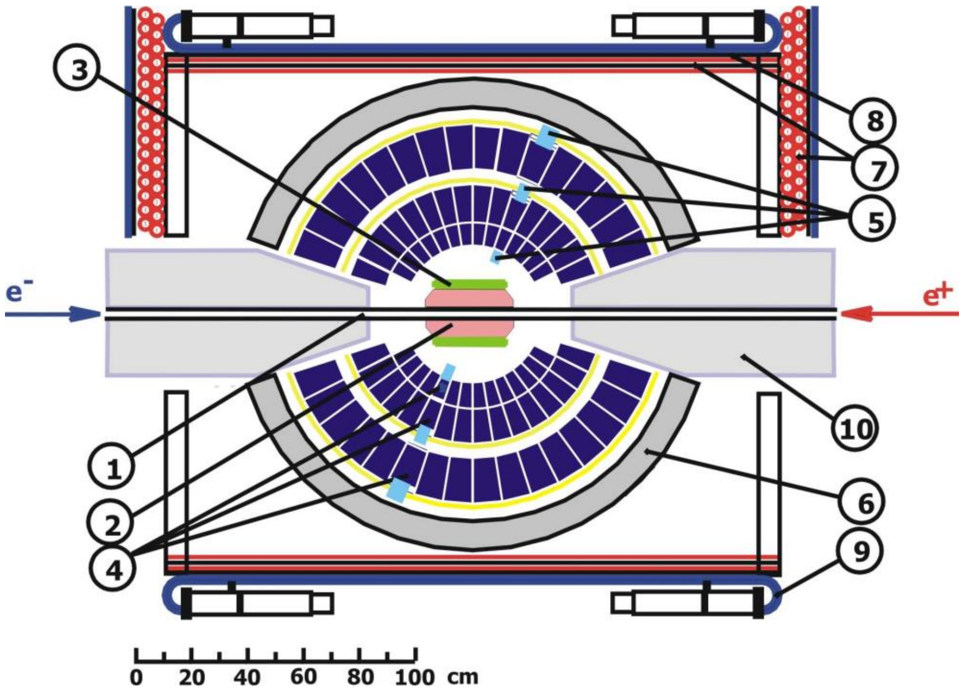
10th International Conference on New Frontiers in Physics

Recent SND experiment results on e+e− annihilation to hadrons

On the behalf of SND Collaboration
Aleksandr Korol (BINP, Novosibirsk)
30.08.2021

SND detector



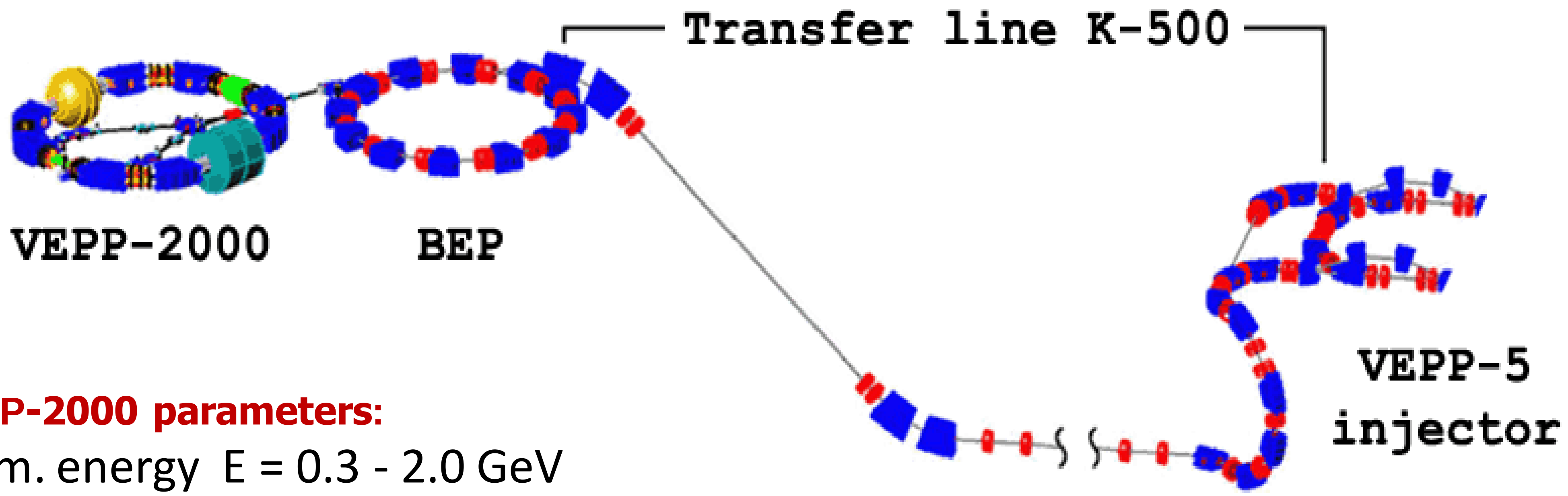
1 – beam pipe, 2 – tracking system, 3 – aerogel Cherenkov counter , 4 – NaI(Tl) crystals, 5 – phototriodes, 6 – iron muon absorber, 7–9 – muon detector, 10 – focusing solenoids.

SND collected data at the VEPP-2M (1996-2000) and VEPP-2000 (2010-2013,2016-…)

Main goal of SND experiment 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.
- ✓ Study of hadronization (dynamics of exclusive processes).
  - Properties of excited vector mesons of the ρ, ω, ϕ families
  - Development of MC event generator for $e^+e^- \to$ hadrons below 2 GeV.

VEPP-2000 e^+e^- collider



VEPP-2000 parameters:

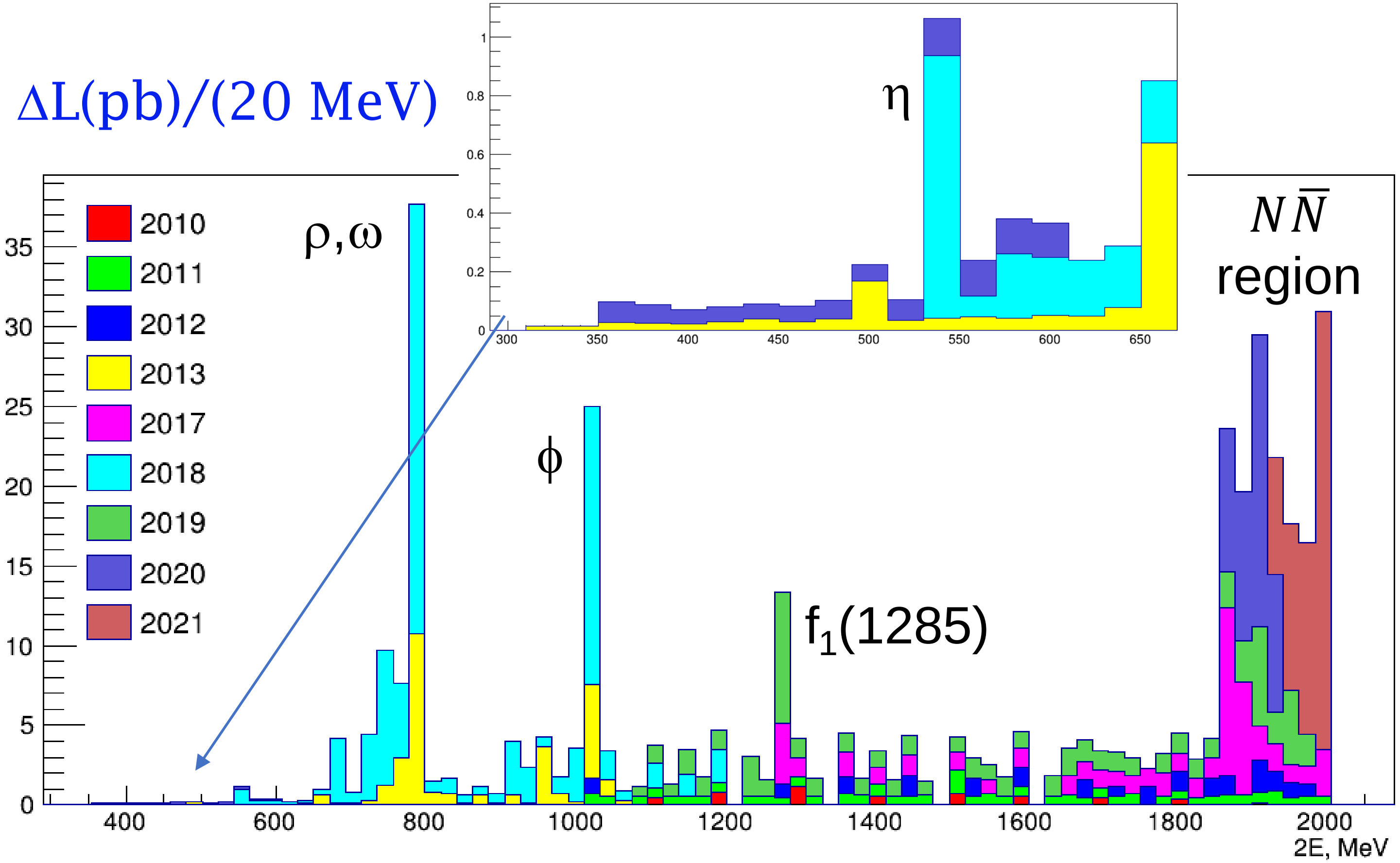
- c.m. energy E = 0.3 - 2.0 GeV
- circumference – 24.4 m
- round beam optics
- Luminosity at E = 1.8 ГэВ
  1×10^{32} cm^{-2} sec^{-1} (project)
  4×10^{31} cm^{-2} sec^{-1} (achieved)
- Two detectors: SND and CMD-3

2010 - 2013 – experiments, 70 pb^{-1}
2013 - 2016 – upgrade, new injector
2016 - now – experiments, 300 pb^{-1}

