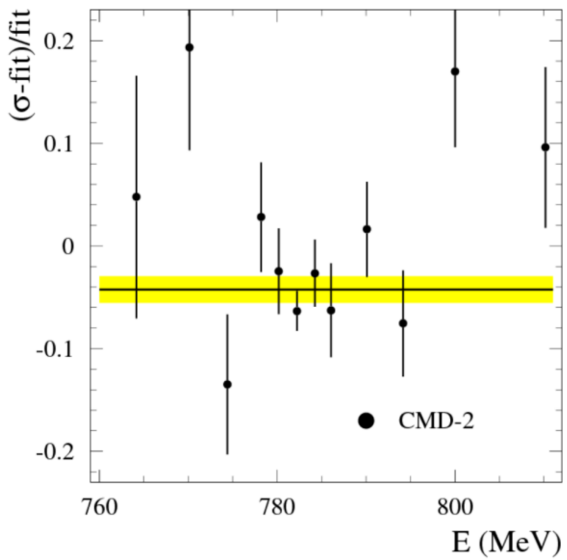
Parameter	Fitted value	PDG value
$\mathcal{B}(\omega \to e^+e^-)\mathcal{B}(\omega \to 3\pi) \times 10^5$	$6.648 \pm 0.022 \pm 0.058$	6.61 ± 0.16
m_ω, MeV	$782.703 \pm 0.011 \pm 0.047$	782.66 ± 0.13
Γ_ω, MeV	$8.598 \pm 0.023 \pm 0.004$	8.68 ± 0.13
$\mathcal{B}(\phi \to e^+e^-)\mathcal{B}(\phi \to 3\pi) \times 10^5$	$4.154^{+0.102}_{-0.066} \pm 0.066$	4.42 ± 0.11
m_ϕ, MeV	$1019.488 \pm 0.017 \pm 0.061$	1019.460 ± 0.016
Γ_ϕ, MeV	$4.265 \pm 0.033 \pm 0.014$	4.249 ± 0.013
φ_ϕ, deg	$156.8^{+6.5}_{-4.6} \pm 1.9$	163 ± 7
$\mathcal{B}(\rho \to 3\pi) \times 10^5$	$4.7 \pm 1.2 \pm 1.3$	9 ± 4
φ_ρ, deg	$-95.3 \pm 8.3 \pm 4.0$	-99 ± 17

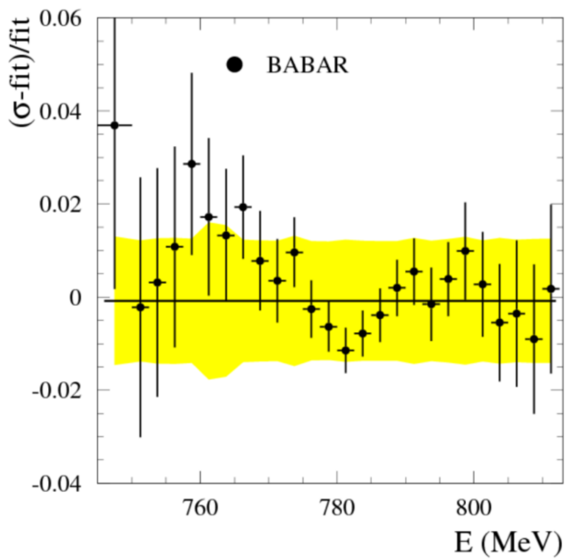
Source of systematics	near ω	near ϕ	Between ω and ϕ
Luminosity	0.7	0.7	0.7
Events	0.2	0.6	0.8
Efficiency	0.5	0.8	1.0
Total	0.9	1.2	1.5

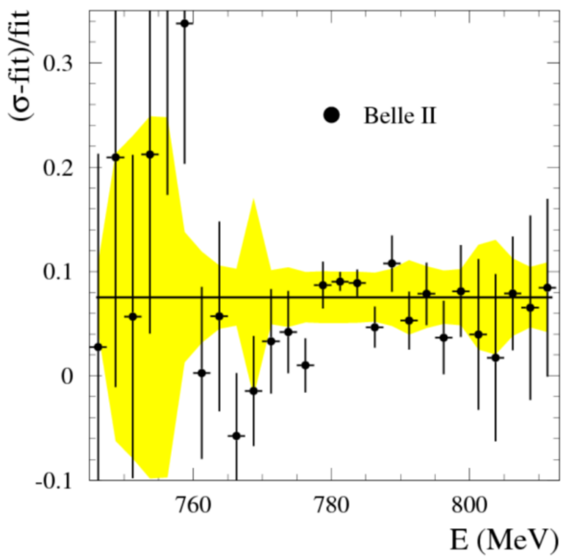
SND in comparison with other experiments near ω



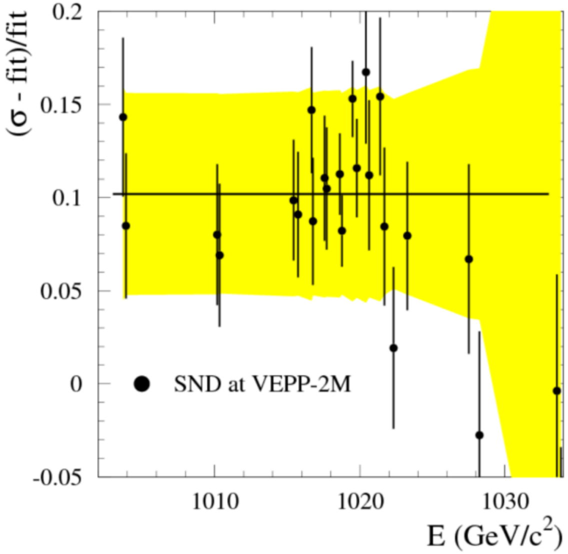
Our measurement is consistent with the BABAR and SND data on VEPP-2M, 4% (2σ) higher than the CMD-2 result and 8% (2σ) lower than the Belle-II result



