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

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on behalf of the SND collaboration

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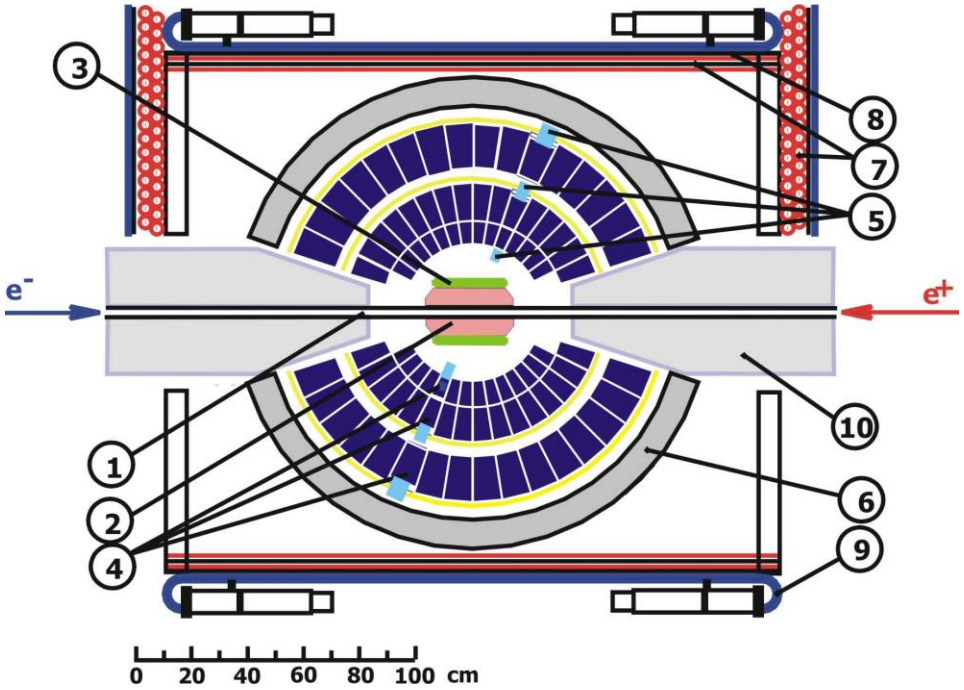
SND detector



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.

SND collected data at the VEPP-2M e^+e^- collider (1996-2000) and then, after modernization, continues to take data at VEPP-2000 (2010-2013,2016-…)

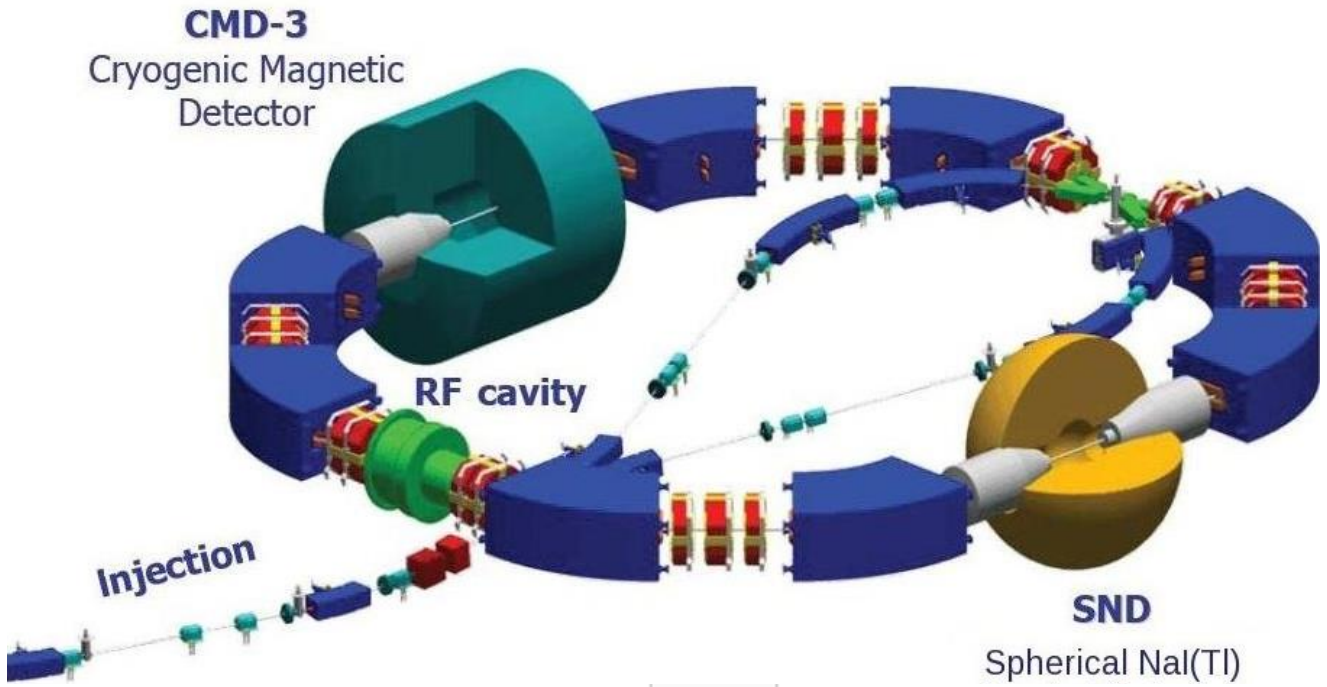
The main physics task of SND is study of all possible processes of e^+e^- annihilation into hadrons below 2 GeV.

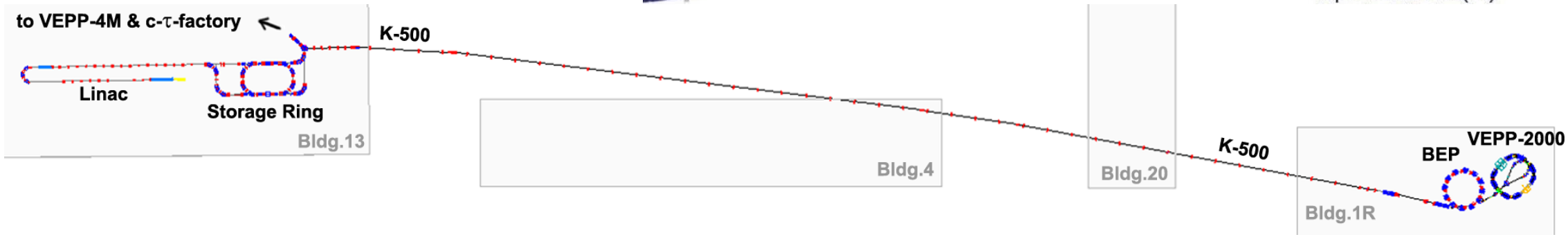
- ✓ The total hadronic cross section, which is calculated as a sum of exclusive cross sections.
- ✓ Dynamics of multihadron exclusive processes.
- ✓ Properties of vector mesons of the ρ, ω, ϕ families.
- ✓ Nucleon-antinucleon production near threshold.
- ✓ …

VEPP-2000 e^+e^- collider

VEPP-2000 parameters:

- C.m. energy E=0.3-2.0 GeV
- Circumference – 24.4 m
- Number of bunches – 1×1
- Round beam optics
- Luminosity at E=1.8 ГэВ
  1×10^{32} cm^{-2} sec^{-1} (project)
  9×10^{31} cm^{-2} sec^{-1} (achieved)
- Two detectors: SND and CMD-3
- Energy measurement using the Compton back-scattering of laser photons on the electron beam.