Since 2013 – beam energy measurements with laser Compton backscattering

SND data

~20 hadronic processes are currently under analysis



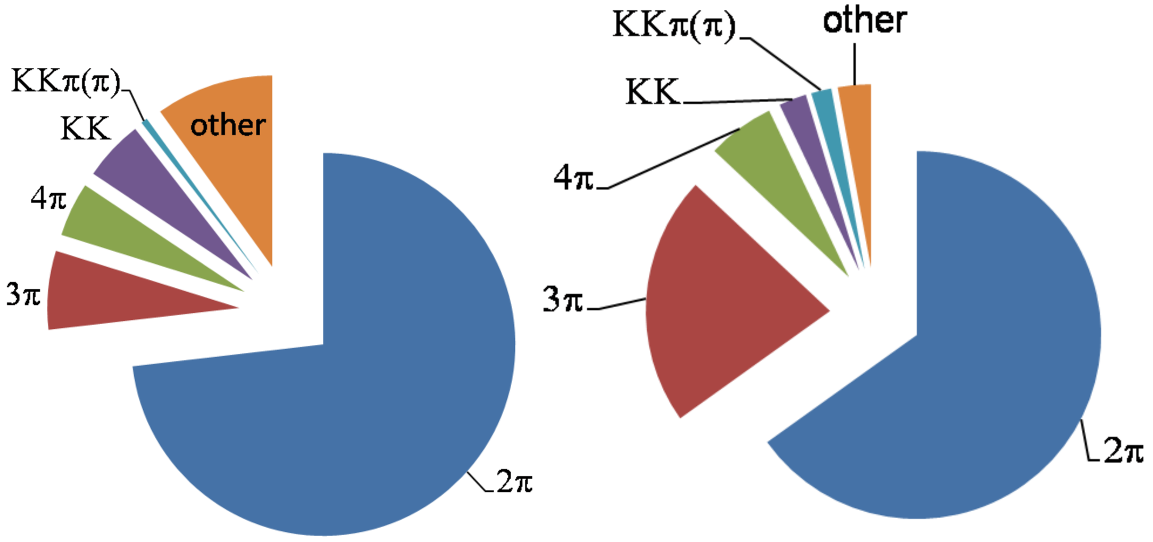
	Below φ	Near φ	Above φ
IL, pb^{-1}	77	31	259.0
E_{cm}, GeV	0.30-0.97	0.98-1.05	1.05-2.00

- $e^+e^- \to \pi^+\pi^-$
- $e^+e^- \to n\bar{n}$
- $e^+e^- \to p\bar{p}$
- $e^+e^- \to \pi^+\pi^-\pi^0$
- $e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$
- $e^+e^- \to K^+K^-\pi^0$
- $e^+e^- \to \pi^0\eta\gamma$
- $e^+e^- \to \eta\eta\gamma$

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

The process $e^+e^- \to \pi^+\pi^-$ gives the largest contribution into $a_\mu^{had,LO-VP}$ and its error.

$a_\mu^{had,LO-VP}$ $\quad$ $a_\mu^{had,LO-VP}$ error squared



- ✓ There are many measurements of the $e^+e^- \to \pi^+\pi^-$ process, some of them have systematic uncertainty less than 1%.
- ✓ The most precise measurements with a systematic uncertainty of about 0.6% were done by BABAR and KLOE using the ISR technique.
- ✓ However, the difference between the BABAR an KLOE cross sections reaches several %.

Experiments at VEPP-2000 use direct scan approach and may provide fully independent measurements with a sub-% accuracy.

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

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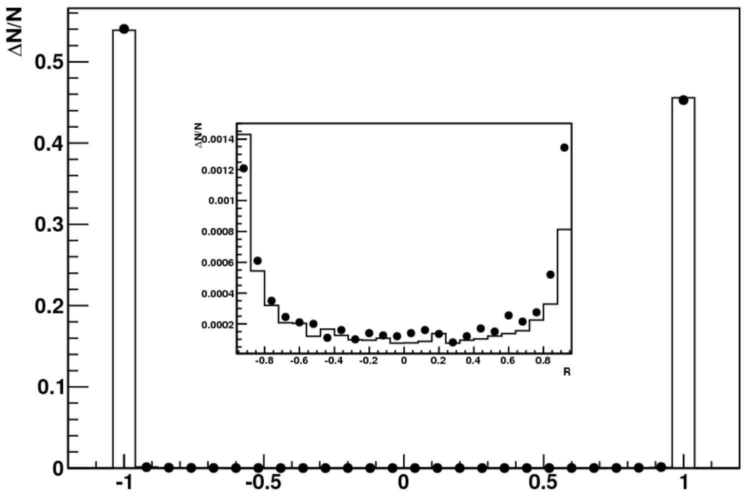
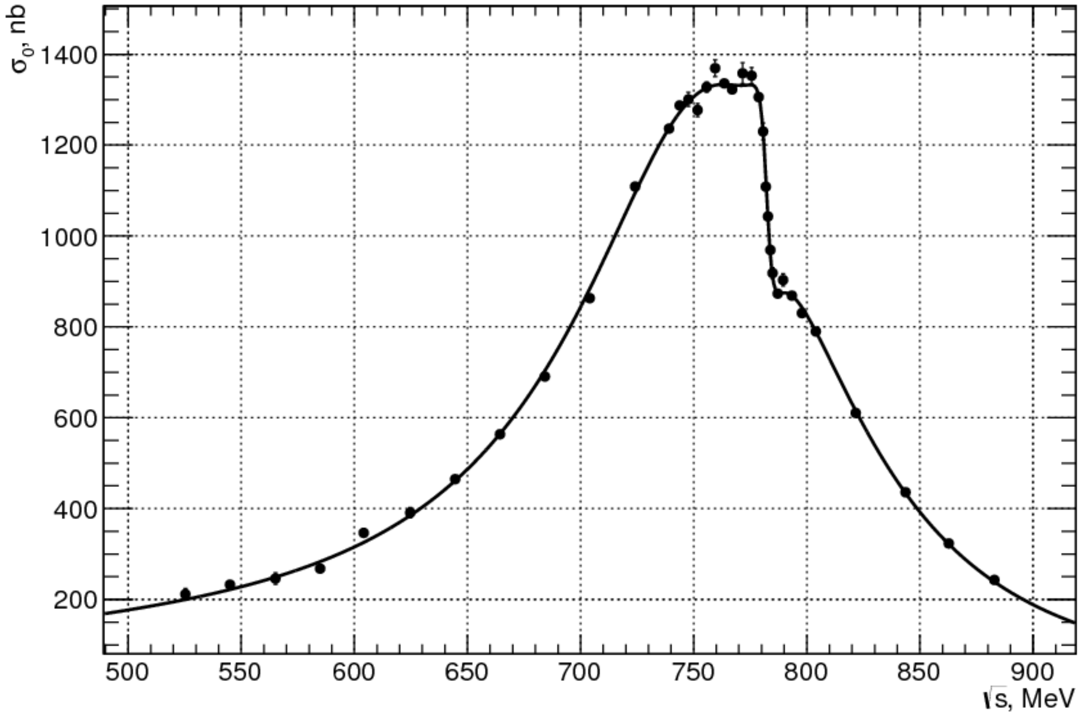
e/π separation parameter



The analysis is based on 4.7 pb^{-1} data recorded in 2013 (1/10 full SND data set)

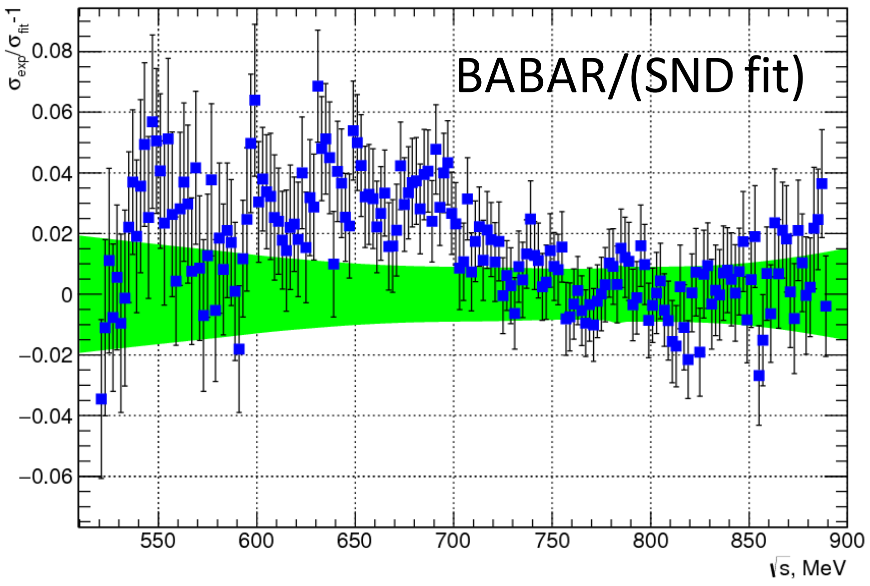


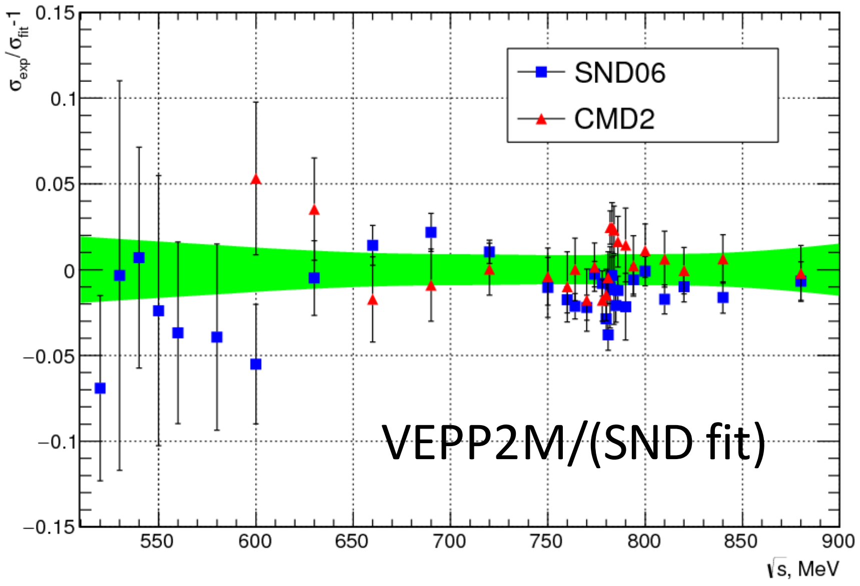
Systematic uncertainty on the cross section (%)