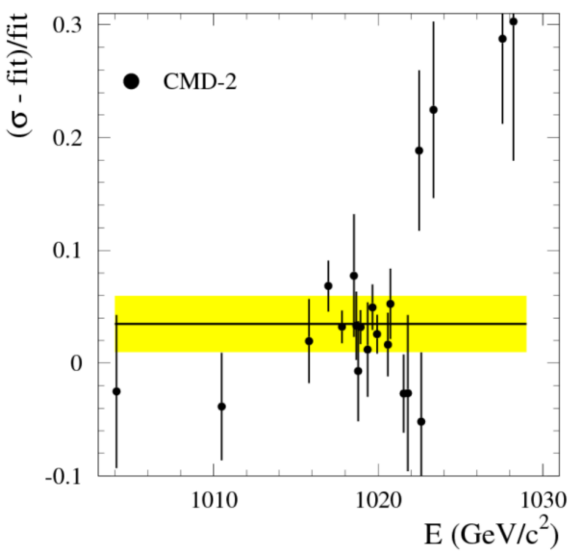


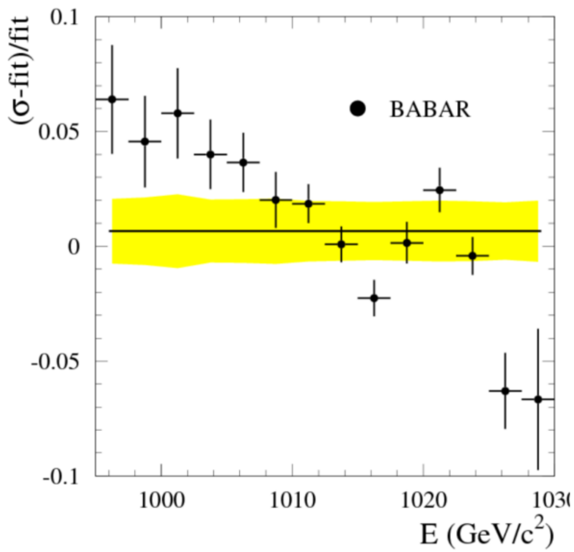


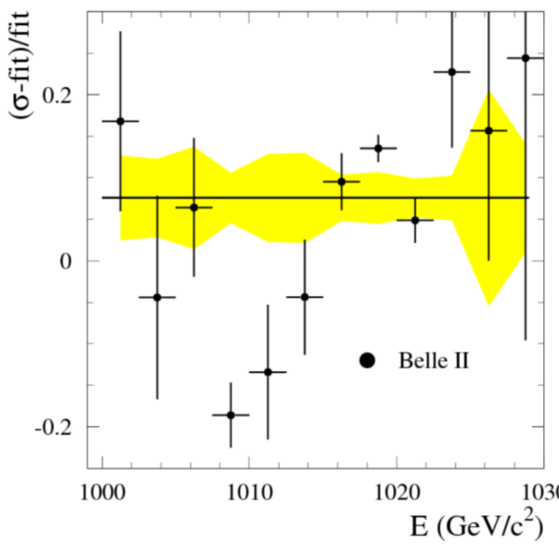
SND in comparison with other experiments near ϕ



Our measurement is consistent with the BABAR and CMD-2 data, 10% (2 σ) lower than the SND results on VEPP-2M and 7% (2 σ) lower than the Belle-II result







Contribution to the anomalous magnetic moment of the muon

https://arxiv.org/abs/2603.01635

$$a_\mu^{3\pi} = \frac{\alpha^2}{3\pi^2}\int_{m_\pi^2}^{\infty}\frac{K(s)}{s}\frac{\sigma(s)|1-\Pi(s)|^2}{4\pi\alpha^2/s}\,ds$$

To calculate $a_\mu^{3\pi}$ below 1.1 GeV, an approximating function was used. The statistical error was determined using the toy MC. The systematic error in $a_\mu^{3\pi}$ was determined by shifting the measured cross section up or down by the systematic error.