Collected data

2010-2013 – 64 pb^{-1}

2013-2016 – upgrade

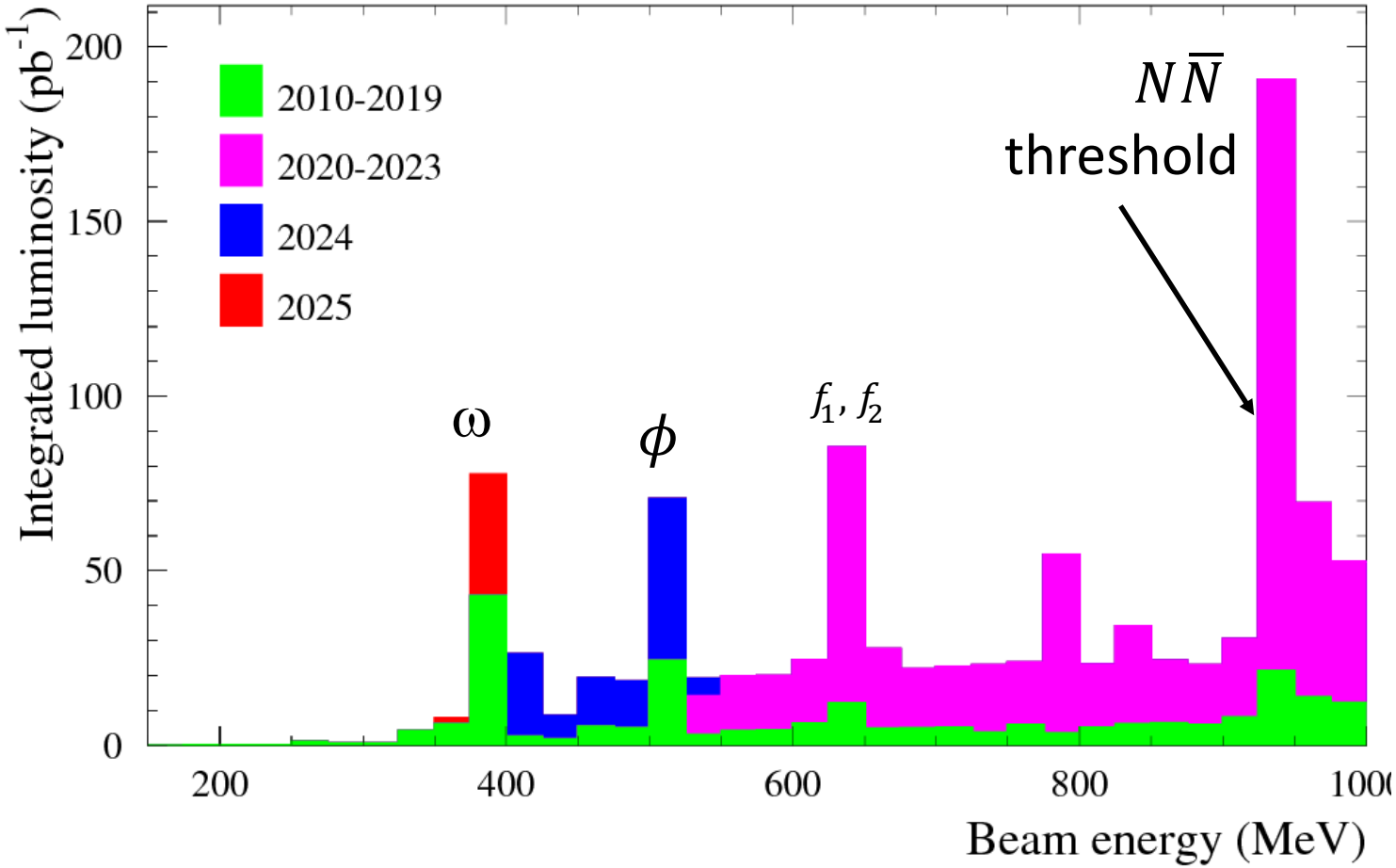
2017-2019 – 167 pb^{-1}

2020-2023 – 648 pb^{-1}

2024-2025 – 146 pb^{-1}

Total ~1 fb^{-1}

Compared with ~30 pb^{-1} at VEPP-2M

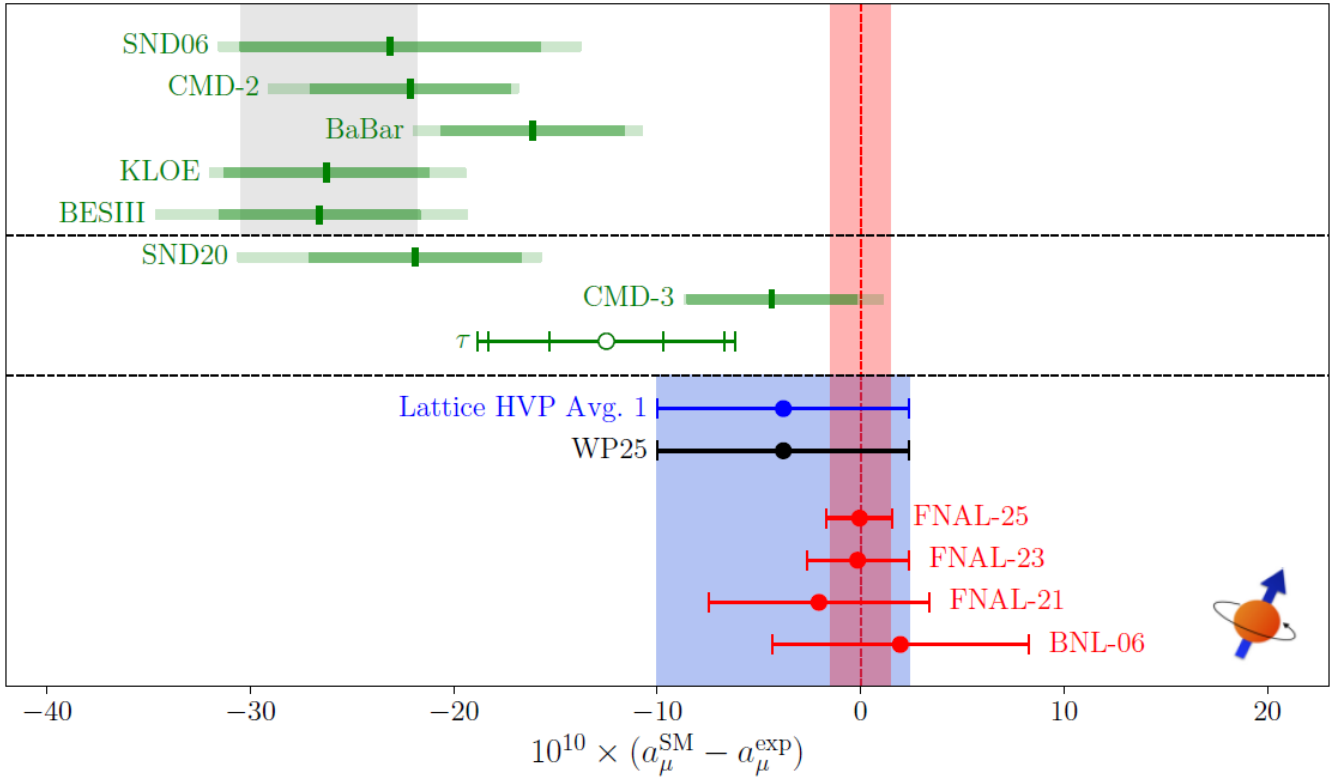


2024-2026 – Scan of the ρ-ω-ϕ regions (150-1060 MeV) with approximately tripled statistics.

Muon anomalous magnetic moment

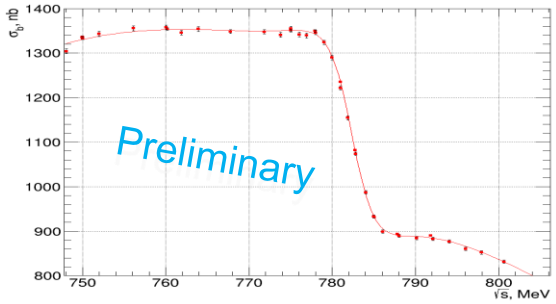
- The Muon g-2 Collaboration measured the muon anomalous magnetic moment with 0.13 ppm accuracy.
- The accuracy of the Standard model prediction based on lattice QCD calculations is 0.56 ppm.
- The CMD-3 measurement of the $e^+e^- \to \pi^+\pi^-$ cross section significantly increased the tensions among data-driven dispersive evaluations of the LO HVP contribution. So, the $\pi^+\pi^-$ data from different experiments currently cannot be averaged.

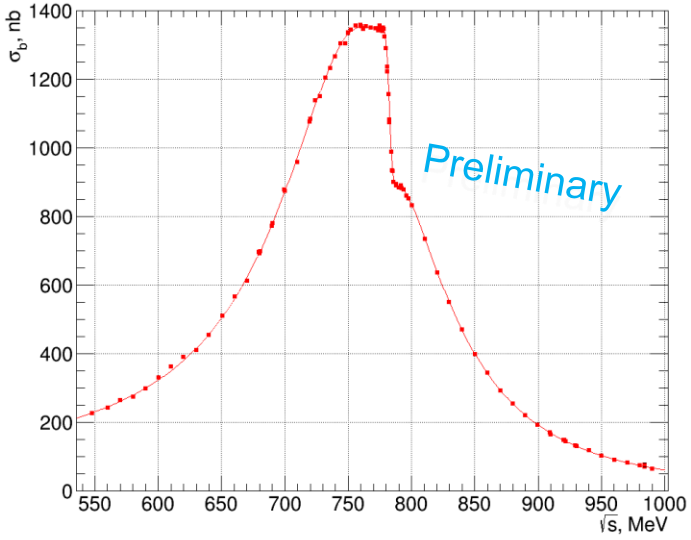
WP2025: arXiv:2505.21476 [hep-ph]

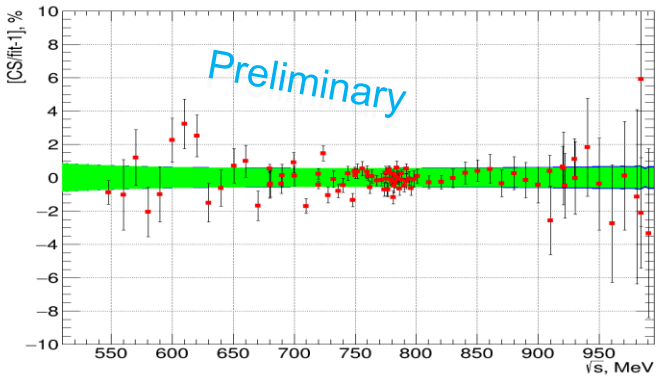


New measurements of the $e^+e^- \to \pi^+\pi^-$ are needed to verify the correctness of the CMD-3 result.

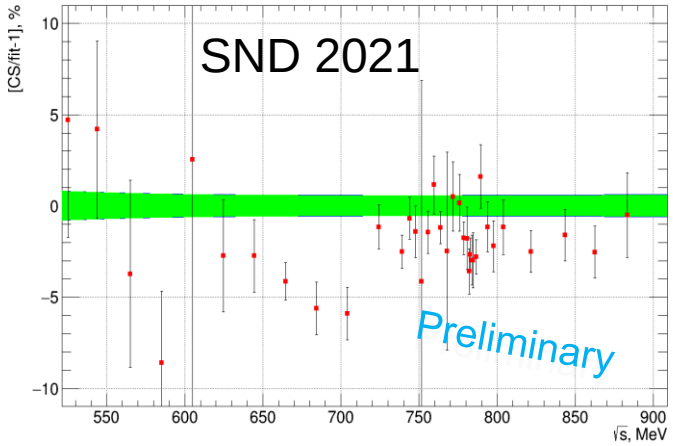
$e^+e^- \to \pi^+\pi^-$

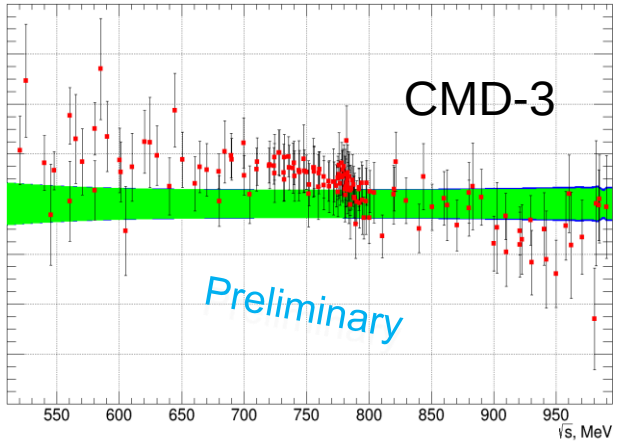


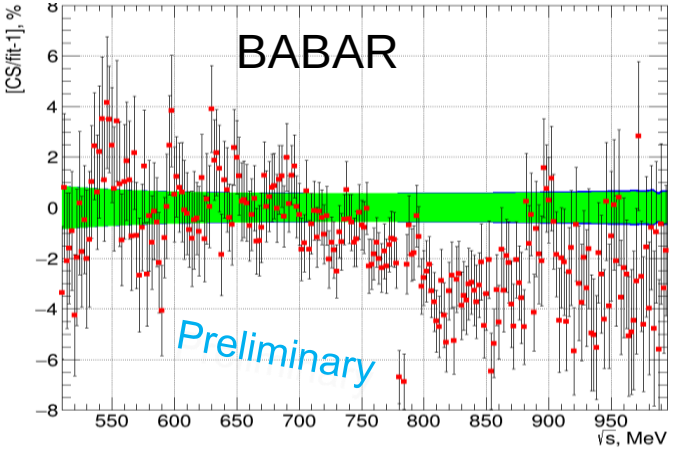


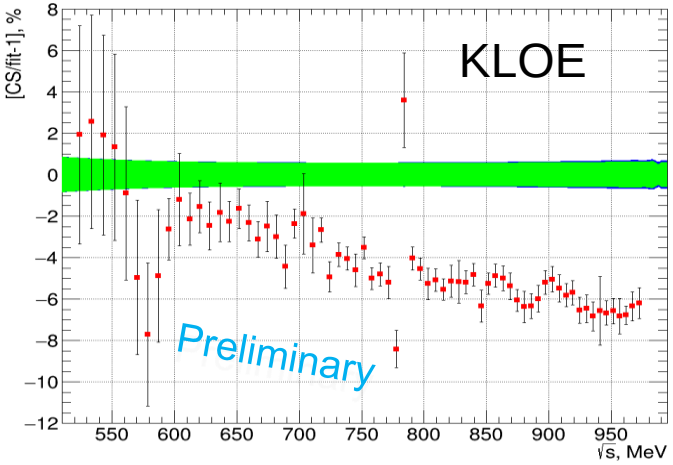


- ✓ 2018 data set – 47 pb^{-1}
- ✓ High precision **MCGPJ** and **BabaYaga-NLO** MC generators
- ✓ The $e^+e^- \to e^+e^-$ process is used for the luminosity measurement
- ✓ Electron/pion/muon separation is based on the machine learning methods using the energy depositions in calorimeter crystals.
- ✓ Efficiency corrections are obtained from study of specially selected data events.
- ✓ The radiative and beam energy spread corrections are calculated.
- ✓ The current estimate of the systematic uncertainty in the cross section is **0.7-0.8%**.
- ✓ The Born cross section is fitted using the VMD model with ρ(770), ω, and ρ(1450) resonances.