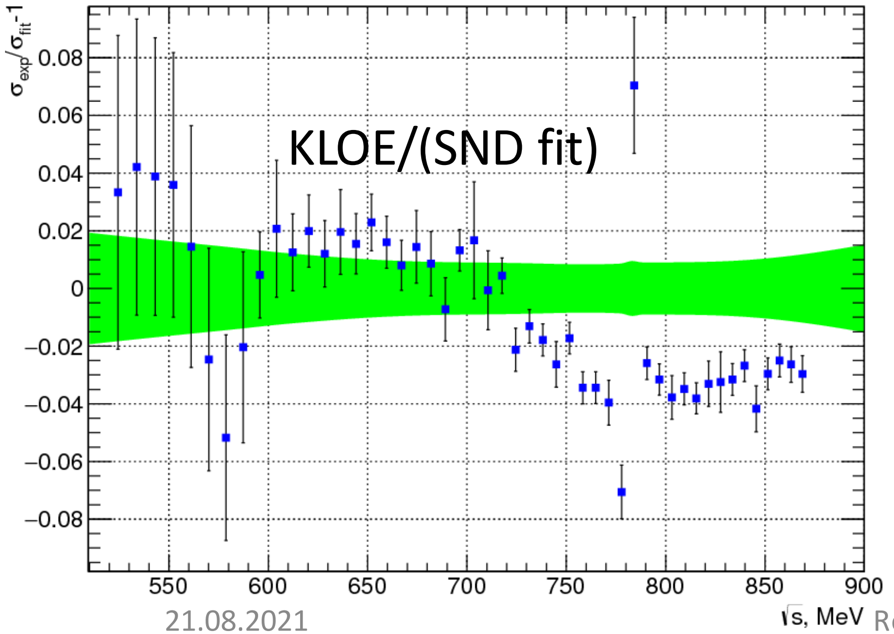
Source	**< 0.6 GeV**	**0.6 - 0.9 GeV**
Trigger	0.5	0.5
Selection criteria	0.6	0.6
e/π separation	0.5	0.1
Nucl. interaction	0.2	0.2
Theory	0.2	0.2
Total	**0.9**	**0.8**

	SND @ VEPP-2000	SND @ VEPP-2M	PDG
M_ρ, MeV	775.3±0.5±0.6	775.6±0.4±0.5	775.3±0.3
Γ_ρ, MeV	145.6±0.6±0.8	146.1±0.8±1.5	147.8±0.9
$B_{\rho ee}\times10^5$	4.89±0.2±0.4	4.88±0.2±0.6	4.72±0.5
$B_{\omega\pi\pi}$, %	1.77±0.08±0.02	1.66±0.08±0.05	1.53±0.06

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



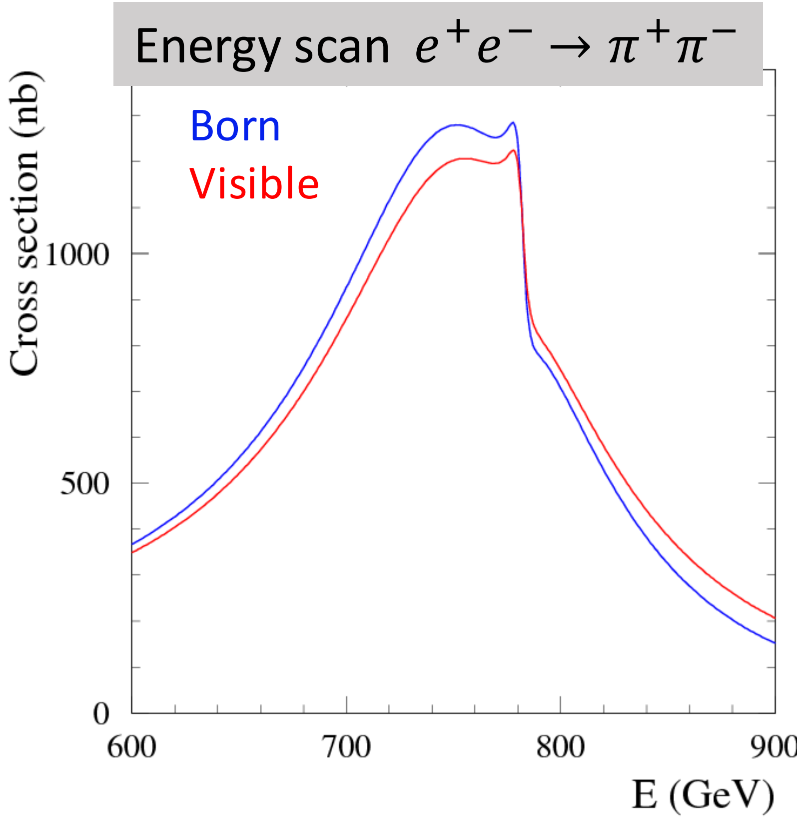




$0.53 < \sqrt{s} < 0.88$ GeV

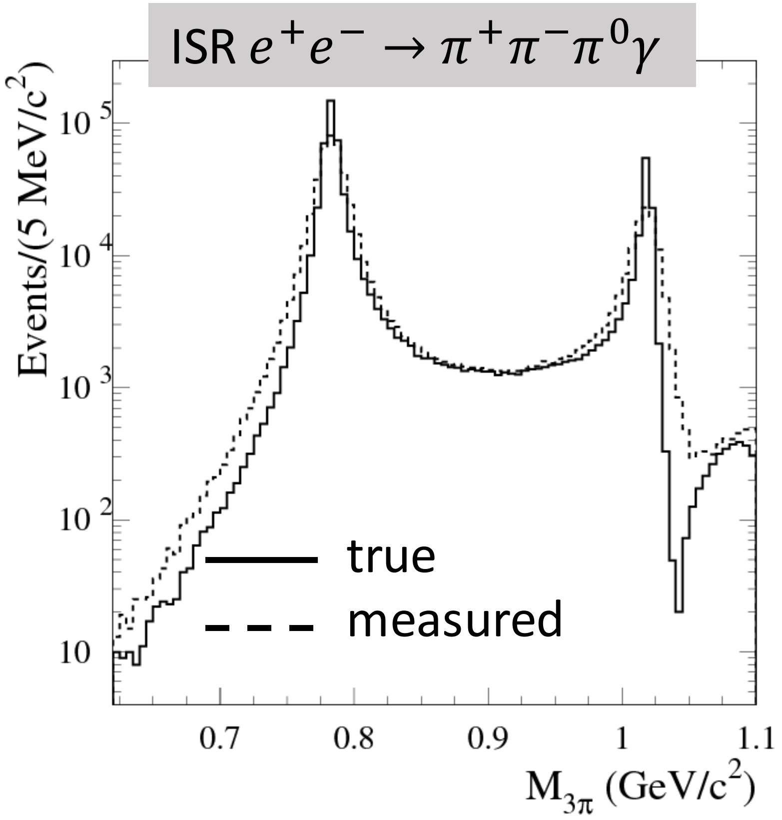
	$a_\mu(\pi^+\pi^-) \times 10^{10}$
SND & VEPP-2000	$409.8 \pm 1.4 \pm 3.9$
SND & VEPP-2M	$406.5 \pm 1.7 \pm 5.3$
BABAR	$413.6 \pm 2.0 \pm 2.3$
KLOE	$403.4 \pm 0.7 \pm 2.5$

Direct scan vs ISR



- In both methods, the integral equation should be resolved to obtain the Born cross section.
- The function W(x,E) is well known theoretically
- The resolution function $R(M_m,M_t)$ is determined using simulation and tested at narrow resonances. The data –MC difference in the tails of the resolution is hard to be tested.