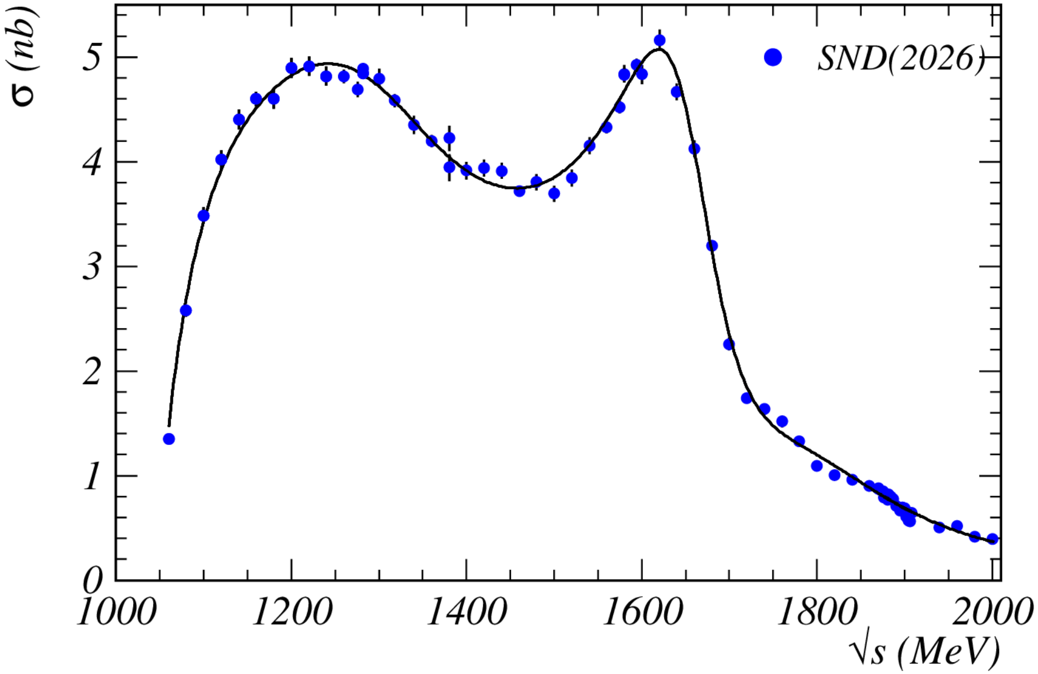
The contribution of the SND to $a_\mu^{3\pi}$ above 1.1 GeV was calculated using data from the paper M.N. Achasov *et al.*, Phys. Atom. Nucl. **87**, 747(2024)

E, GeV	$a_\mu^{3\pi}\times 10^{10}$
0.61–1.10 (SND)	$42.96\pm0.06\pm0.45$
1.10–1.975 (SND)	$2.99\pm0.02\pm0.08$
0.61–1.975 (SND)	$45.95\pm0.06\pm0.46$
0.62–1.10 (BABAR)	$42.91\pm0.14\pm0.55\pm0.09$
1.10–2.00 (BABAR)	$2.95\pm0.03\pm0.16$
<2.00 (BABAR)	$45.86\pm0.14\pm0.58$
0.62–1.80 (Belle II)	$48.91\pm0.23\pm1.07$
<1.8 (до 2021 года)*	$46.2\pm0.6\pm0.6$

* M. Hoferichter, B. L. Hoid and B. Kubis, JHEP 2019, 137 (2019)

The SND result is in agreement with the BABAR and $a_\mu^{3\pi}$ result calculated using data up to 2021, but is 2.5σ lower than the Belle II result