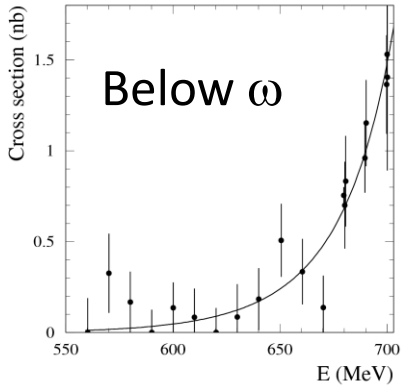


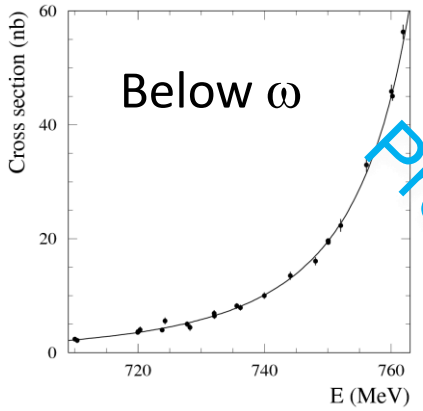


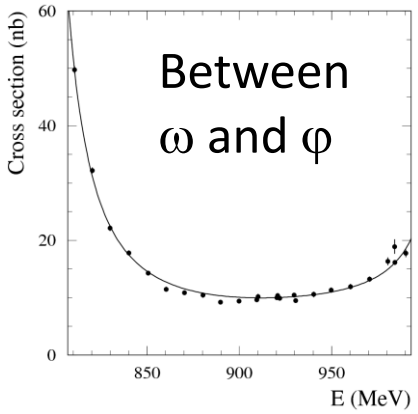
$e^+e^- \to \pi^+\pi^-$: comparison with previous measurements

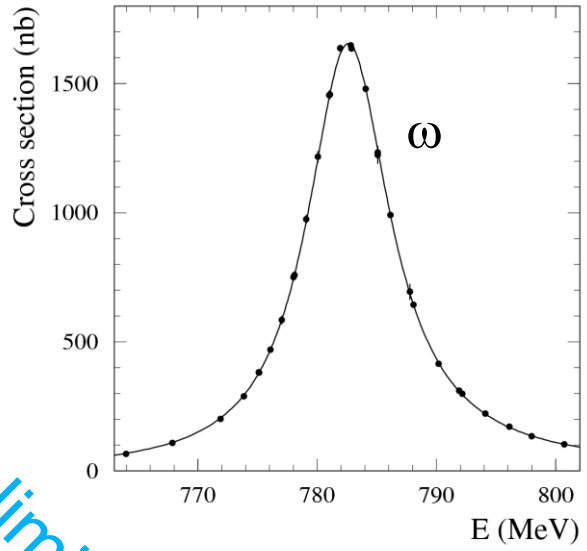
- ✓ The new SND measurement is 2% higher than the previous one based on the 2013 data set. The reanalysis of these data yield the result consistent with the new analysis. **Explanation:** shortcomings of the previous version of the event reconstruction algorithm resulted in the loss of pion tracks.
- ✓ The SND result is consistent with **CMD-3,** which is 1.3% higher below ρ and 0.7% lower above 0.9 GeV.
- ✓ SND is consistent with the **BABAR** measurement below ρ, and 3% higher above 0.78 GeV.
- ✓ Our measurement is 2-6% higher than the **KLOE** measurement.

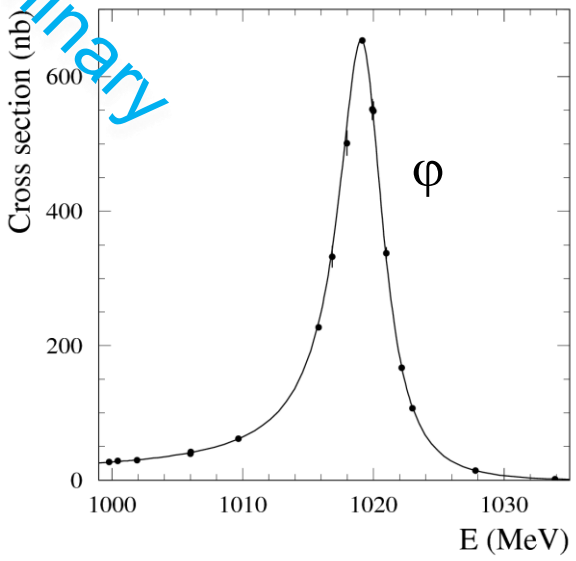
$e^+e^- \to \pi^+\pi^-\pi^0$







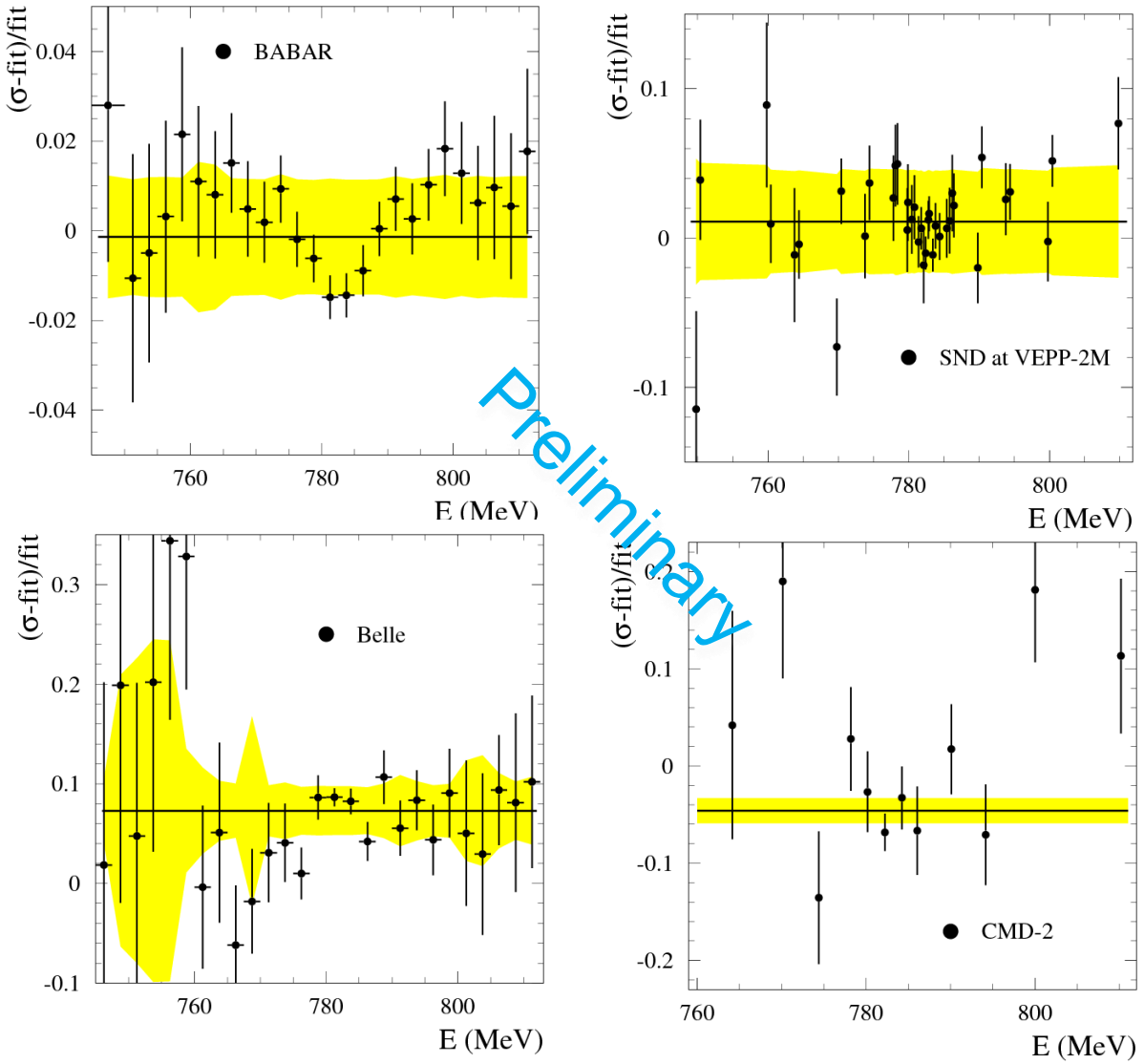




Preliminary

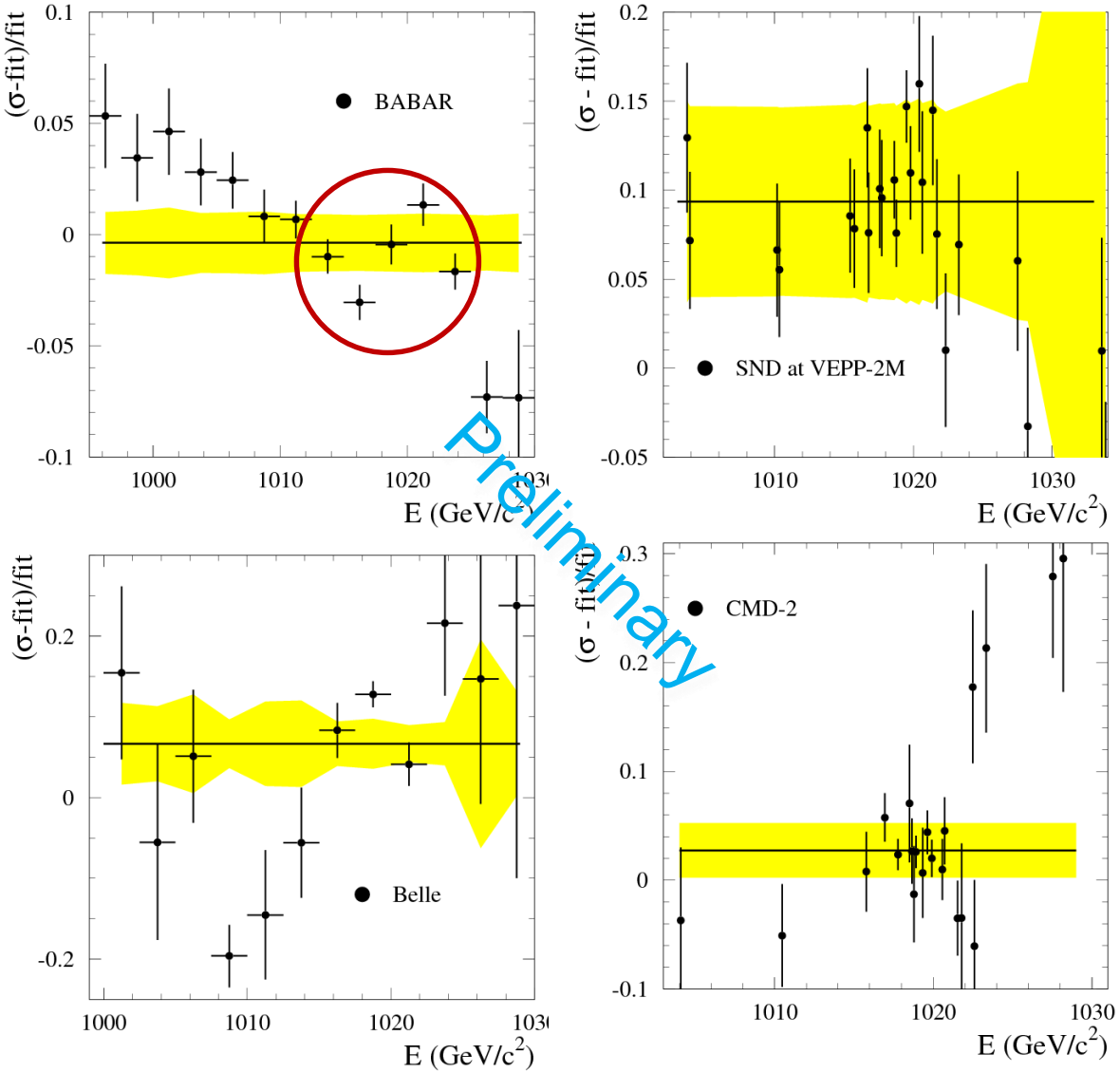
- Below 1.05 GeV the $e^+e^- \to \pi^+\pi^-\pi^0$ cross section is dominated by the ω and φ resonances.
- The most precise measurement (1.3% sys. err.) was carried out by BABAR in 2021 using ISR method.
- The BABAR results agrees with the SND data obtained at the VEPP-2M e^+e^- collider, but 2σ larger than the CMD-2 data.
- In 2024, the Belle-II ISR measurement with a systematic uncertainty 2.2% was published. The Belle-II cross section is about 7% higher than that of BABAR.
- In the ω region, $e^+e^- \to \pi^+\pi^-\pi^0$ events can be selected with very loose selection criteria. This feature is used in our analysis to perform the precise cross section measurement.