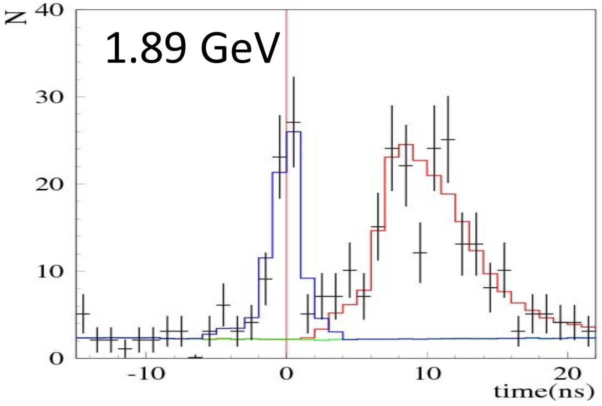
BABAR report at EPSHEP21

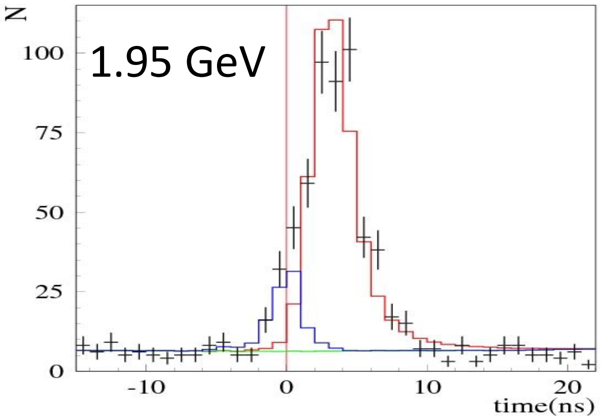


$$\sigma_{vis} = \int_0^{x_m} W(x,E)\sigma_b(\sqrt{E(1-x)})dx$$

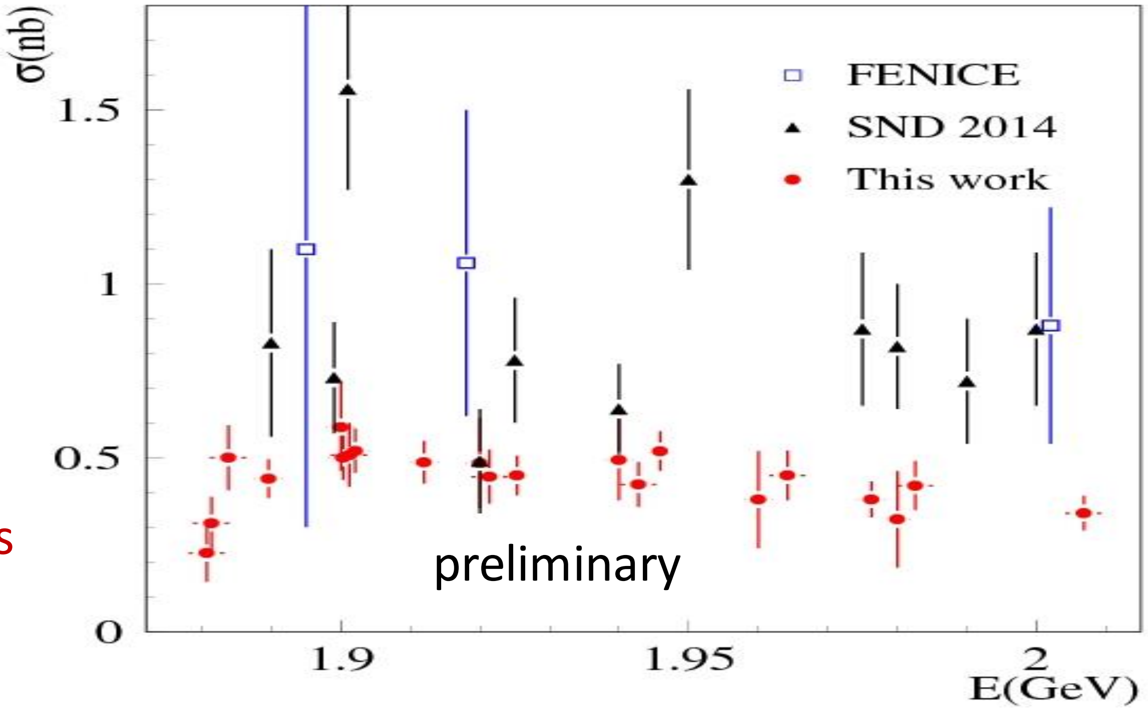
$$\frac{dN}{dM_m} = \int_0^{\infty} R(M_m,M_t)\frac{dN}{dM_t}\,dM_t$$

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

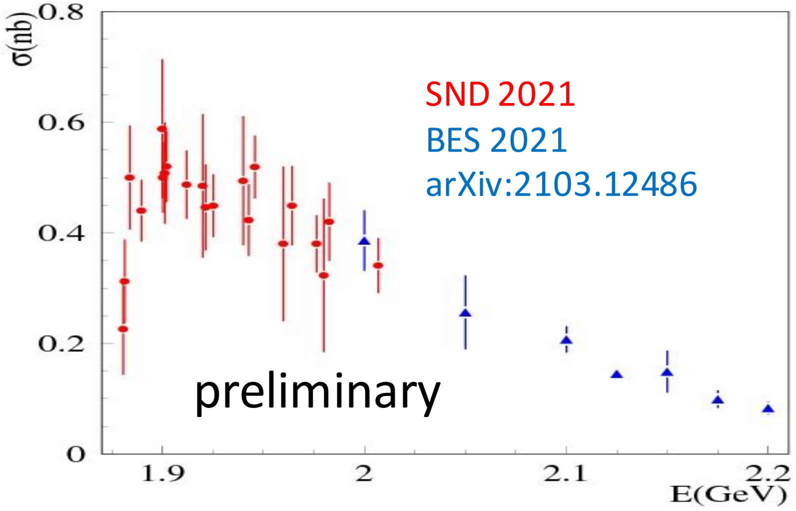




- This process near threshold was previously measured by FENICE and SND using the 2011-2012 dataset.
- The new measurement is based on the 2017, 2019 data and uses time measurement in the calorimeter.
- The time distribution is fitted by a sum of distributions for signal, cosmic background, and beam + e^+e^- annihilation background.
- Our new result is lower than the previous. The reasons are underestimated beam background and incorrect MC simulation.



The systematic uncertainty is 10%



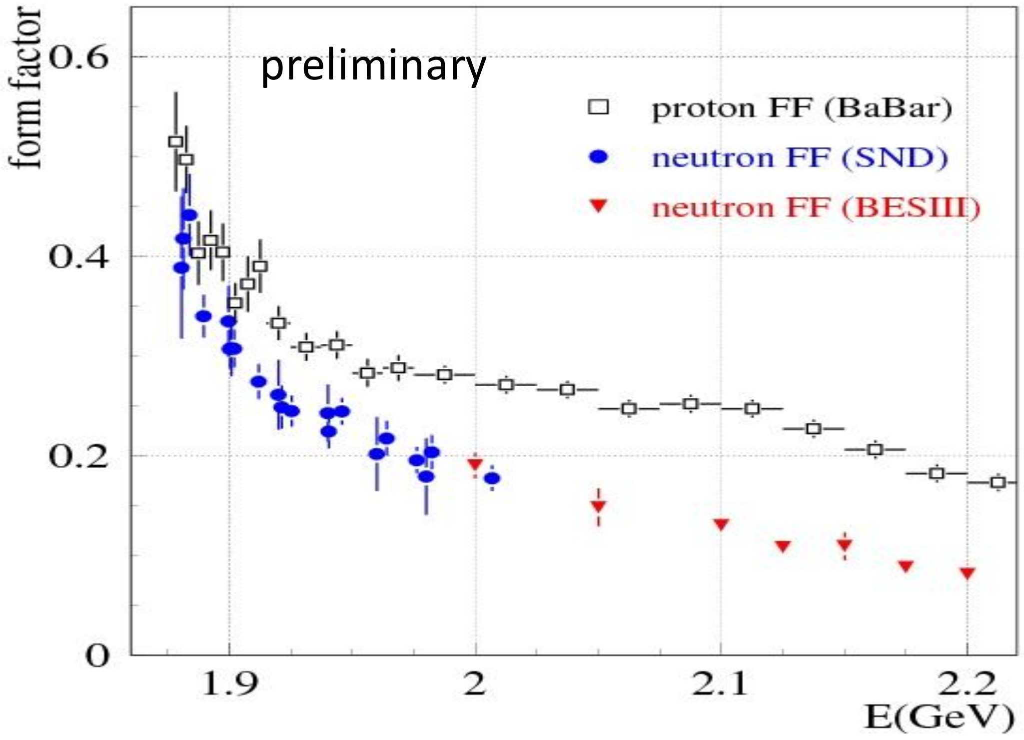
Neutron electromagnetic form factors

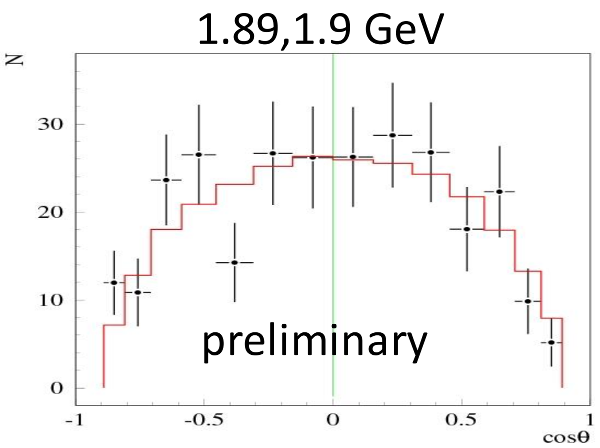
From the measured cross section, we determine effective form factor

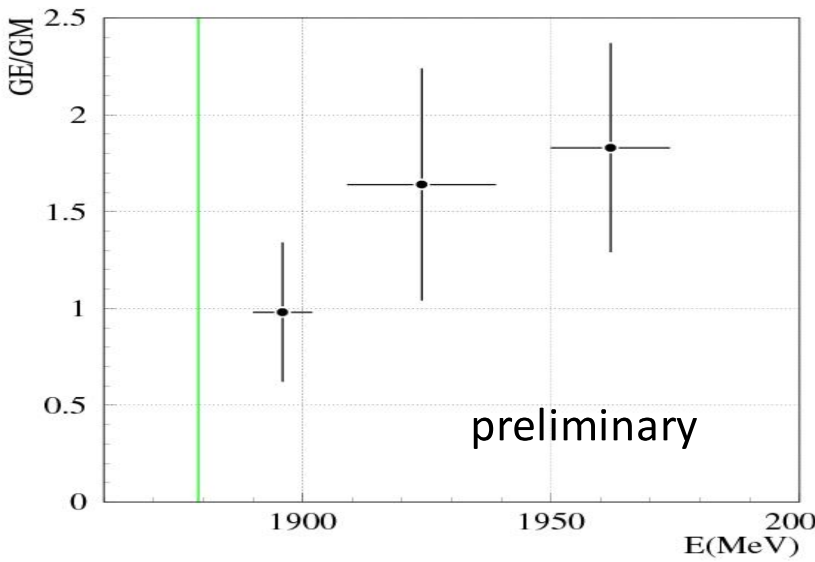
$$|F|^2 = \frac{|G_M|^2 + \frac{2m_n^2}{s}|G_E|^2}{1 + \frac{2m_n^2}{s}}$$

$$\sigma(e^+e^- \to n\bar{n}) = \frac{\alpha^2\beta}{4s}\left[|G_M|^2(1+\cos^2\theta) + \frac{4m_n^2}{s}|G_E|^2\sin^2\theta\right]$$

From analysis of the antineutron polar-angle distribution we determine the ratio of the form factors