$e^+e^- \to \pi^+\pi^-\pi^o$ above 1 GeV

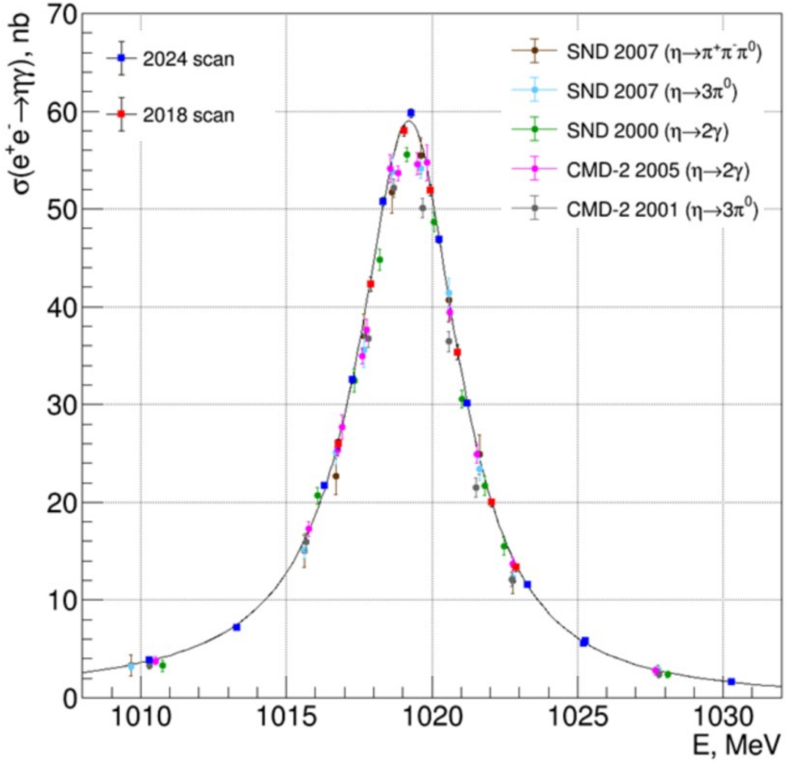


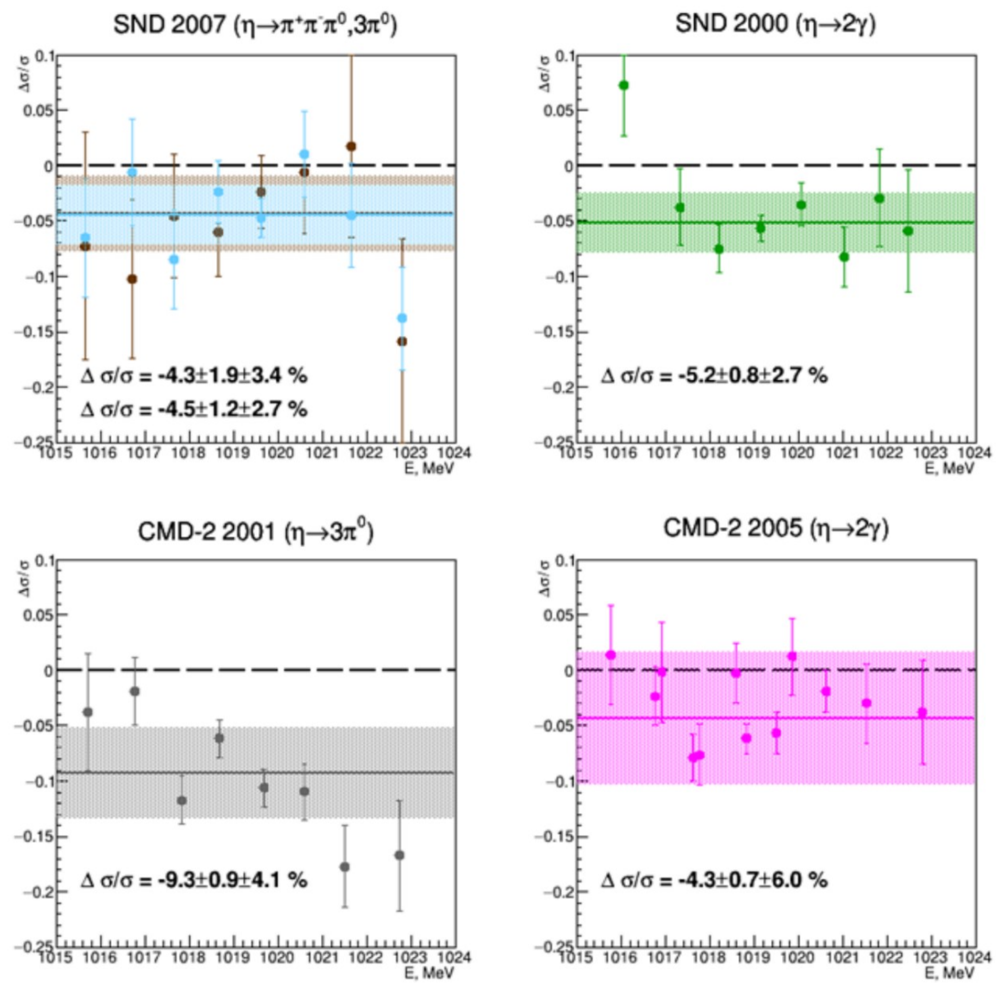
Данные: 2020-2024 года
Диапазон энергий 1.06 - 2.00 ГэВ
Светимость: 600 пб$^{-1}$

3 июн. 2026 г., 17:50, **Спектроскопия адронов**
Изучение динамики в процессе e+e- → π+π-π0 на детекторе СНД:
В докладе будут представлены результаты изучения распределений Далитца в рамках модели, включающей промежуточные состояния $\rho(770)\pi$, $\rho(1450)\pi$ и $\omega\pi^0$. В итоге были получены сечения для промежуточных состояний $\rho(770)\pi$, $\rho(1450)\pi$ и фаза между соответствующими амплитудами.

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

Data from 2018 & 2024, luminosity 73 pb^{-1}

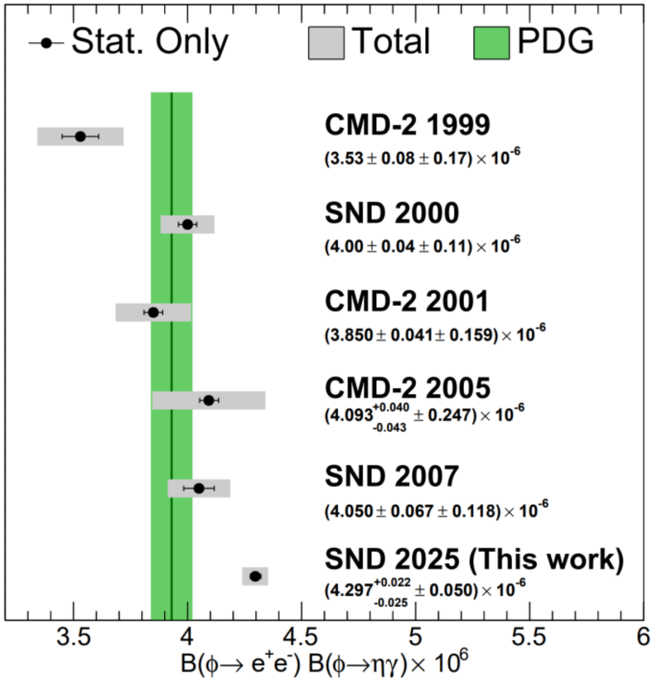




Fit model:

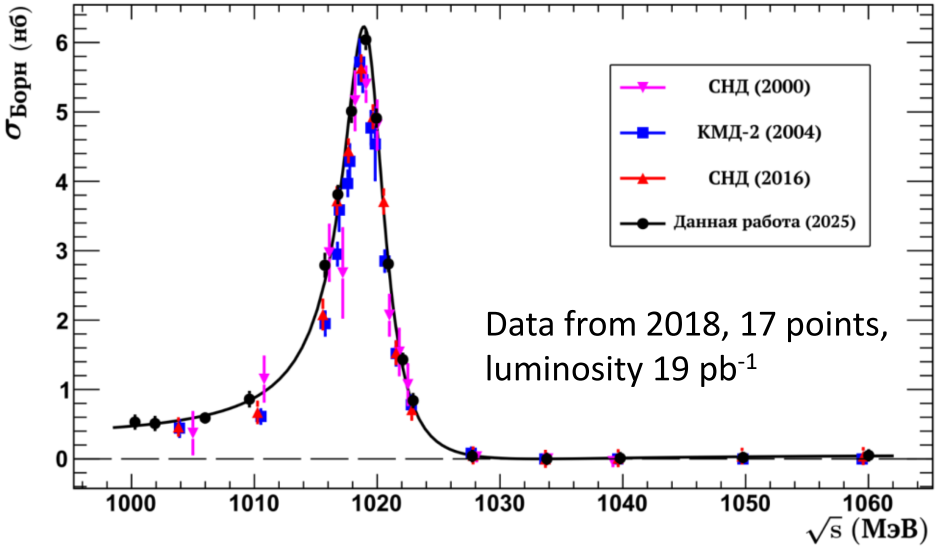
- VDM: $\rho(770),\ \omega(782),\ \phi(1020),\ \rho(1450), \phi(1680)$
- $\varphi_\omega = 0^\circ, \varphi_{\phi(1680)} = \varphi_{\rho(1450)} + 180^\circ$

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



- The $e^+e^- \to \eta\gamma$ cross section was measured in the energy range of 980-1060 MeV.
- The total systematic error of the measured cross section at the phi meson maximum was 1.5%.
- The measured cross section has the highest accuracy.
- The most precise measurement of $B(\phi \to e^+e^-)B(\phi \to \eta\gamma)$ was obtained.
- The results are published in the Phys.Rev.D 113 (2026) 052003.

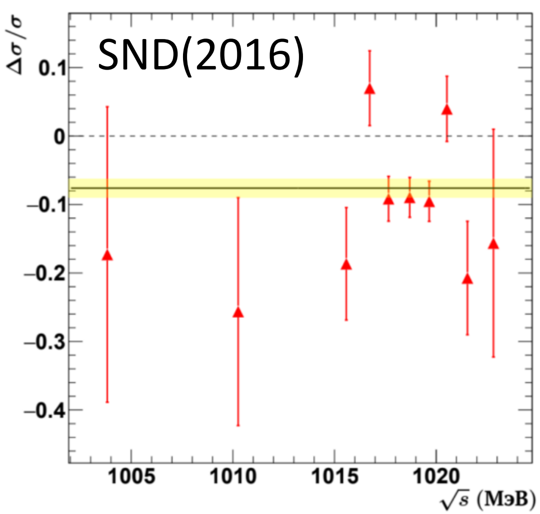
$e^+e^- \to \pi^0\gamma$ near ϕ

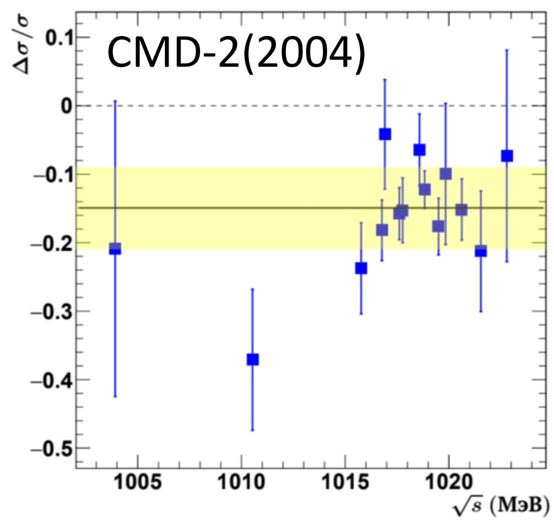


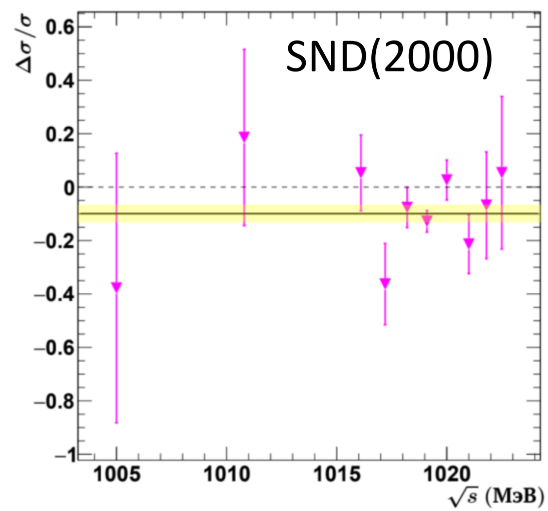
$$\sigma_{\pi^0\gamma}(s) = \frac{q^3(s)}{s^{\frac{3}{2}}}\Big|\sum_V A_V(s)\Big|^2,$$

$$A_V(s) = \frac{m_V \Gamma_V e^{i\varphi_V}}{m_V^2 - s - i\sqrt{s}\Gamma_V(s)}\sqrt{\frac{m_V^3}{q(m_V^2)^3}\sigma_V},$$