Comparison with previous measurements near ω



- ✓ The SND systematic uncertainty in this region is estimated to be 1.2%.
- ✓ The new SND measurement is in good agreement with the BABAR and SND@VEPP-2M data, about 7% lower than the Belle-II data, and about 5% higher than the CMD-2 data.

Comparison with previous measurements near ϕ



- ✓ The SND systematic uncertainty is 1.5%.
- ✓ The new SND measurement is in reasonable agreement with the BABAR and CMD-2 data, about 7% lower than the Belle-II data, and about 10% lower than the SND@VEPP-2M data.

$e^+e^- \to \pi^+\pi^-\pi^0$ above 1.05 GeV

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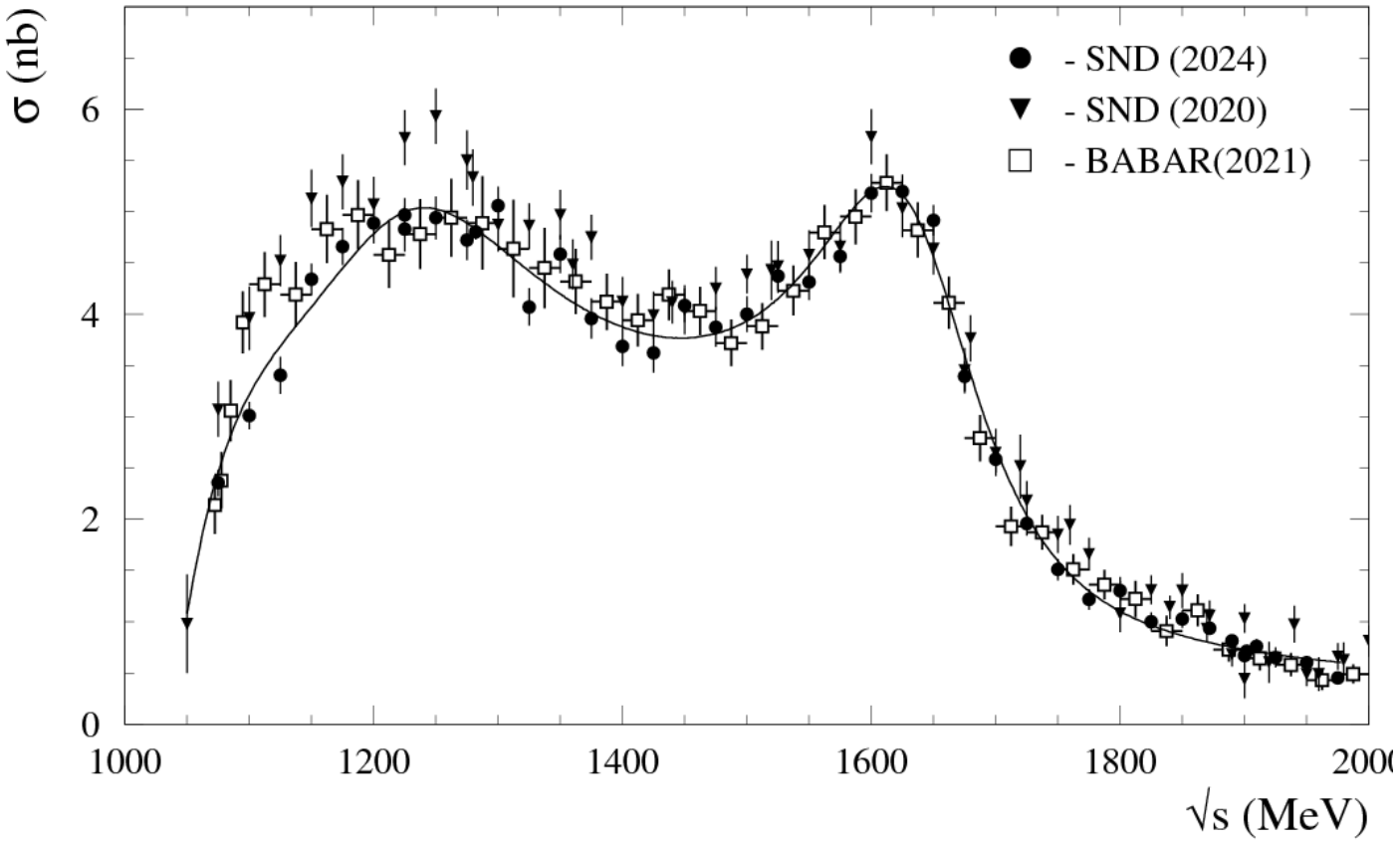
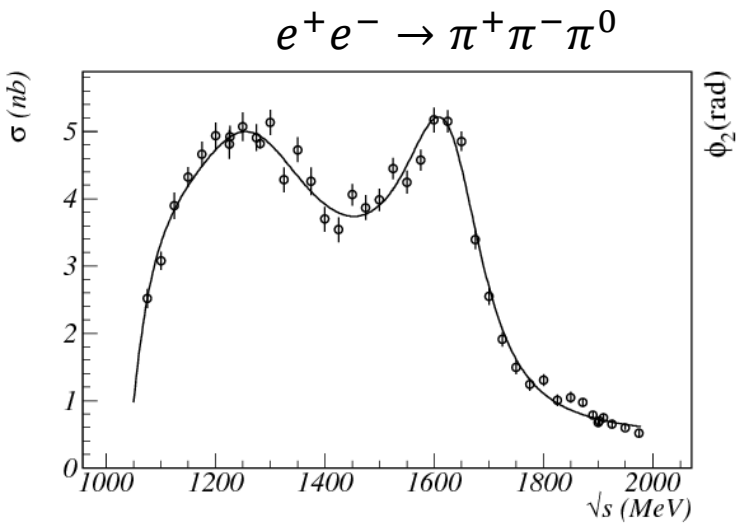
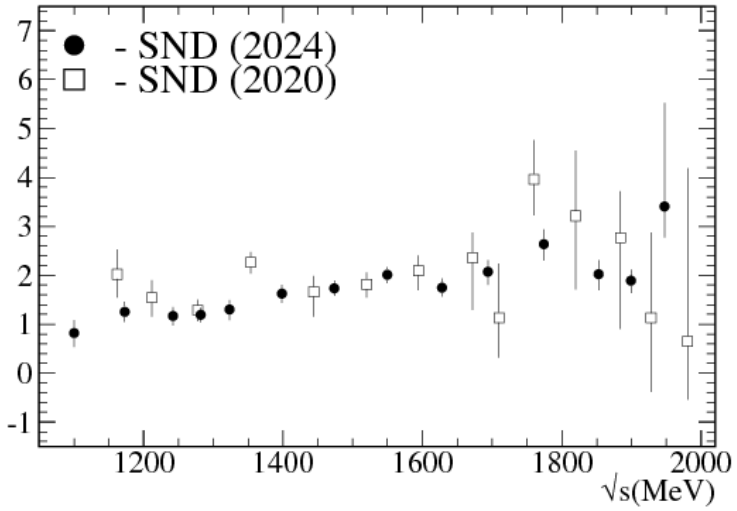
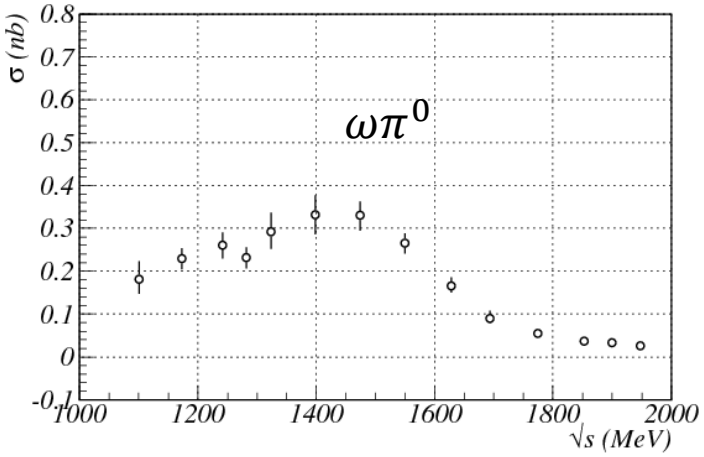


- We have made a new measurement of the $e^+e^- \to \pi^+\pi^-\pi^0$ cross section above 1.05 GeV using the 2019 data set. A more careful analysis of background sources has led to a decrease in the cross section compared to the previous SND (2020) measurement.
- The two peaks in the $e^+e^- \to \pi^+\pi^-\pi^0$ cross section above 1.05 GeV are associated with the excited ω-like states: ω(1420) and ω(1650).
- The Dalitz plot analysis has been used to separate between the ρ(770)π, ρ(1450)π, and $\omega\pi^0$ intermediate states.

$e^+e^- \to \pi^+\pi^-\pi^0$ above 1.05 GeV ($\omega\pi^0$)





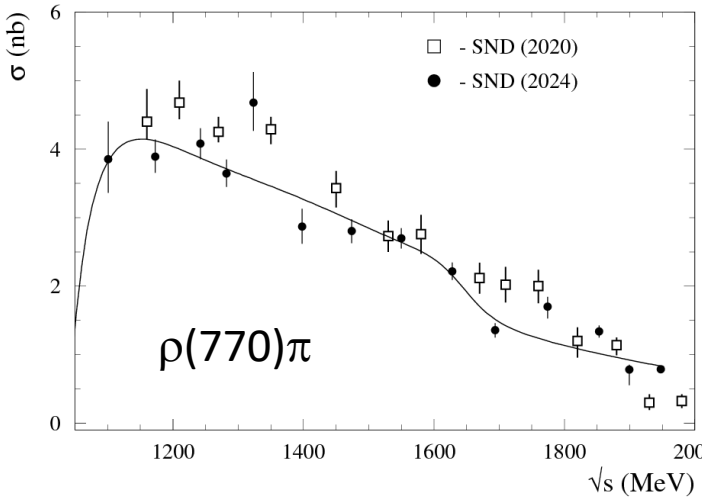


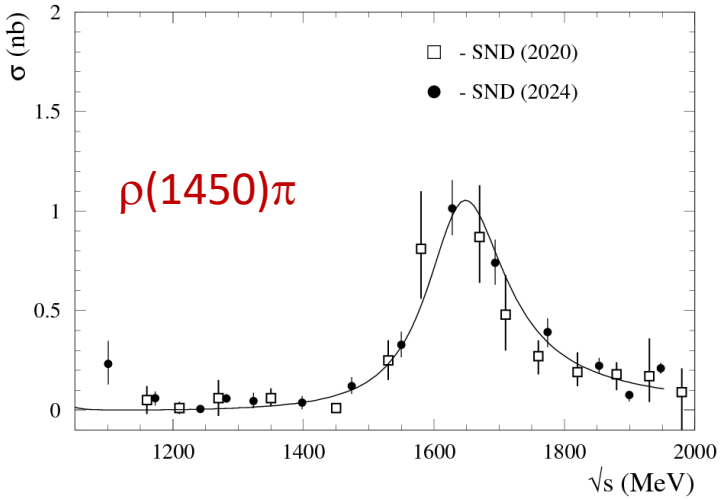
- In the Dalitz plot analysis, the modulus of the $\omega\pi^0$ amplitude is calculated using the SND data on the $e^+e^- \to \omega\pi^0$ cross section and the PDG value for the $\omega \to \pi^+\,\pi^-$ branching fraction.
- The phase between the ρπ and $\omega\pi^0$ amplitudes is determined from the fit to the Dalitz plot.

- The total contribution (including interference) of the isovector $\omega\pi^0$ state to the total $e^+e^- \to \pi^+\pi^-\pi^0$ cross section reaches 16% at 1.4 GeV.