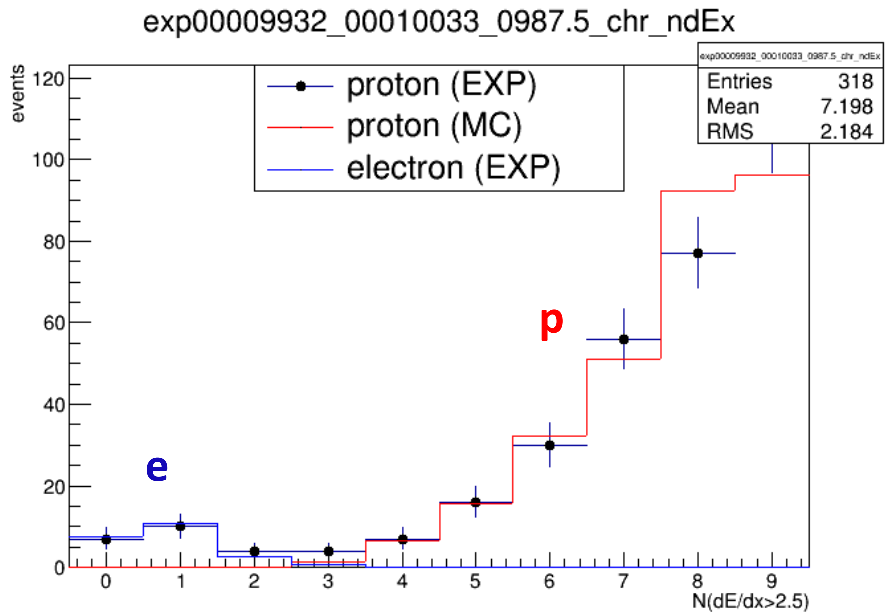


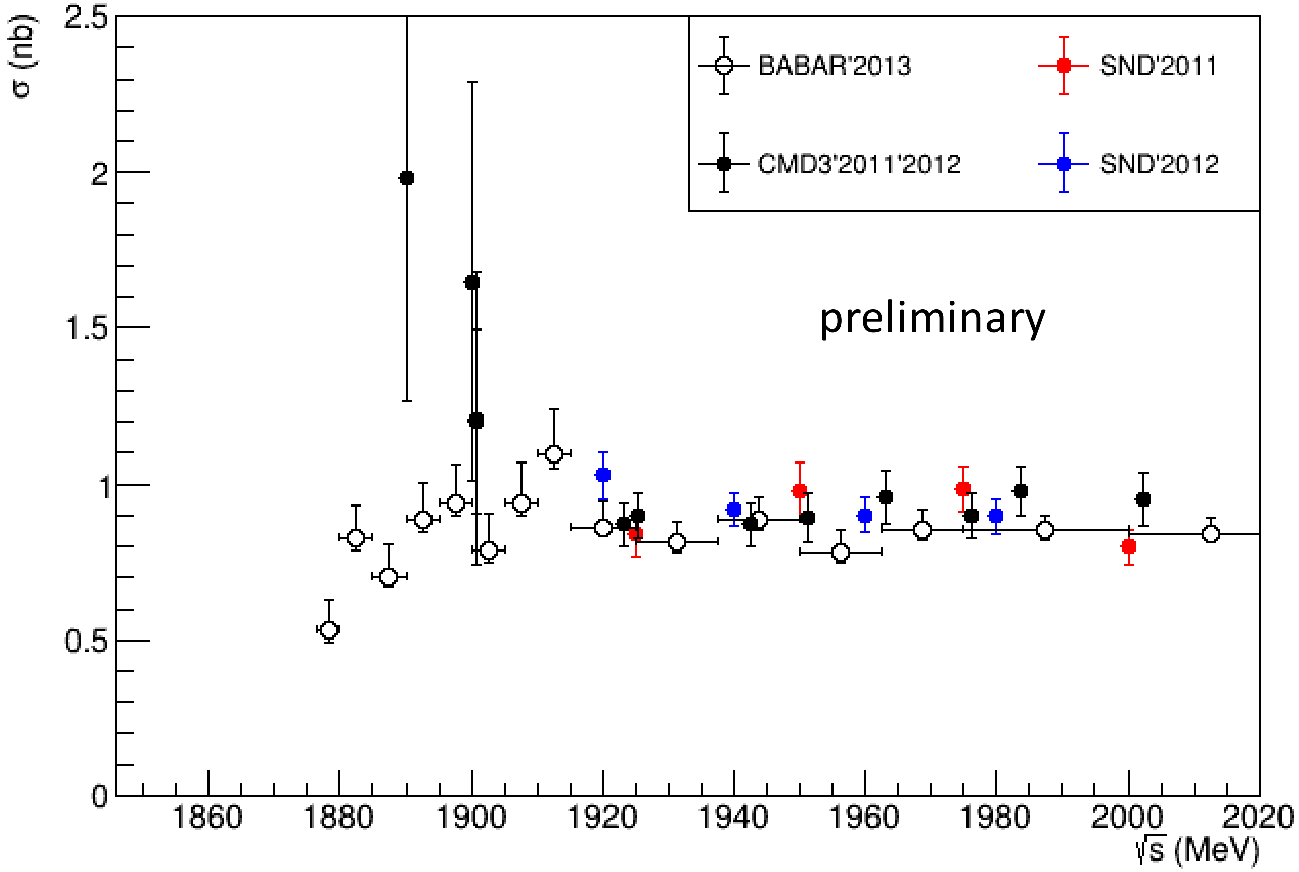




$e^+e^- \to p\bar{p}$

- This process near threshold was previously measured by BABAR and CMD3.
- Our measurement is based on the 2011-2012 data and uses energy deposition measurement in the drift chamber.





The number of DC layers with dEdx exceeding 2.5*dEdx of the electron

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

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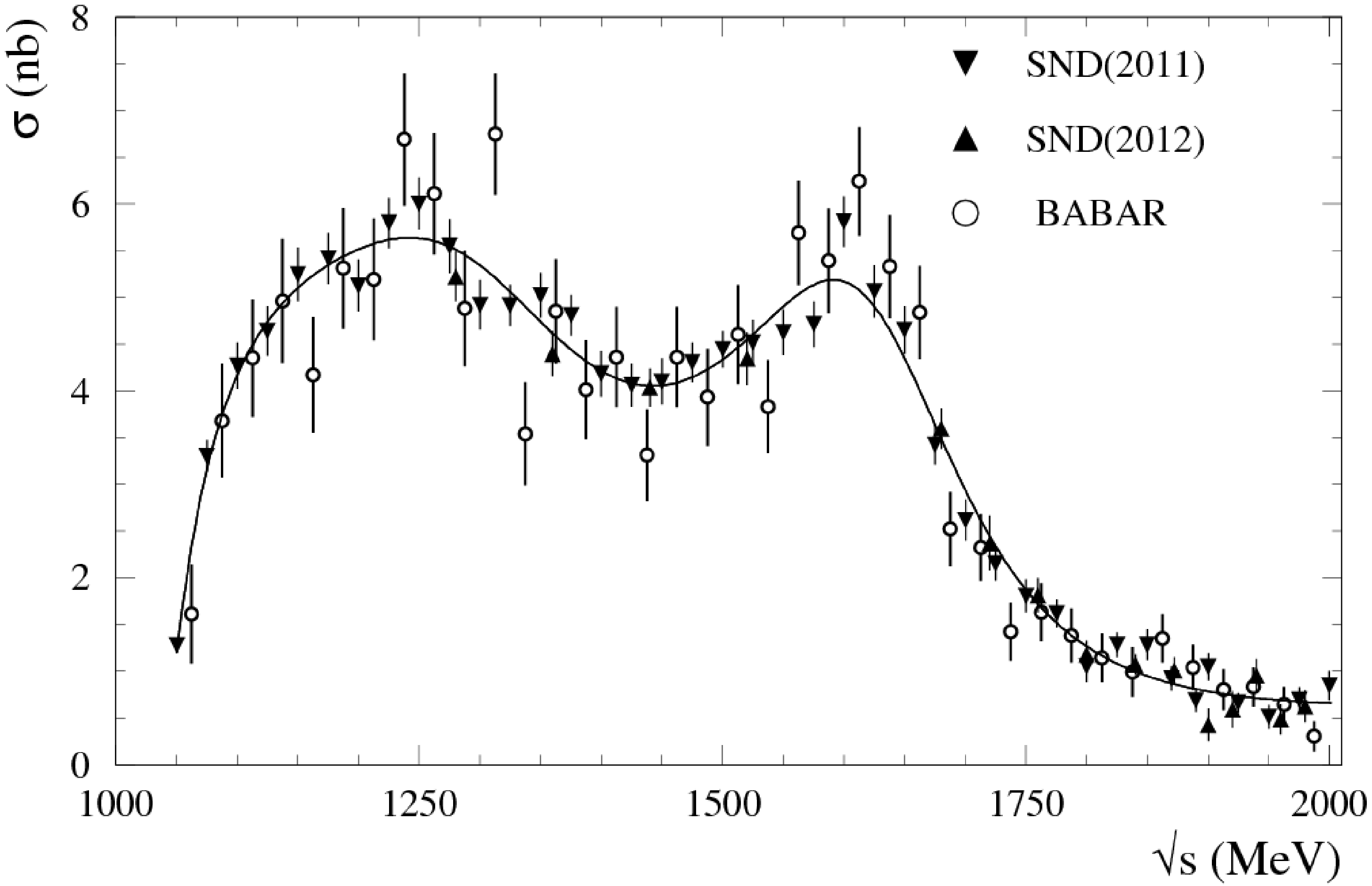
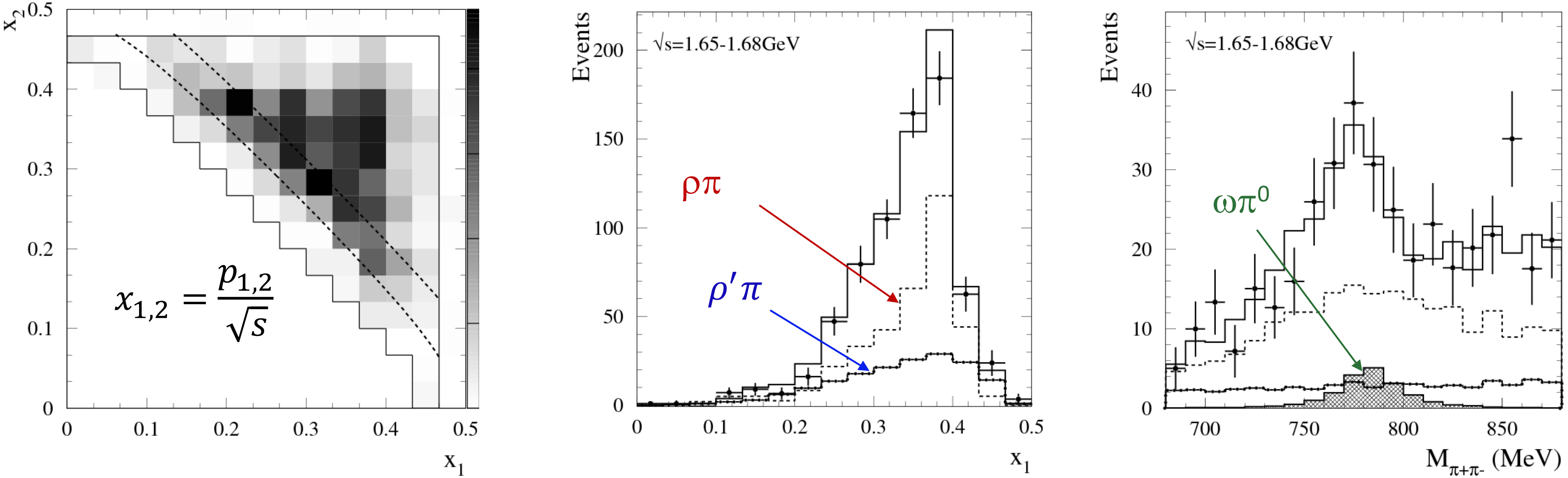


- ✓ Both SND measurements are consistent with each other and with the the BABAR measurement.
- ✓ Two peaks in the cross section corresponds to the $\omega' \equiv \omega(1420)$ and $\omega'' \equiv \omega(1650)$ resonances.
- ✓ The systematic uncertainty on the cross section is 4.4%.