VDM: ρ, ω, ϕ and their excitations

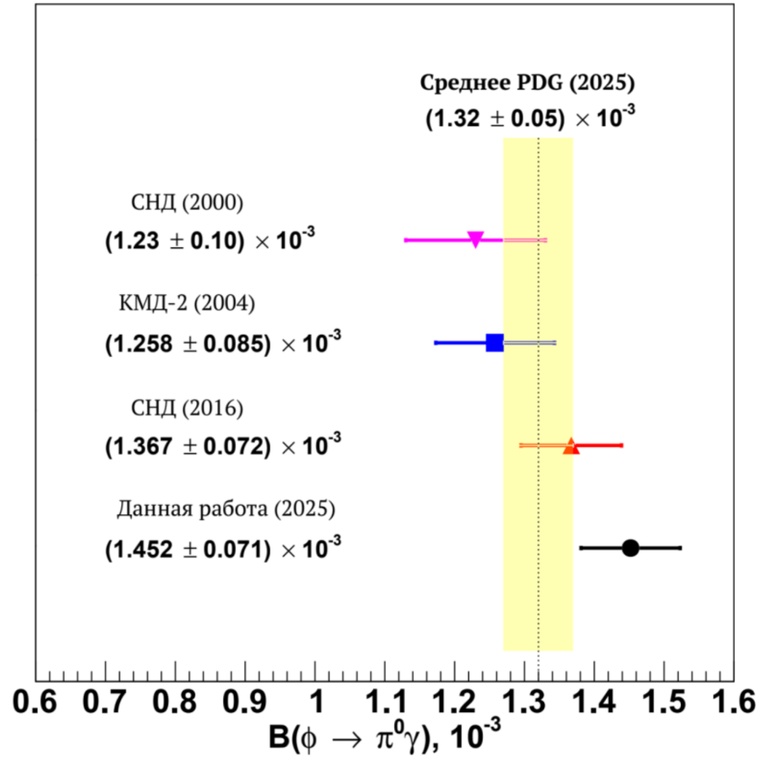






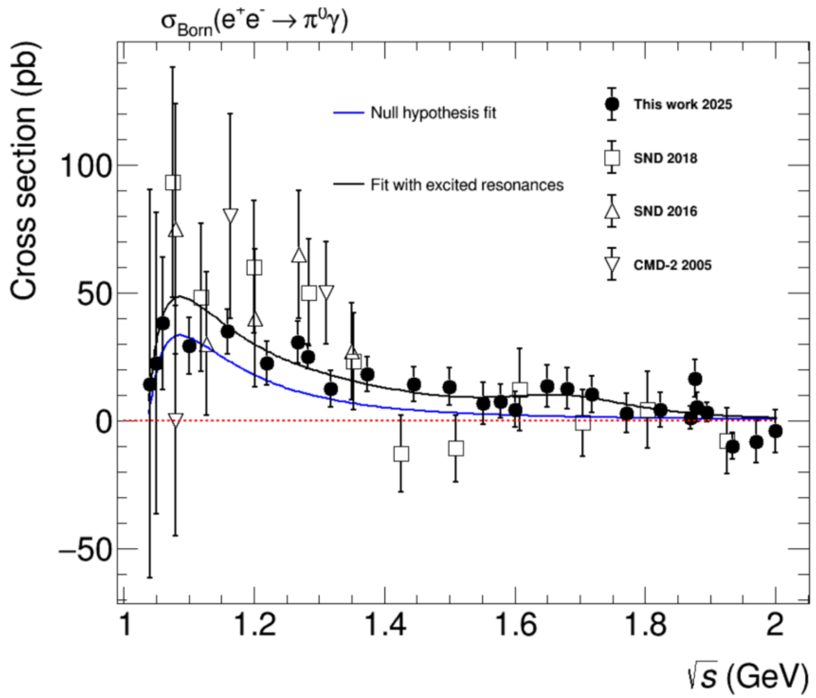
$e^+e^- \to \pi^0\gamma$

- The process $e^+e^- \to \pi^0\gamma$ was studied near φ.
- The systematic error of the cross section at the $\varphi(1020)$ resonance maximum is 1.3%, while the statistical error is 2.1%.
- To date, this is the most accurate measurement of the cross section for the process $e^+e^- \to \pi^0\gamma$.
- The cross section is well described by VDM.
- The measured cross section for the $e^+e^- \to \pi^0\gamma$ process is 7–15% higher than the results of previous measurements performed in the SND and CMD-2 experiments at the VEPP-2M collider. This difference significantly exceeds the systematic measurement errors.



The decay probability was measured to be $B(\varphi \to \pi^0\gamma) = (1.452 \pm 0.024 \pm 0.067) \times 10^{-10}$. The systematic error in the decay probability is dominated by the contribution associated with the uncertainty in the phase of the interference between the amplitudes of the ω and ϕ resonances.