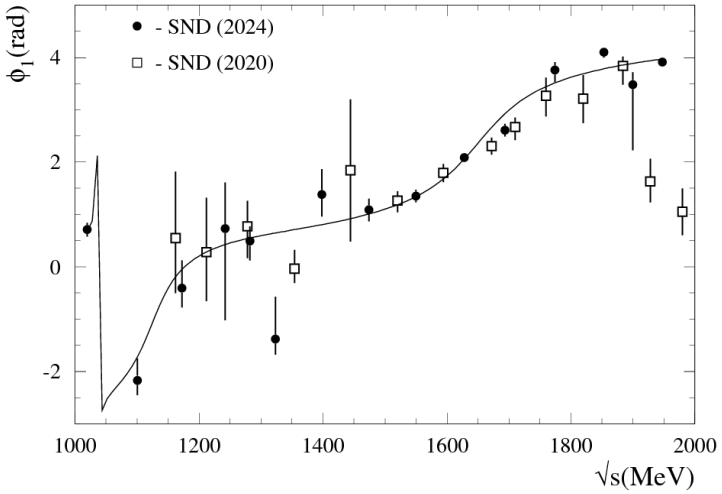
$e^+e^- \to \pi^+\pi^-\pi^0$ above 1.05 GeV

- The parameters of the ω(1420) and ω(1650) resonances are obtained from a simultaneous fit to the data on the $e^+e^- \to \rho(770)\pi$ and $\rho(1450)\pi$ cross sections and the relative phase between the amplitudes of these intermediate states.
- The ω(1650) resonance is produced mainly via the ρ(1450)π mechanism, while ω(1420) via the ρ(770)π.
- The ω(1650) width in the $\pi^+\pi^-\pi^0$ channel became 150 MeV and is now consistent with the other decay channels, $\omega\eta$ and $\omega\pi\pi$.

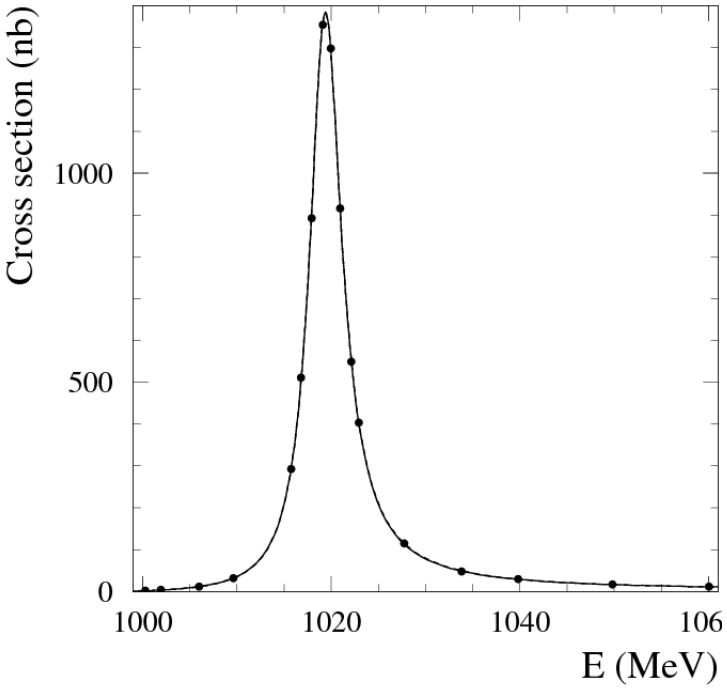


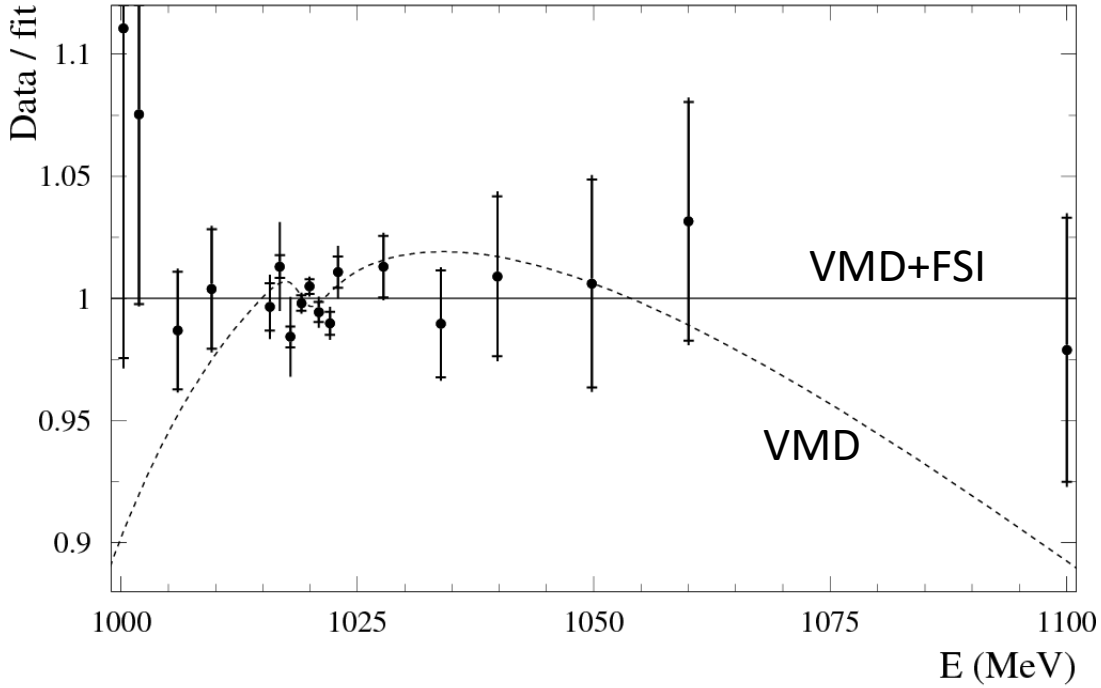


Parameter	This work	PDG
$m_{\omega(1420)}$, MeV	1350 ± 43	1410 ± 60
$\Gamma_{\omega(1420)}$, MeV	590 ± 90	290 ± 190
$m_{\omega(1650)}$, MeV	1643 ± 6	1670 ± 30
$\Gamma_{\omega(1650)}$, MeV	148 ± 13	315 ± 35



$e^+e^- \to K_S K_L$ cross section near $\phi(1020)$





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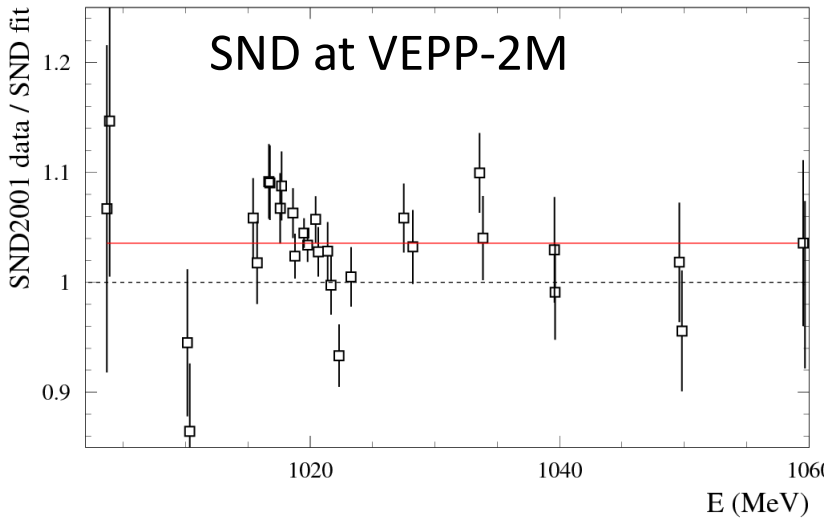
The process $e^+e^- \to K_S K_L$ is studied in the decay mode $K_S \to \pi^0\pi^0 \to 4\gamma$. In the multiphoton final state, $K_S K_L$ events can be selected with very loose conditions.

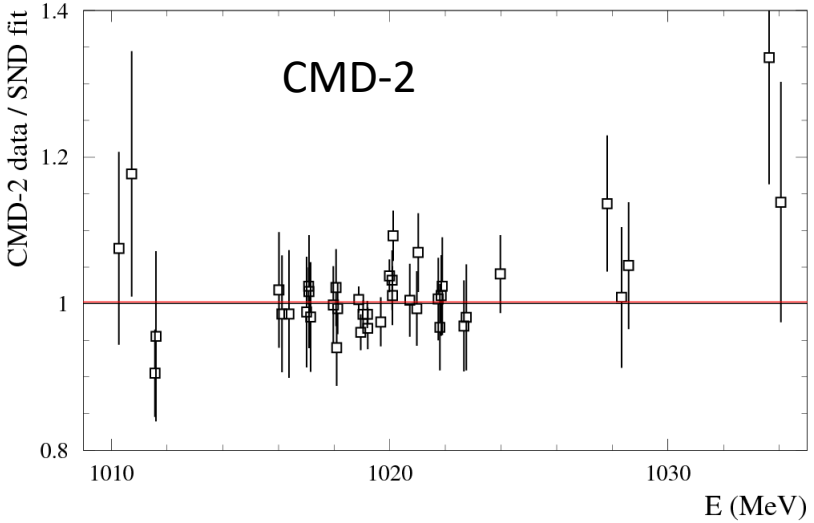
Two models are used to describe the cross section: VMD and VMD+FSI. The latter provides significantly better fit quality, χ^2/ndf=13.7/14 against 23.7/14 for the pure VMD model. The FSI significance is 3.2σ.

The FSI effect was calculated by S.Salnikov and A.Milstein (work in progress). The scale factor to the cross section is 1.16 at E=1000 MeV, 1 at E=m_ϕ, and 0.92 at E=1100 MeV