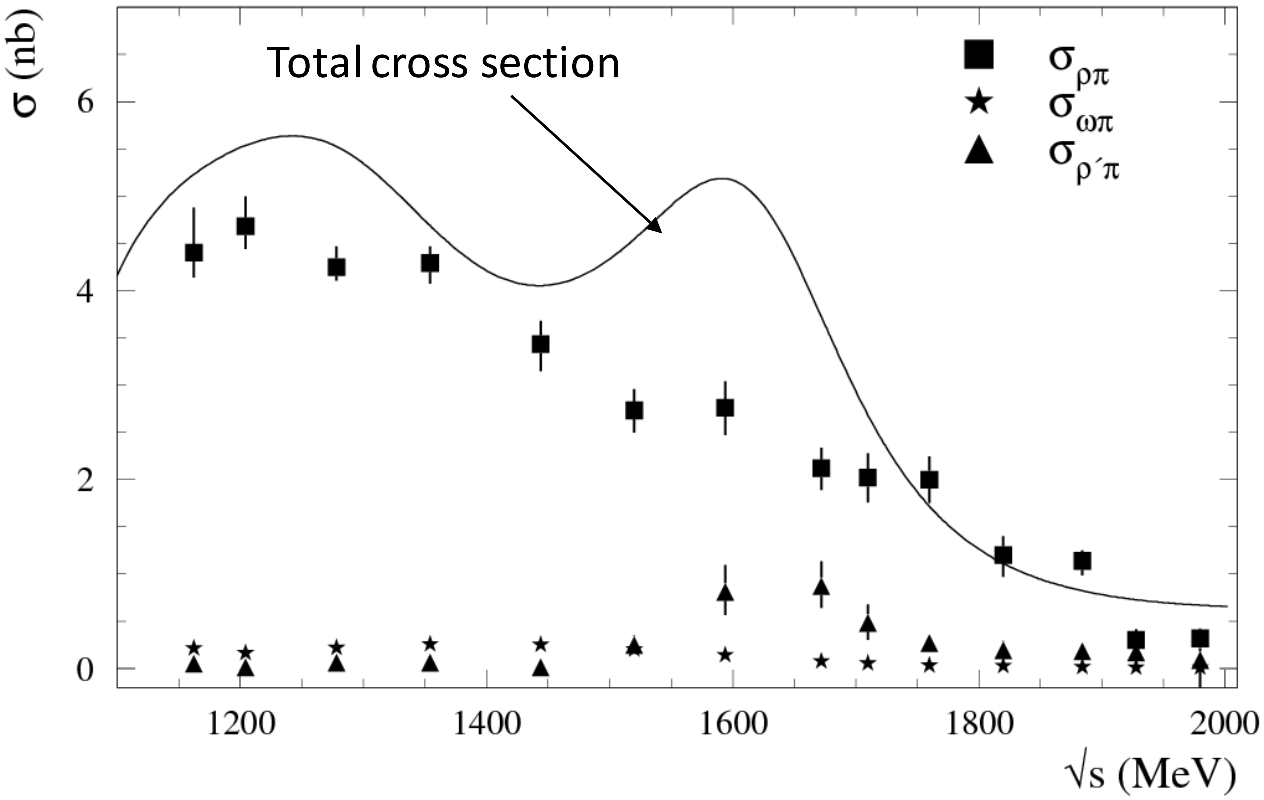
The previous SND measurement [J. Exp. Theor. Phys. 121, 27 (2015)] is based on 2011 data set. The 2012 data set has been added.

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



- We analyze the two-dimensional distribution of the charged-pion momenta and the $\pi^+\pi^-$ mass spectrum.
- These distributions are fitted with a model including the ρπ, $\rho'\pi \equiv \rho(1450)\pi$, and $\omega\pi^0$ states.
- A significant fraction of the $\rho'\pi$ intermediate state is observed in the energy region 1.55-1.75 GeV.

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



- ✓ The isovector intermediate state $\omega\pi^0$ gives sizable (up to 20%) contribution to the $e^+e^- \to \pi^+\pi^-\pi^0$ cross section.
- ✓ The cross section for the intermediate state $\rho'\pi$ differs significantly from zero in the range 1.55 - 1.75 GeV, where the resonance ω'' is located.
- ✓ In the $\rho\pi$ cross section the resonance structure near 1650 MeV is not seen.

We conclude that the $\rho'\pi$ intermediate state gives a significant contribution to the decay $\omega'' \to \pi^+\pi^-\pi^0$, and that the $\omega' \to \pi^+\pi^-\pi^0$ decay is dominated by the $\rho\pi$ intermediate state.

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

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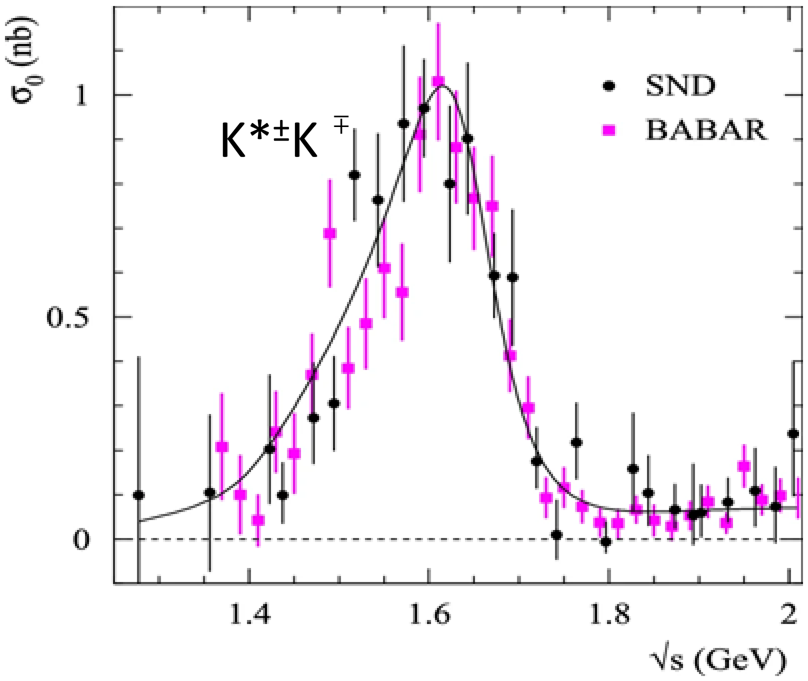

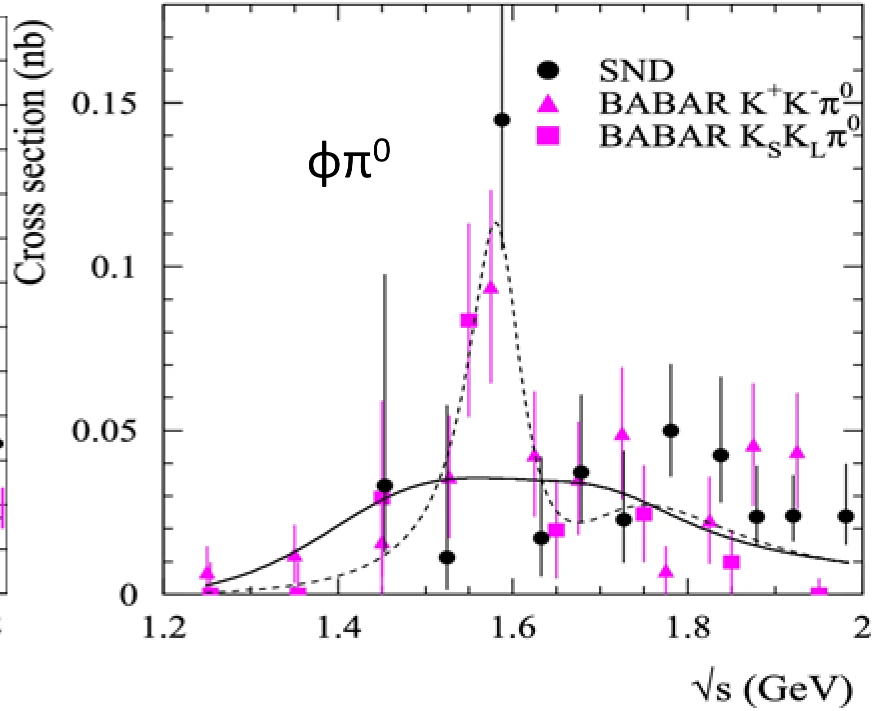

- The analysis is based on 26 pb^{-1} data recorded in the c.m. energy range 1.27 – 2 GeV.
- The cross sections for the $K^{*\pm}K^{\mp}$ and $\phi\pi^0$ intermediate states are measured separately.
- The $e^+e^- \to K^{*\pm}K^{\mp}$ cross section is dominated by the $\phi' \equiv \phi(1680)$ resonance.