$e^+e^- \to \pi^0\gamma$ above 1 GeV



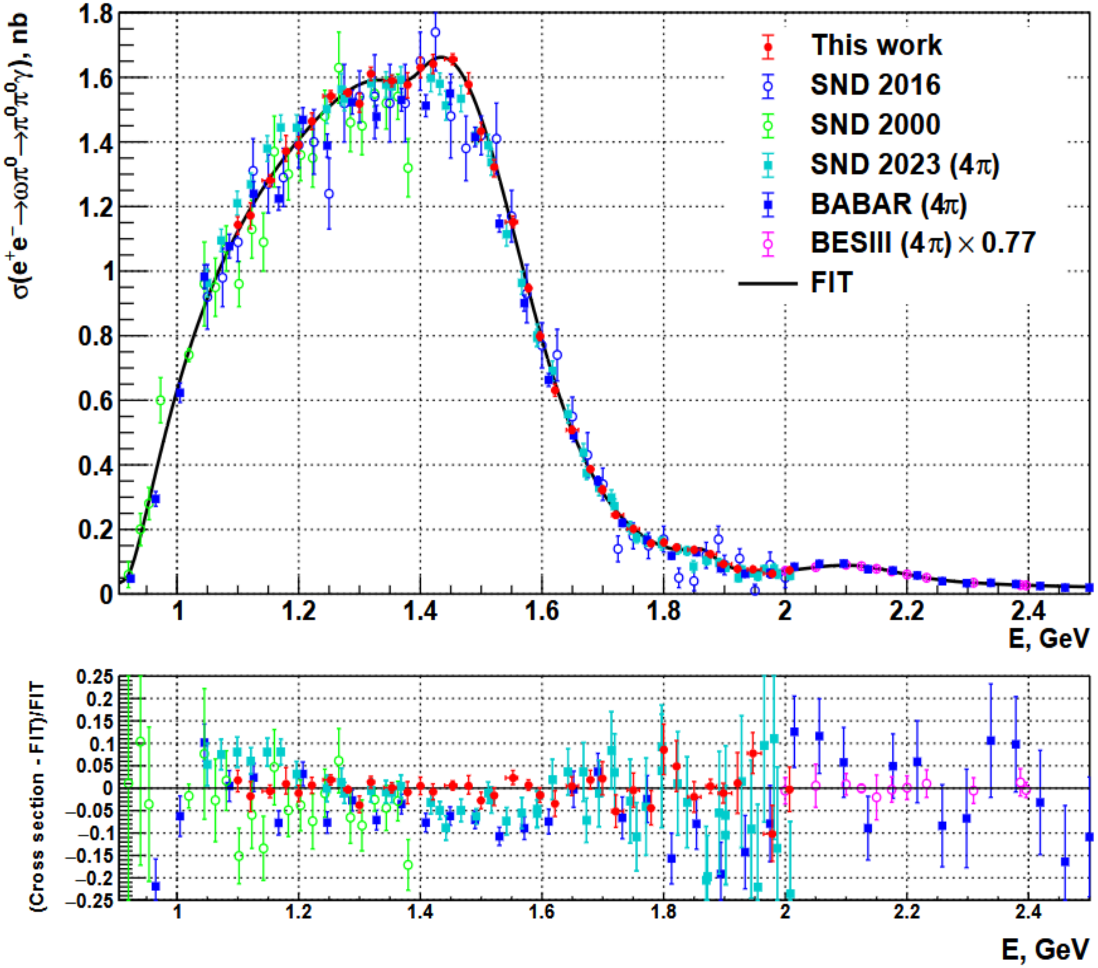
Data from 2017-2024, 153 points, luminosity 909 pb^{-1}

- The most accurate measurement of the process cross section was performed in the energy range of 1.08-2.00 GeV.
- The systematic error varies from 2.5% to 10.4% in the energy range from 1.1 to 1.5 GeV, respectively.
- The cross section is well described by a VDM with two effective resonances.
- The null hypothesis (without excited resonances) is excluded at the 4.65 σ level.

The null hypothesis: used only ρ, ω, ϕ
Hypothesis with excited resonances: used ρ, ω, ϕ and their excitations, but instead of $\omega(1420), \rho(1450), \omega(1650)$ and $\rho(1700)$, two effective resonances were used $m_{V_1} = 1450$ MeV and $m_{V_2} = 1700$ MeV

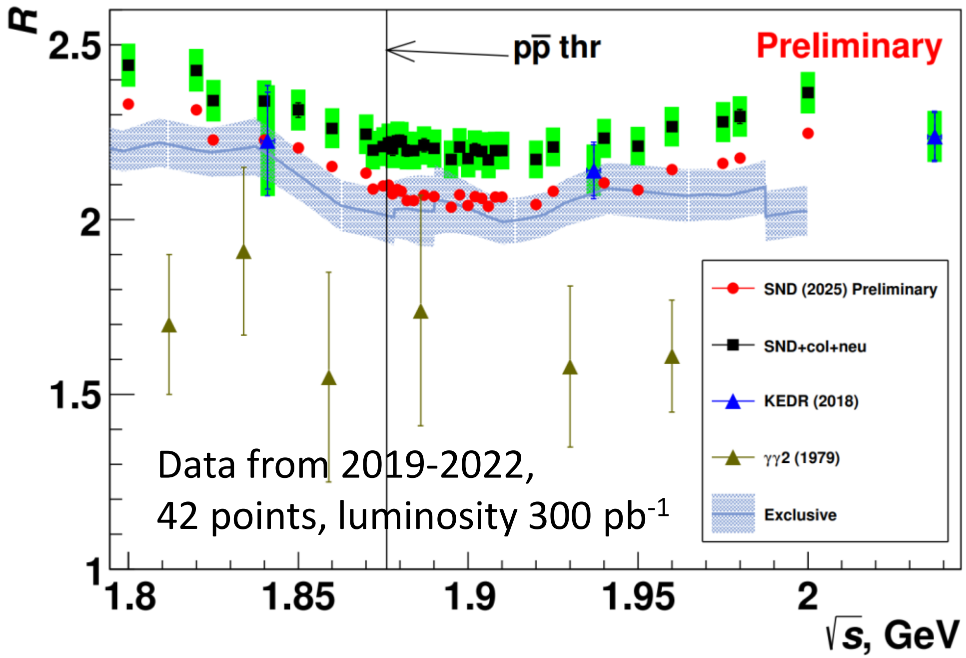
$e^+e^- \to \omega\pi^0(\omega \to \pi^0\gamma)$