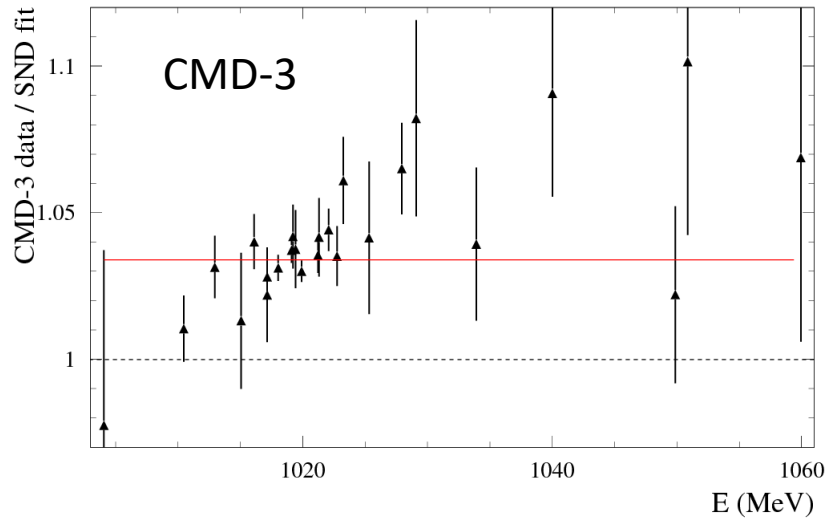
Comparison with previous measurements



1.036 ± 0.005 ± 0.032



1.003 ± 0.006 ± 0.017

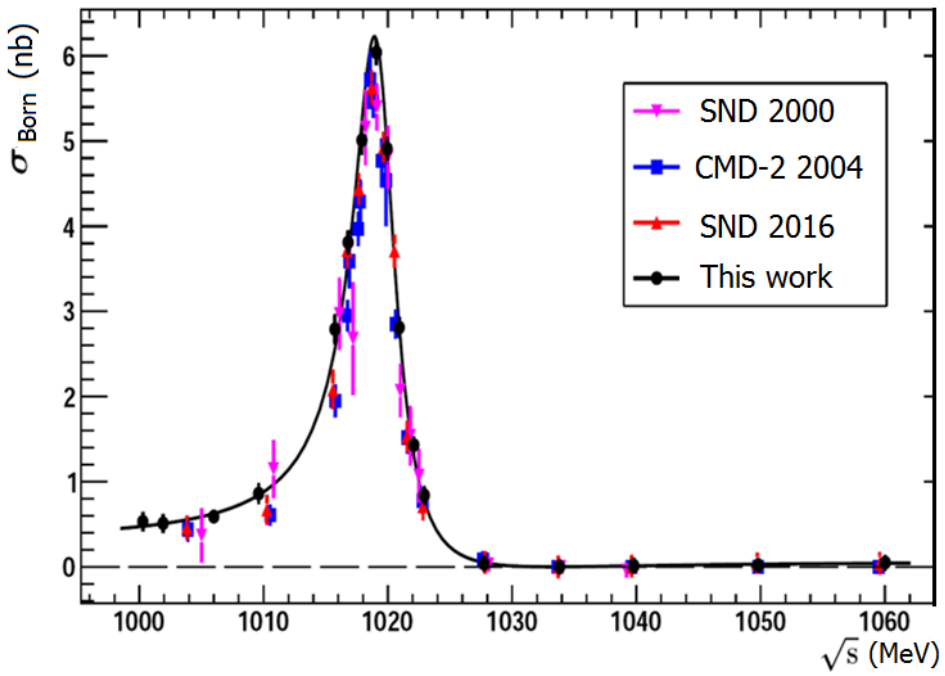


1.034 ± 0.002 ± 0.018

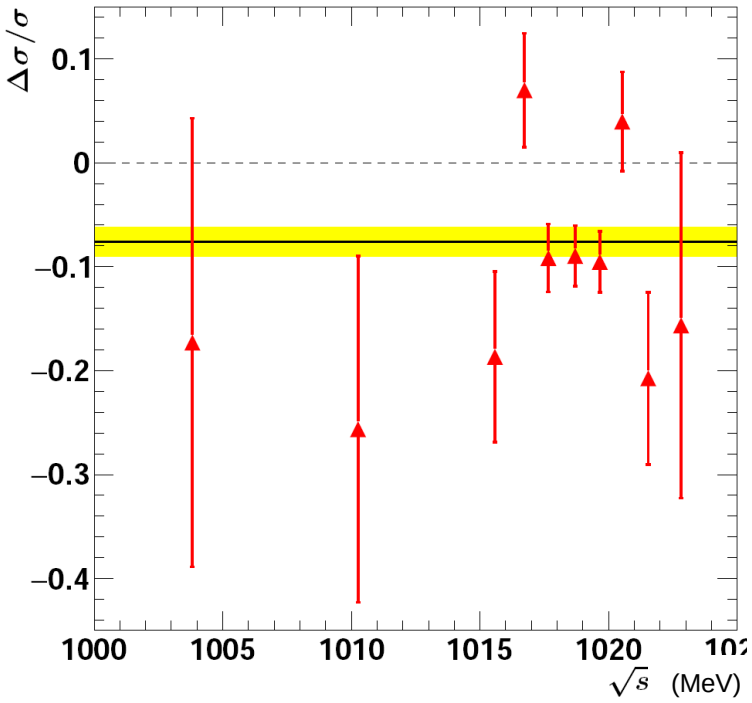
- ✓ The SND systematic uncertainty on the cross section is 0.9%. Compared with previous most precise measurements, the accuracy is improved by a factor of 2.
- ✓ The SND at VEPP-2M and CMD-2 measurements agree with our measurement within the systematic errors. The difference with the CMD-3 measurement is 1.7σ.

$e^+e^- \to \pi^0\gamma$ near $\phi(1020)$

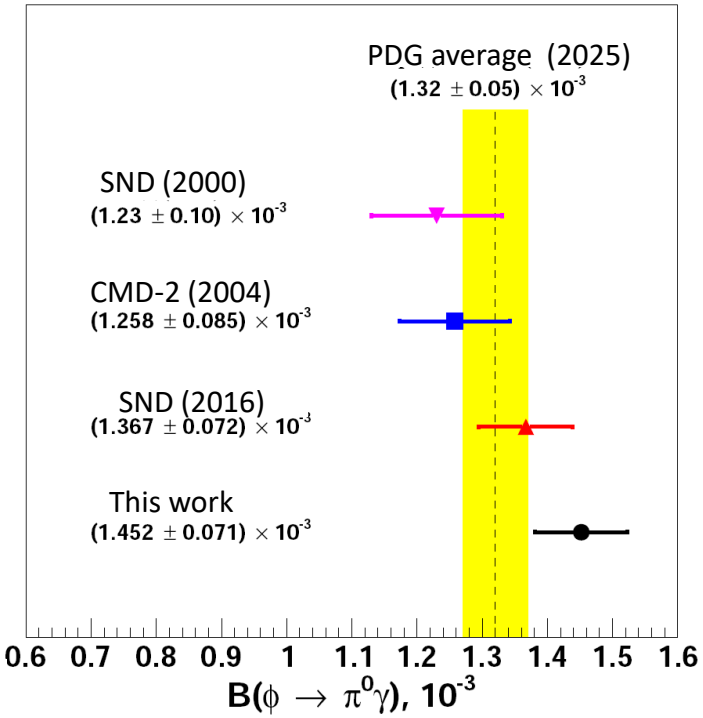
Accepted to Phys. Atom. Nucl.



The Born cross section at the ϕ meson peak is measured with 2.2% statistical and 1.3% systematic uncertainty. It is fitted using the VMD model with ρ, ω, ϕ, and ρ(1450).

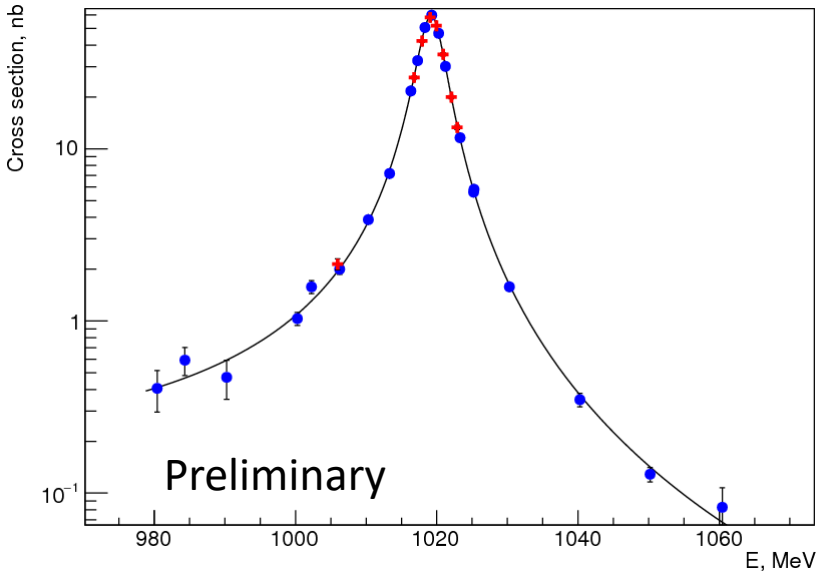


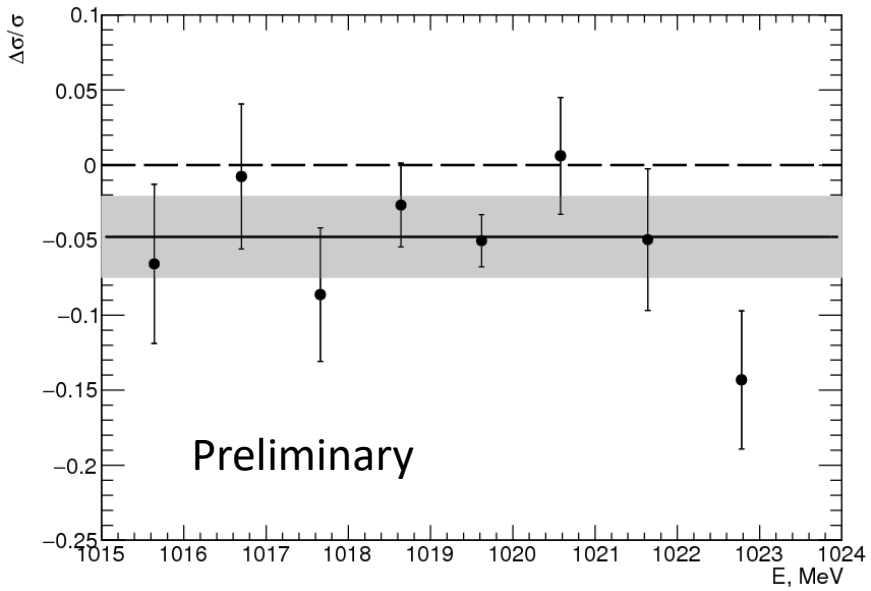
Comparison with the previous SND measurement at VEPP-2M. The new measurement is about 9% higher.

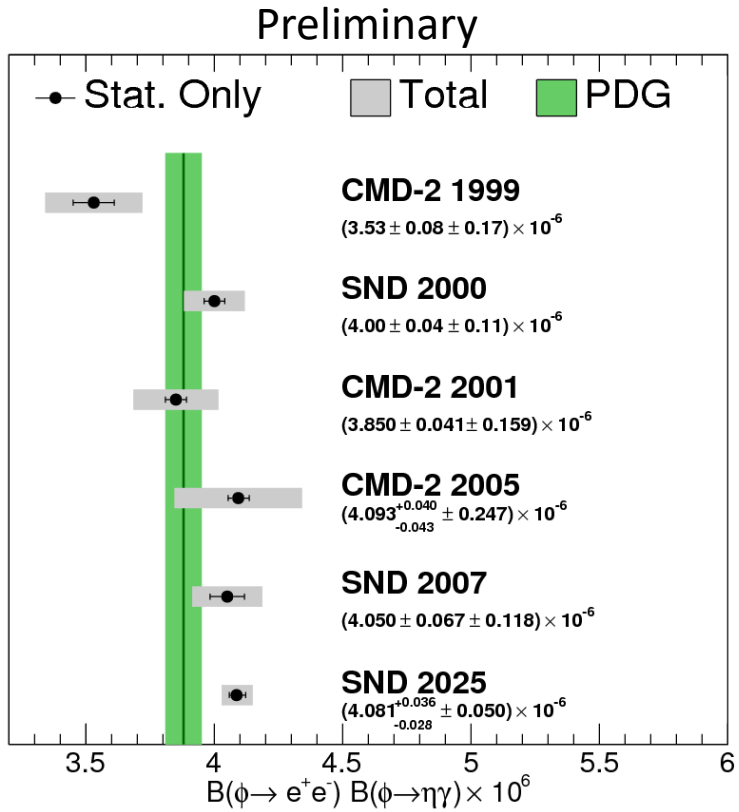


The error of the branching fraction is dominated by the systematic uncertainty, mainly due to the interference with the ρ and ω tails.