The isovector process $e^+e^- \to \phi\pi^0$ is suppressed by the Okubo-Zweig-Iizuka (OZI) rule. Three measurements of the cross section are fitted simultaneously. The fit by a sum of the ρ' and ρ'' contributions cannot describe data near 1.6 GeV. The inclusion of an unknown resonance with m=1585±15 MeV and Γ=75±30 MeV improves fit. The significance of the structure is about 3σ.

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

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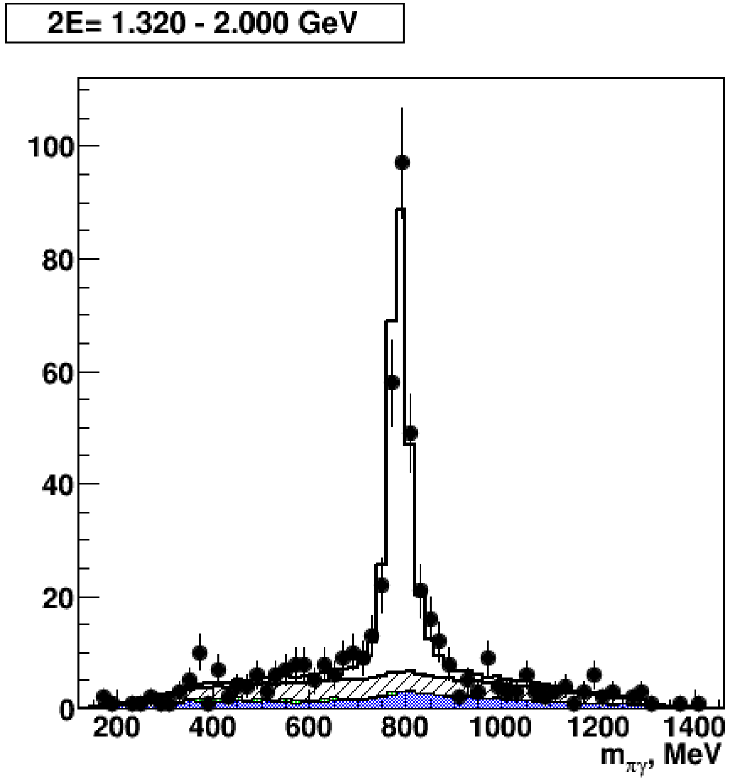
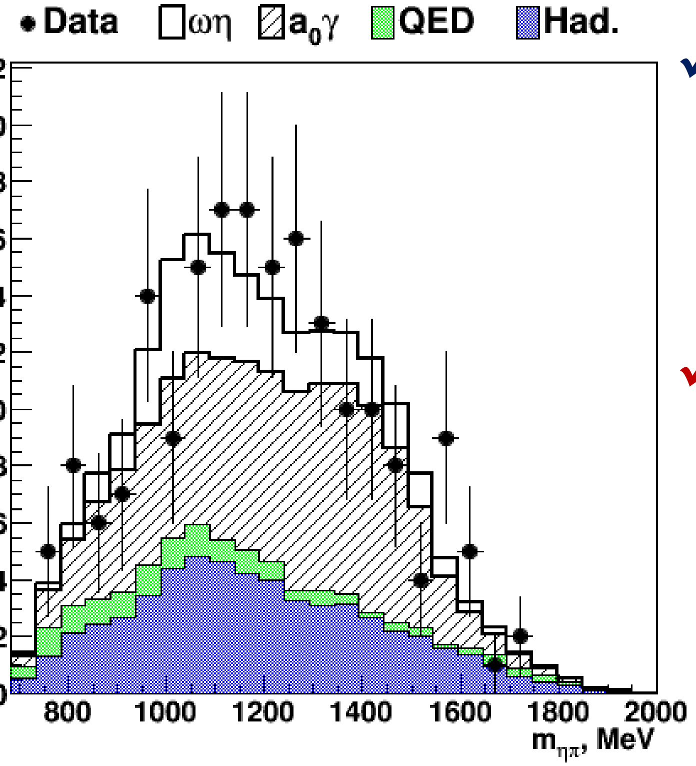
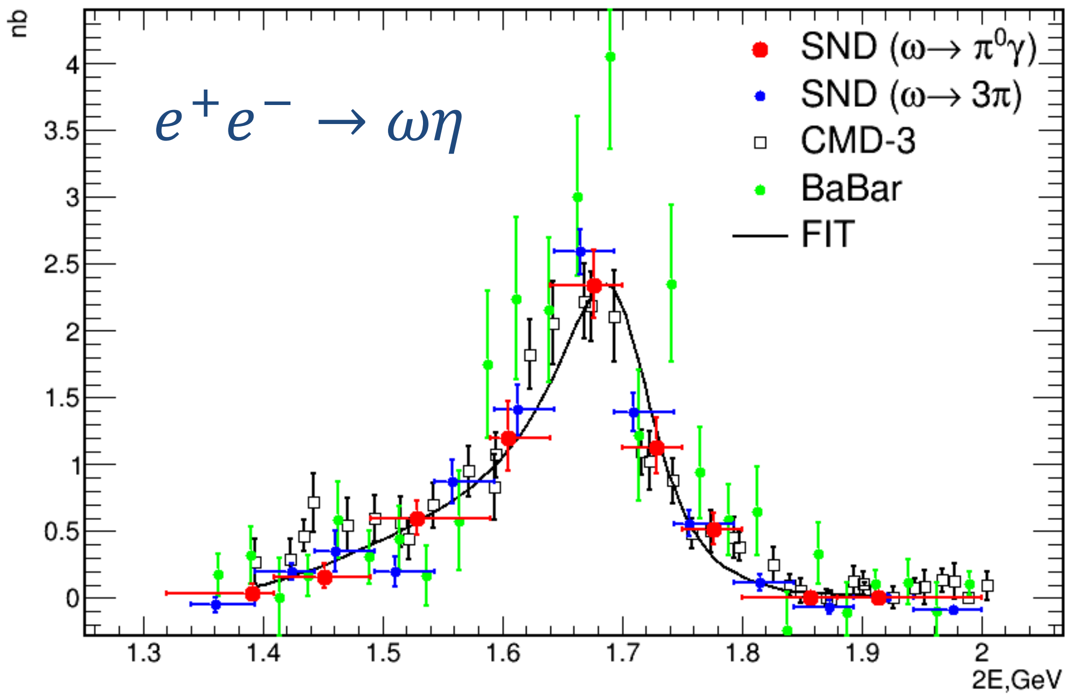


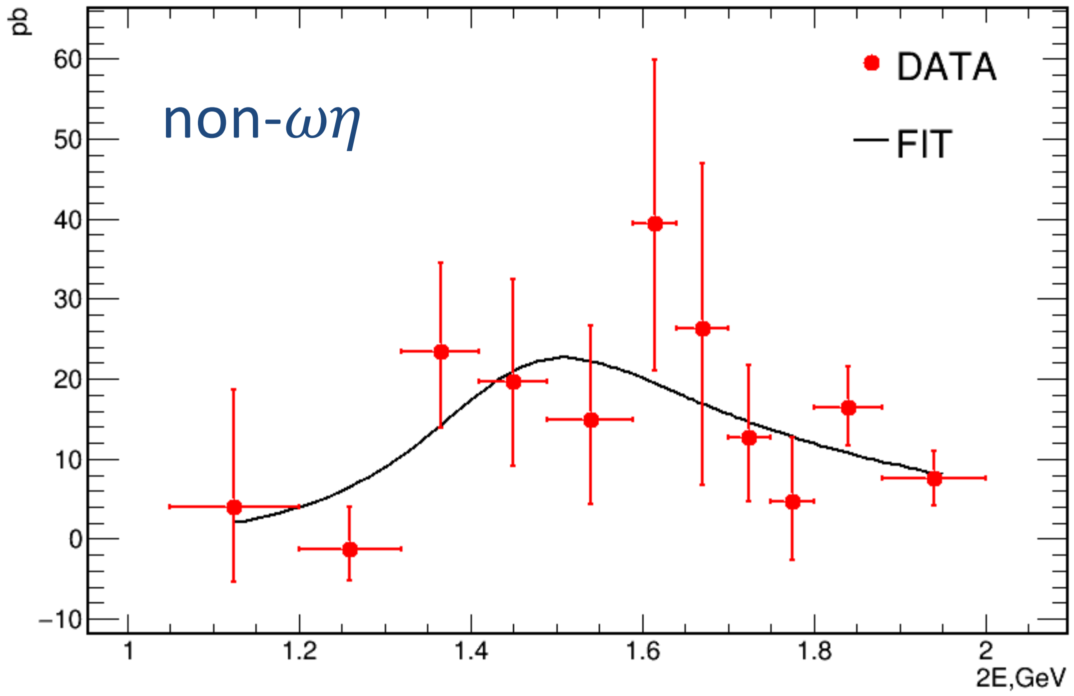


- ✓ There is a significant contribution of the ωη intermediate state, which is seen as a peak in the $\pi^0\gamma$ mass distribution.
- ✓ The non-ωη signal is observed with significance of 5.6σ. It has a wide $\eta\pi^0$ mass distribution and may arise from the processes $e^+e^- \rightarrow a_0(1450)\gamma$ and $a_2(1320)\gamma$.

- The process $e^+e^- \rightarrow \eta\pi^0\gamma$ above 1.05 GeV is studied for the first time.
- Data set with IL≈100 pb^{-1} recorded in 2010-2012 and 2017
- The five-photon final state is used.