- Fit quality is good $\chi^2/ndf = 39.4/40$
- Good agreement with previous measurements in decay channel $\omega \to \pi^0\gamma$
- Notable disagreement (10%) with measurements in decay channel $\omega \to \pi^+\pi^-\pi^0$ below 1.6 GeV
- Good agreement with SND 2023 above 1.6 GeV
- A scale factor 0.77±0.04 obtained from the fit was applied to BESIII data



$e^+e^- \to hadrons$ (incl.)

Motivation:
- important for new physics search
- valuable to compare inclusive cross section with sum of exclusive cross sections
- In this work the inclusive cross section of e^+e^--annihilation is measured:
  - into charged hadronic states
  - with more than two particles
  - in the region of $\sqrt{s} = 1.8 - 2.0$ GeV



The measured value $R = \sigma_B/\sigma_{ee\to\mu\mu}$ (red points).
The total R value is a sum of measured R and contributions of the collinear charged processes and processes with neutral particles in the final state (black points)
SND data is compared with $\gamma\gamma2$(gray) and KEDR (blue) results and with the sum of exclusive cross sections

R measured in this work is systematically greater than sum of exclusive cross sections and compatible with KEDR results, but have much greater statistical accuracy

Conclusions

- $e^+e^- \to \pi^+\pi^-$:
  - ✓ The total cross section of the $e^+e^- \to \pi^+\pi^-$ process was measured in the $\sqrt{s} = 548 - 990$ MeV energy range with a systematic error of 0.7-0.8% at $\sqrt{s} < 600$ and $\sqrt{s} > 900$ MeV and 0.7% at $600 < \sqrt{s} < 900$ MeV. The measurement accuracy is at the level of world-leading precision measurements.
  - ✓ Contribution of the $e^+e^- \to \pi^+\pi^-$ process to the anomalous magnetic moment of the muon is $a_\mu^{\pi\pi} = (430.15 \pm 0.49 \pm 2.94) \cdot 10^{-10}$ in the $548 < \sqrt{s} < 990$ MeV energy range
  - ✓ The results are consistent with the CMD-3 and KLOE measurements. There is a difference with BABAR data at the 2σ level.
  - ✓ It is planned to process data from 2024-2026, which will significantly reduce statistical error.

Conclusions

- $e^+e^- \to \pi^+\pi^-\pi^o$
  - ✓ The most precise measurement of the $e^+e^- \to \pi^+\pi^-\pi^o$ process cross section at energies below 1.1 GeV has been achieved. The systematic error in measuring the cross section near the ω and φ resonance maxima is 0.9% and 1.2%, respectively.
  - ✓ The SND data are consistent with the BABAR measurements and are approximately 7-8% (2σ) lower than the Belle II data.
  - ✓ The most precise measurements of the $B(\phi \to e^+e^-)B(\phi \to \pi^+\pi^-\pi^o)$, m_ω and Γ_ω parameters have been made within of the VDM.
- $e^+e^- \to \eta\gamma$
  - ✓ The most accurate measurement of the $e^+e^- \to \eta\gamma$ process was obtained in the 980-1060 MeV energy range. The systematic measurement error at the $\phi(1020)$ resonance maximum is 1.5%.
  - ✓ The most precise measurement of $B(\phi \to e^+e^-)B(\phi \to \eta\gamma)$ was obtained.
  - ✓ The results are published in the Phys.Rev.D 113 (2026) 052003.

Conclusions

- $e^+e^- \to \pi^0\gamma$
  - ✓ The most accurate measurement of the $e^+e^- \to \pi^0\gamma$ process in the 1000-1060 MeV energy range was obtained. The systematic measurement error at the $\phi(1020)$ resonance maximum is 1.3%, and the statistical error is 2.1%.
  - ✓ The decay probability was measured $\mathrm{B}(\phi \to \pi^0\gamma) = (1.452 \pm 0.024 \pm 0.067) \cdot 10^{-3}$.
  - ✓ The most accurate measurement of the $e^+e^- \to \pi^0\gamma$ process cross section was performed in the energy range of 1.08-2.00 GeV.
  - ✓ The systematic error varies from 2.5% to 10.4% in the energy range from 1.1 to 1.5 GeV, respectively.
- $e^+e^- \to \omega\pi^0$
  - ✓ The cross section of the process $e^+e^- \to \omega\pi^0$ has been measured with the best accuracy to date
- $e^+e^- \to hadrons\ (\mathrm{incl.})$
  - ✓ In this work the inclusive cross section of e^+e^--annihilation into charged hadronic states with more than two particles in the region of $\sqrt{s} = 1.8 - 2.0$ GeV is measured
  - ✓ R measured in this work is systematically greater than sum of exclusive cross sections and compatible with KEDR results, but have much greater statistical accuracy