$e^+e^- \to \eta\gamma$ near $\phi(1020)$





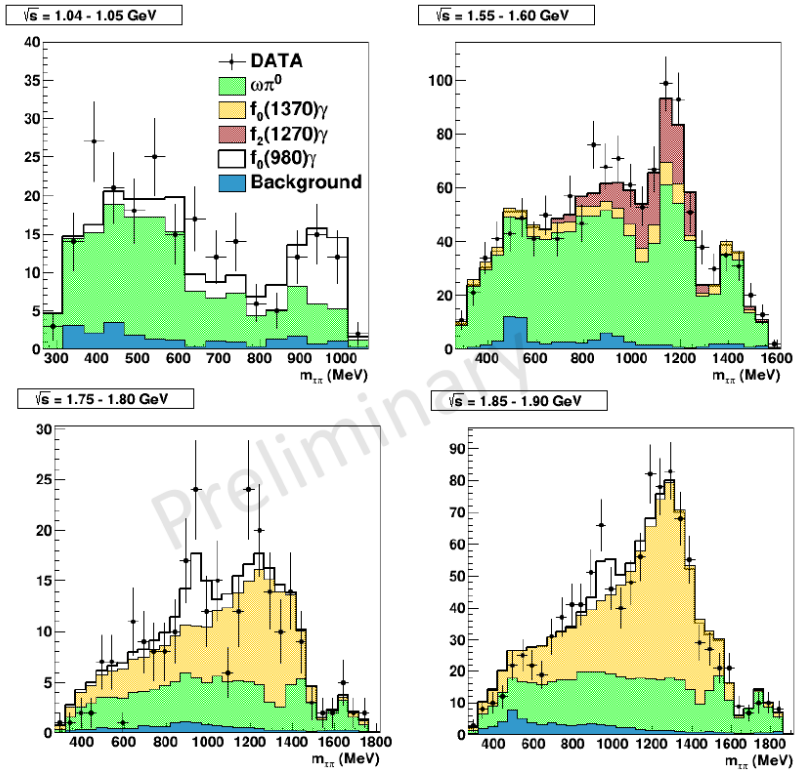


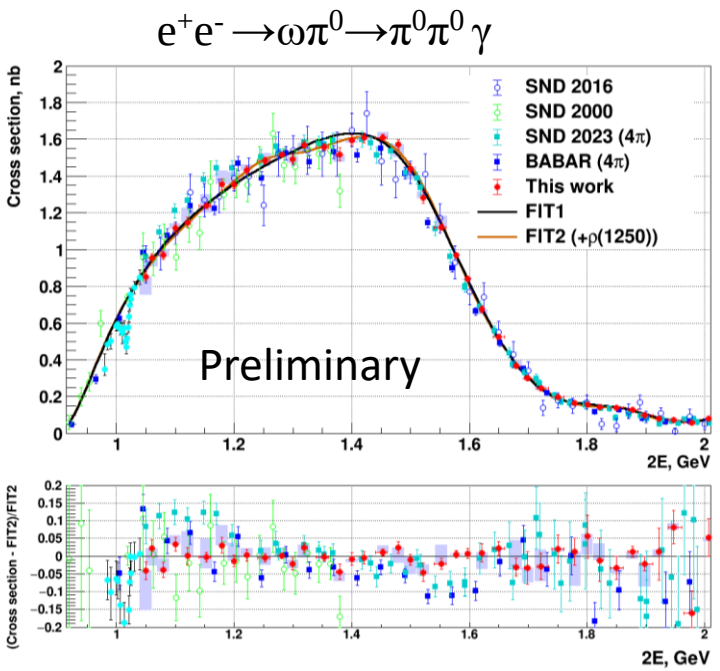
The Born cross section at the ϕ meson peak is measured with 0.5% statistical and 1.0% systematic uncertainty. It is fitted using the VMD model with ρ, ω, ϕ, ρ(1450) and ϕ(1680).

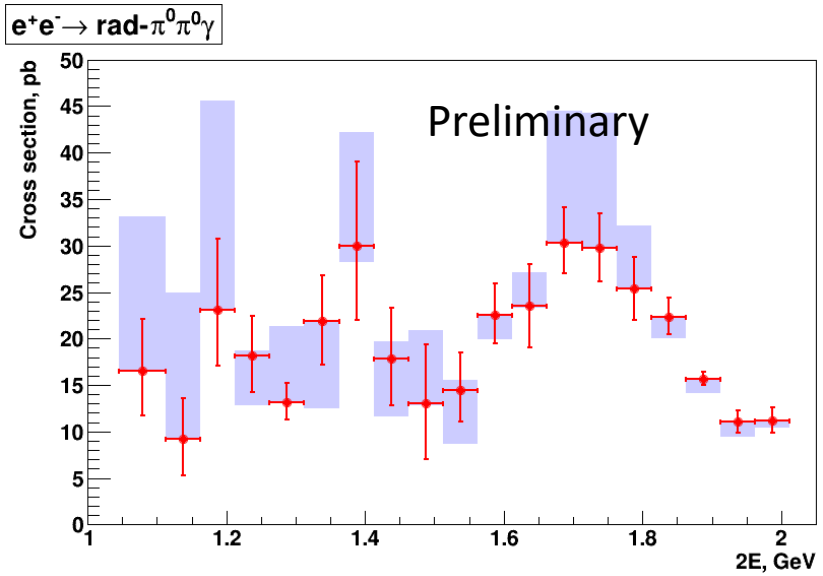
Comparison to the previous SND measurement at VEPP-2M. The new measurement is about 5% higher.

Most accurate measurement of the product $B(\phi \to \eta\gamma)B(\phi \to e^+e^-)$.

$e^+e^- \to \pi^0\pi^0\gamma$ in the 1.05-2 GeV range



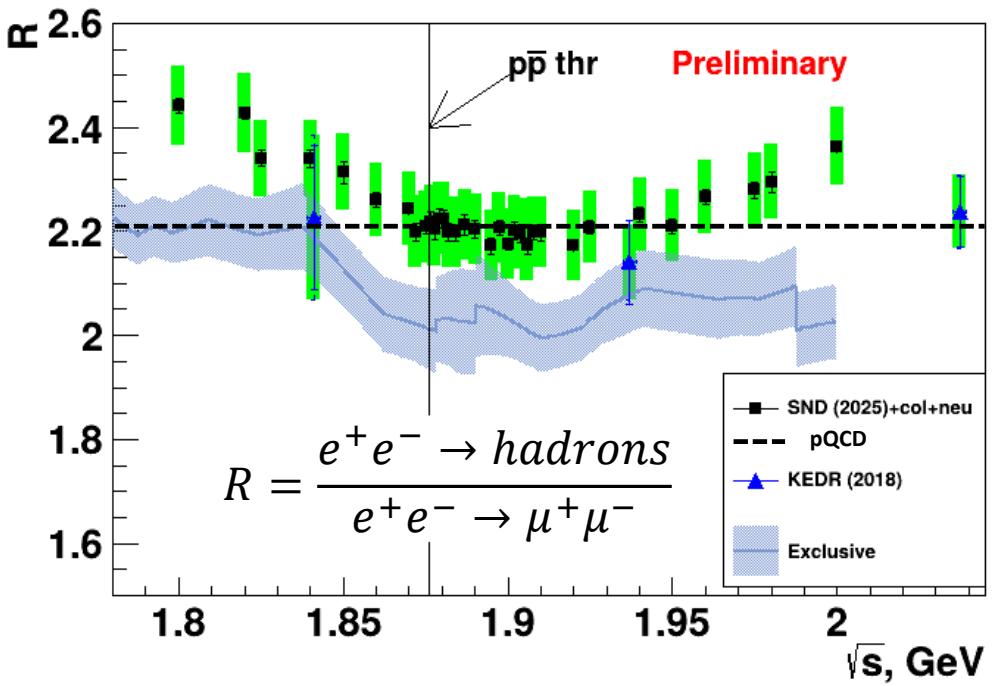




- The Dalitz plot fit allows to separate intermediate states.
- The dominant process is $e^+e^- \to \omega\pi^0$. Its cross section is measured with an accuracy of a few percent.
- The following radiative processes are seen : **$f_0(980)\gamma$, $f_2(1270)\gamma$, $f_0(1370)\gamma$**
- The total cross section of the radiative processes is about 15-30 pb. The peak near 1.7 GeV is seen in the radiative cross section.

Inclusive cross-section measurement between 1.8 and 2.0 GeV

- Events with three or more hadrons in the final state are studied. Selection criteria:
  - 2 charged tracks and 2 or more photons,
  - 3 or more charged tracks,
  - Special conditions for suppression of the QED, beam-generated, and cosmic-ray backgrounds.
- Remaining QED ($e^+e^-N\gamma$, $\mu^+\mu^-N\gamma$) and hadronic background ($\pi^+\pi^-(\gamma)$, $K^+K^-(\gamma)$, $p\bar{p}$) are subtracted.
- Radiative correction is calculated and imposed.
- Then the well-known cross sections for $e^+e^- \to \pi^+\pi^-$, K^+K^-, $p\bar{p}$ and processes with purely neutral particles in the final state are added ($\sim 7\%$).
- The systematic uncertainty on the cross section is estimated to be 3.5%.



- ✓ The SND results are in agreement with the KEDR inclusive measurement, but about 10% higher than the sum of exclusive measurements.
- ✓ The non-monotonic R energy dependence is observed, with a minimum near 1.9 GeV, just above the $p\bar{p}$ threshold.

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

$$\sigma(s) = \frac{4\pi\alpha^2\beta C}{3s}\left(|G_M(s)|^2 + \frac{2m_n^2}{s}|G_E(s)|^2\right), \quad s = 4E_b$$

The cross section depends on two form factors, electric G_E and magnetic G_M

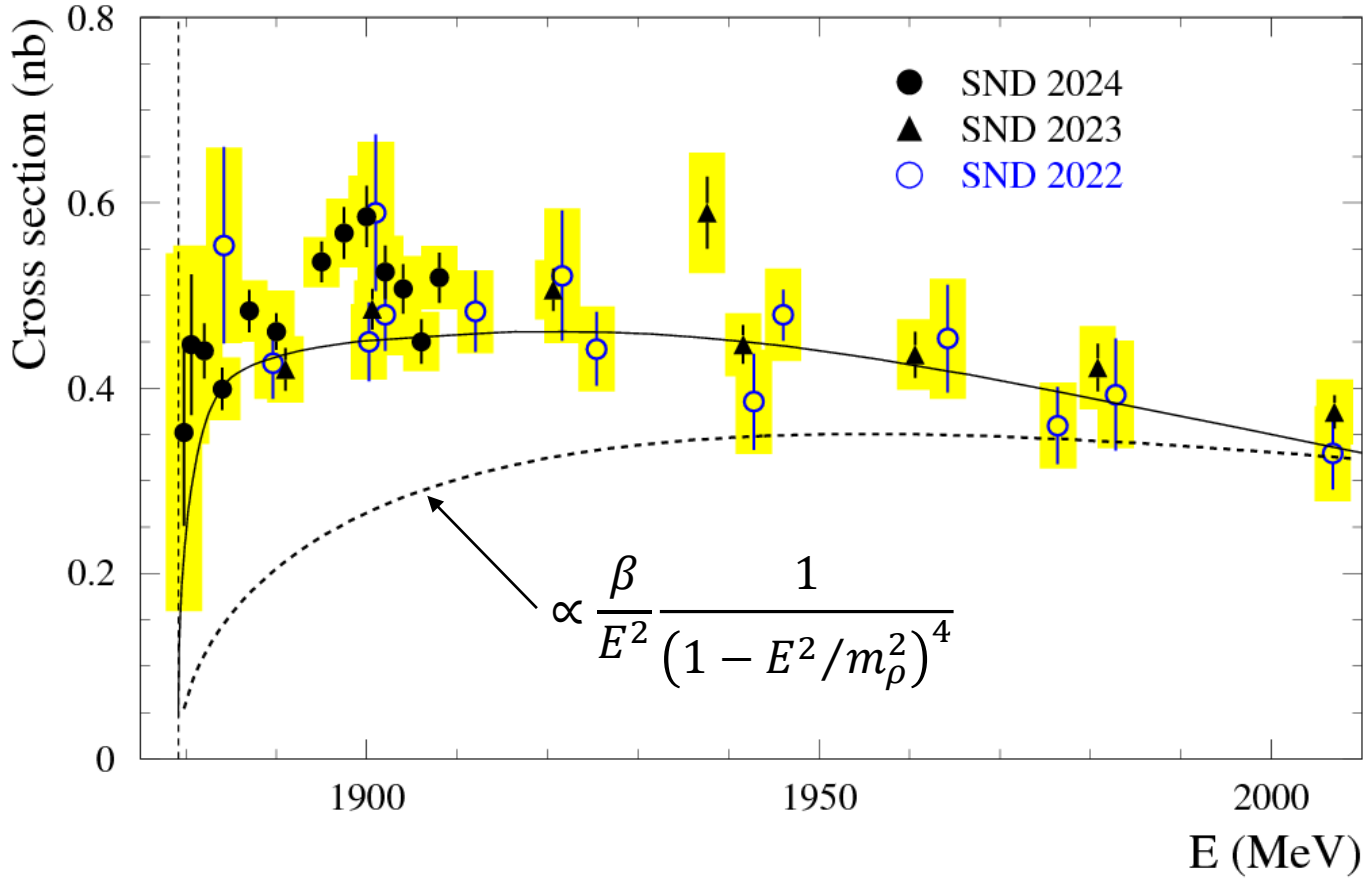
$$|F_p(s)| = \sqrt{\frac{|G_M(s)|^2 + (2m_p^2/s)|G_E(s)|^2}{1 + 2m_p^2/s}}$$

From the total cross-section measurement, the so-called “effective” form factor is extracted.

From the analysis of the angular distribution, the ratio of the form factors $|G_E/G_M|$ is extracted. At the threshold $|G_E/G_M| = 1$.

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

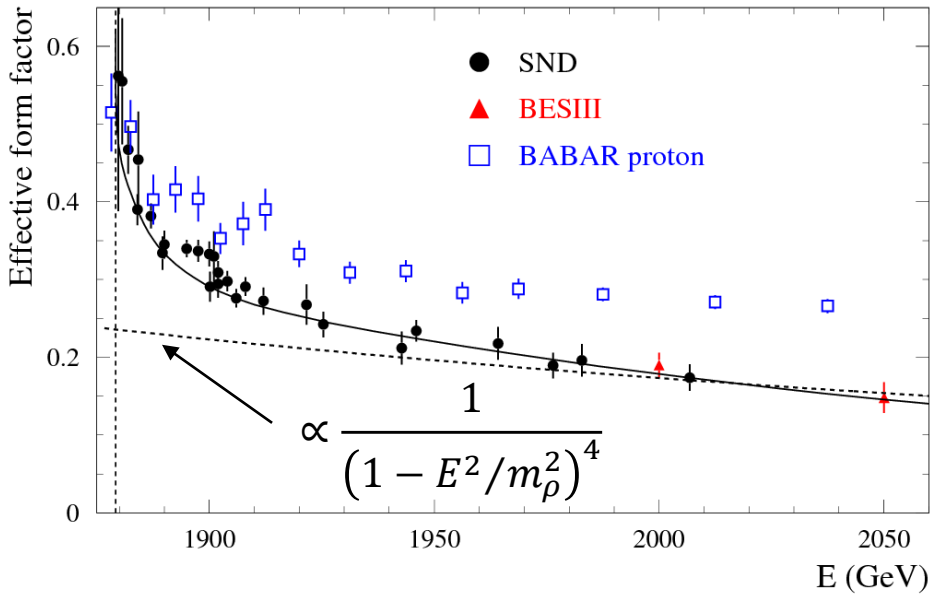
$e^+e^- \to n\bar{n}$

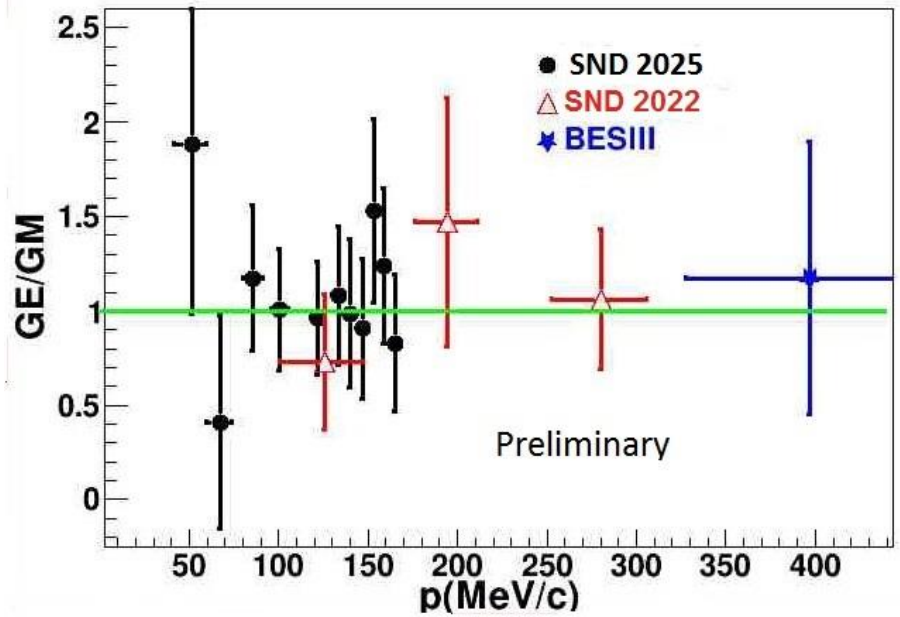


M.N. Achasov *et al*, Eur. Phys. J. C **22**, 761 (2022)
(2017 and 2019 datasets)
Phys. Atom. Nucl. **86**, 1165 (2023)
(2020 and 2021 datasets)
Phys. Atom. Nucl. (2024) (2022 dataset)

- ✓ The $e^+e^- \to n\bar{n}$ cross section in the below 2 GeV has been measured with about 5% statistical and 10-15% systematic uncertainty.
- ✓ The cross section is flat and very different from the energy dependence of the S-wave phase space ($\propto \beta$).
- ✓ The difference is explained by the $n\bar{n}$ final state interaction (A.I.Milstein and S.G.Salnikov, Phys. Rev. D **106**, 074012 (2022)), which leads to a large effect.

Neutron form factors

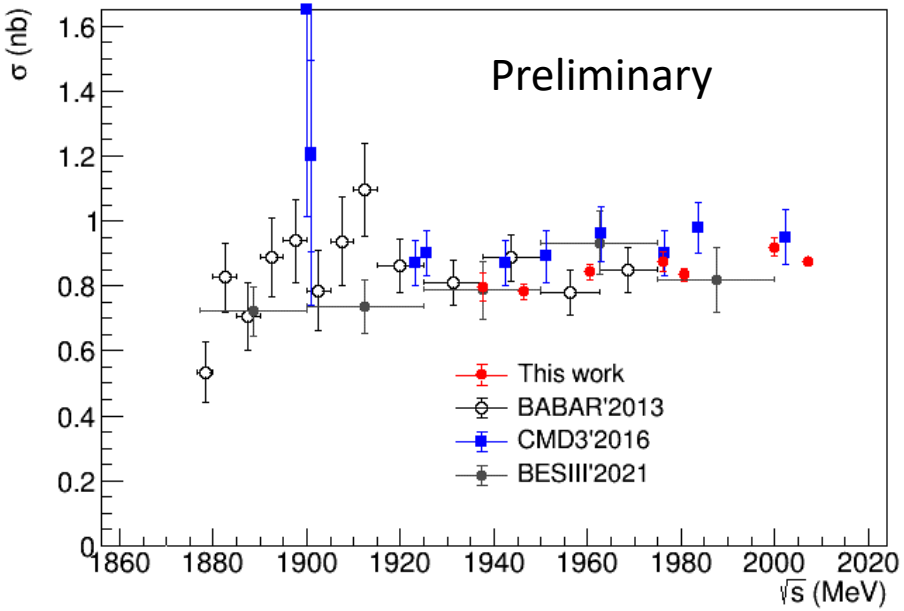


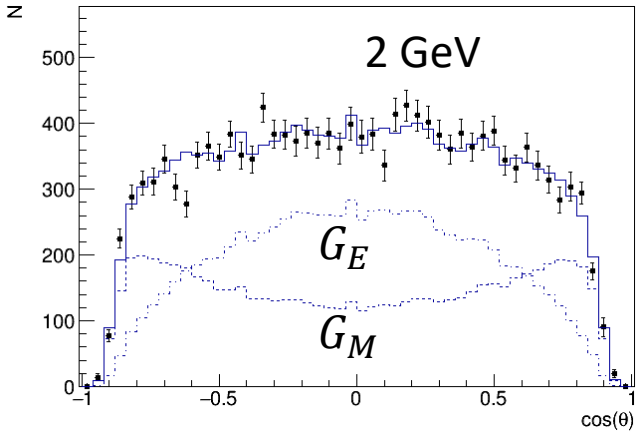


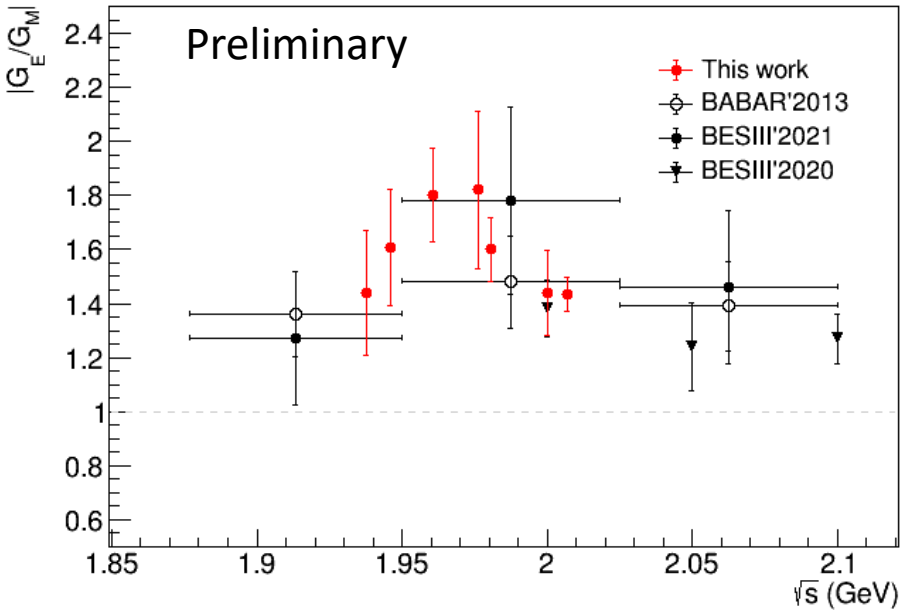
SND 2025 average:
$|G_E/G_M|$=1.03 ± 0.11

- ✓ Above E=1.89 GeV, the proton effective form factor is higher than the neutron one.
- ✓ However, in the narrow region (~5 MeV) near the threshold the proton and neutron form factors are close to each other.
- ✓ The $|G_E/G_M|$ ratio obtained on the 2019 and 2022 data set agrees with unity.

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







- ✓ The $e^+e^- \to p\bar{p}$ process is studied at E_{beam}>960 MeV, where two back-to-back charged tracks are reconstructed in the drift chamber (DC).
- ✓ The event selected is based on dE/dx measurements in DC and total energy deposition in the EMC.
- ✓ The measured cross section is in reasonable agreement with previous measurements.
- ✓ The measurered $|G_E/G_M|$ ratio also agree with previous measurements.

Summary

✓The SND detector accumulated about 1 fb^{-1} of integrated luminosity in the energy range 0.3 – 2 GeV.

✓The preliminary SND result on the $e^+e^- \to \pi^+\pi^-$ cross section is in reasonable agreement with the CMD-3 measurement.

✓The $e^+e^- \to \pi^+\pi^-\pi^0$ cross section has been measured. The preliminary SND result agrees with the BABAR measurement.

✓In the ϕ meson region the most accurate measurements of the $e^+e^- \to K_S K_L$, $e^+e^- \to \pi^0\gamma$, and $e^+e^- \to \eta\gamma$ cross sections have been performed.

✓ The Dalitz plot distributions for the $e^+e^- \to \pi^0\pi^0\gamma$ process have been studied. In addition to the dominant $\omega\pi^0$ intermediate state, the contributions of radiative processes are observed.

✓The inclusive measurement of the $e^+e^- \to$ hadrons has been performed in the energy region 1.8-2 GeV.

✓The new data on the $n\bar{n}$ and $p\bar{p}$ production near threshold have been obtained.