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

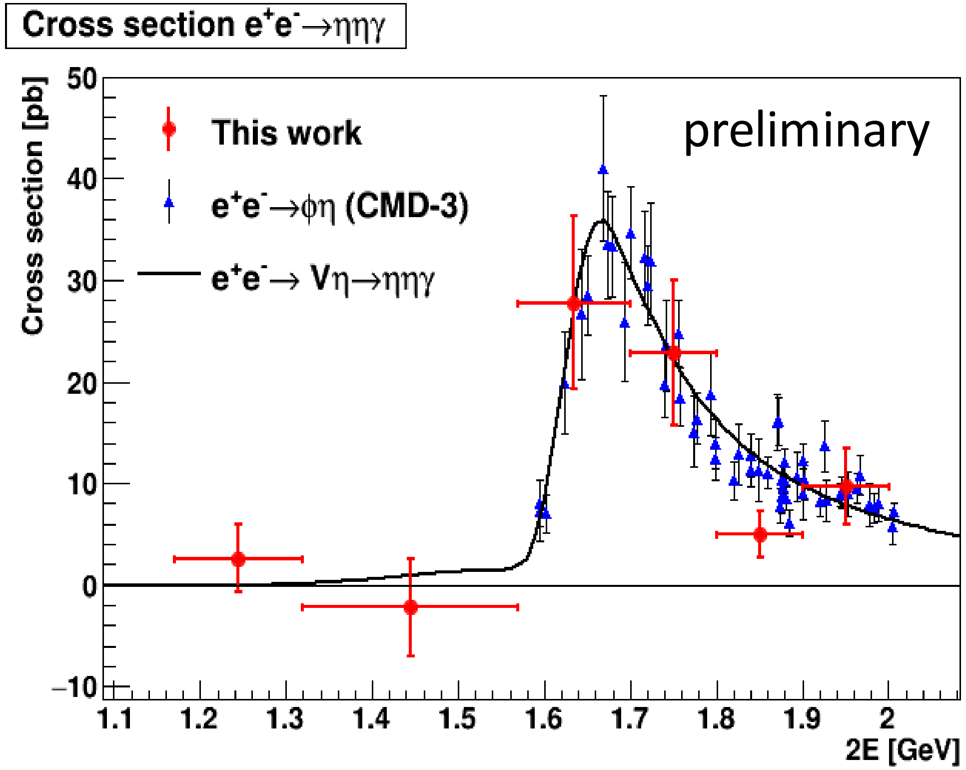




The measured $e^+e^- \to \omega\eta$ cross section is in good agreement with the SND and CMD-3 measurements in the $\omega \to \pi^+\pi^-\pi^0$ decay mode.

The non-VP $e^+e^- \to \eta\pi^0\gamma$ process is observed with significance of 5.6σ. This is the first measurement of this cross section.

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



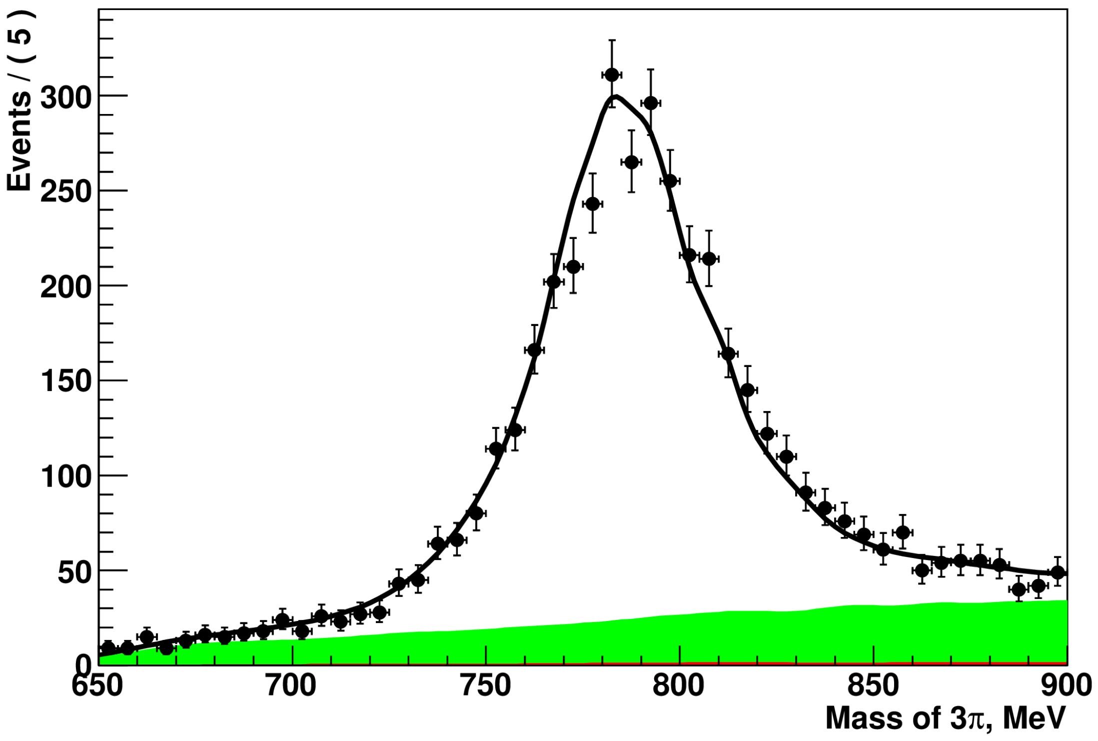
- The $e^+e^- \to \eta\eta\gamma$ cross section is measured for the first time in the energy range 1.17 – 2.0 GeV.
- The main intermediate state is ϕη.
- The measured cross section is consistent with CMD-3 result on $e^+e^- \to \phi\eta$, $\phi \to K^+K^-$.
- The contribution from intermediate states other than ϕη is not seen.

preliminary

2E, GeV	95% CL Upper limit,pb
1.17-1.32	9
1.32-1.57	5
1.57-1.80	11
1.80-2.00	4

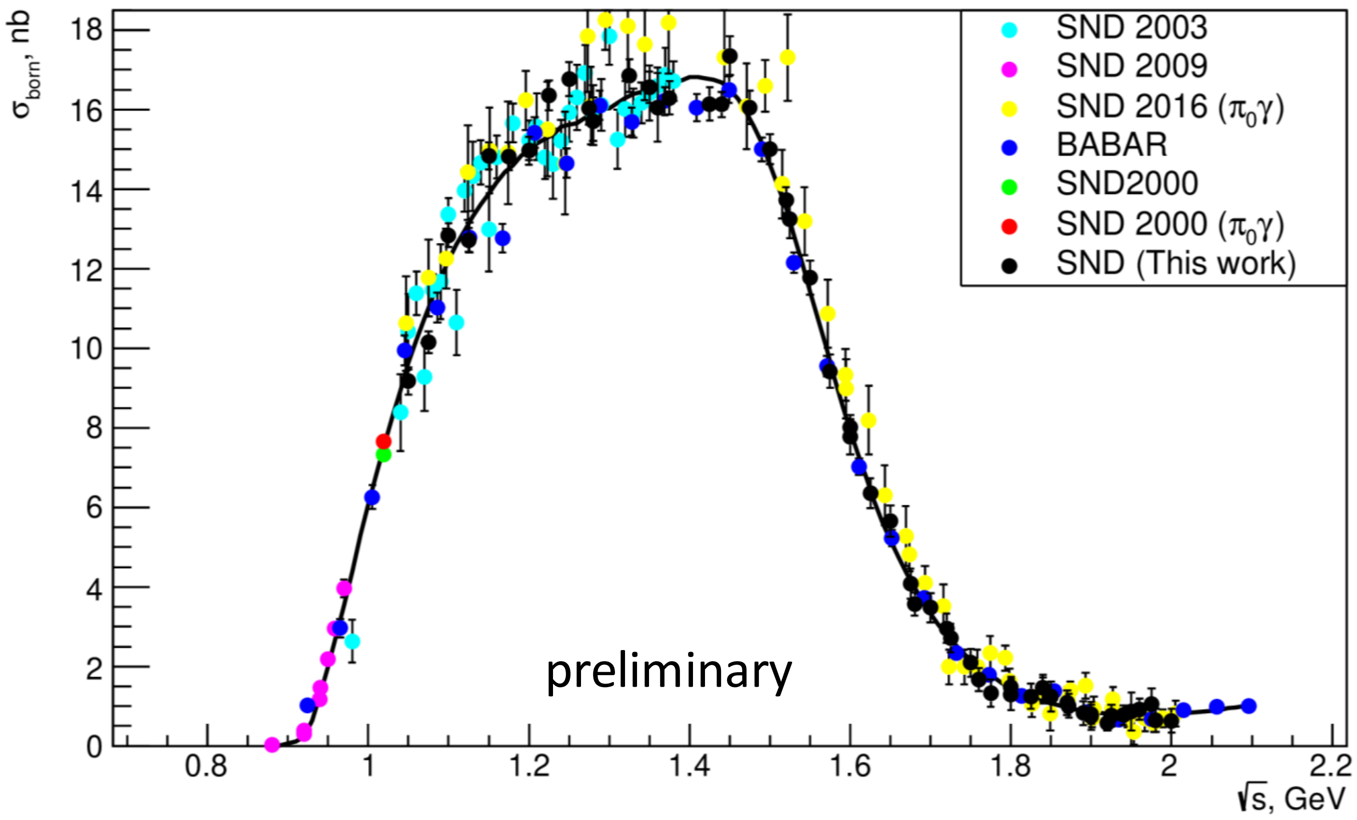
Upper limits on possible contribution of radiative intermediate states ($f_0(1500)\gamma$, $f'_2(1525)\gamma$) is set.

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



- The analysis is based on 35 pb^{-1} data collected in 2011 – 2012.
- The measurement of the $e^+e^- \rightarrow \omega\pi^0$ process is the first step in the study of the $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ reaction.
- Allows to study all sources of systematic uncertainties
- The $\omega\pi^0$ contribution is separated from other intermediate states ($a_1\pi$, $\rho^+\rho^-$, …) by fitting the $\pi^+\pi^-\pi^0$ invariant-mass spectrum in the range 650 – 900 MeV.

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



- The $\omega\pi^0$ cross section measured with the restriction $M(3\pi) < 0.9$ GeV is expected to be independent of the model for the ω line shape.
- The measured $e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$ cross section is in agreement with previous measurements but has better accuracy.
- The cross section is fitted with the VMD model including three ρ-like states

Summary

✓The SND detector accumulated 370 pb^{-1} of integrated luminosity in the energy range 0.3 – 2 GeV.

✓The $e^+e^- \to \pi^+\pi^-$cross section has been measured in the energy range 0.53-0.88 GeV with a systematic uncertainty better than 1%.

✓The accuracy of the $e^+e^- \to n\bar{n}$ measurement has been significantly improved.

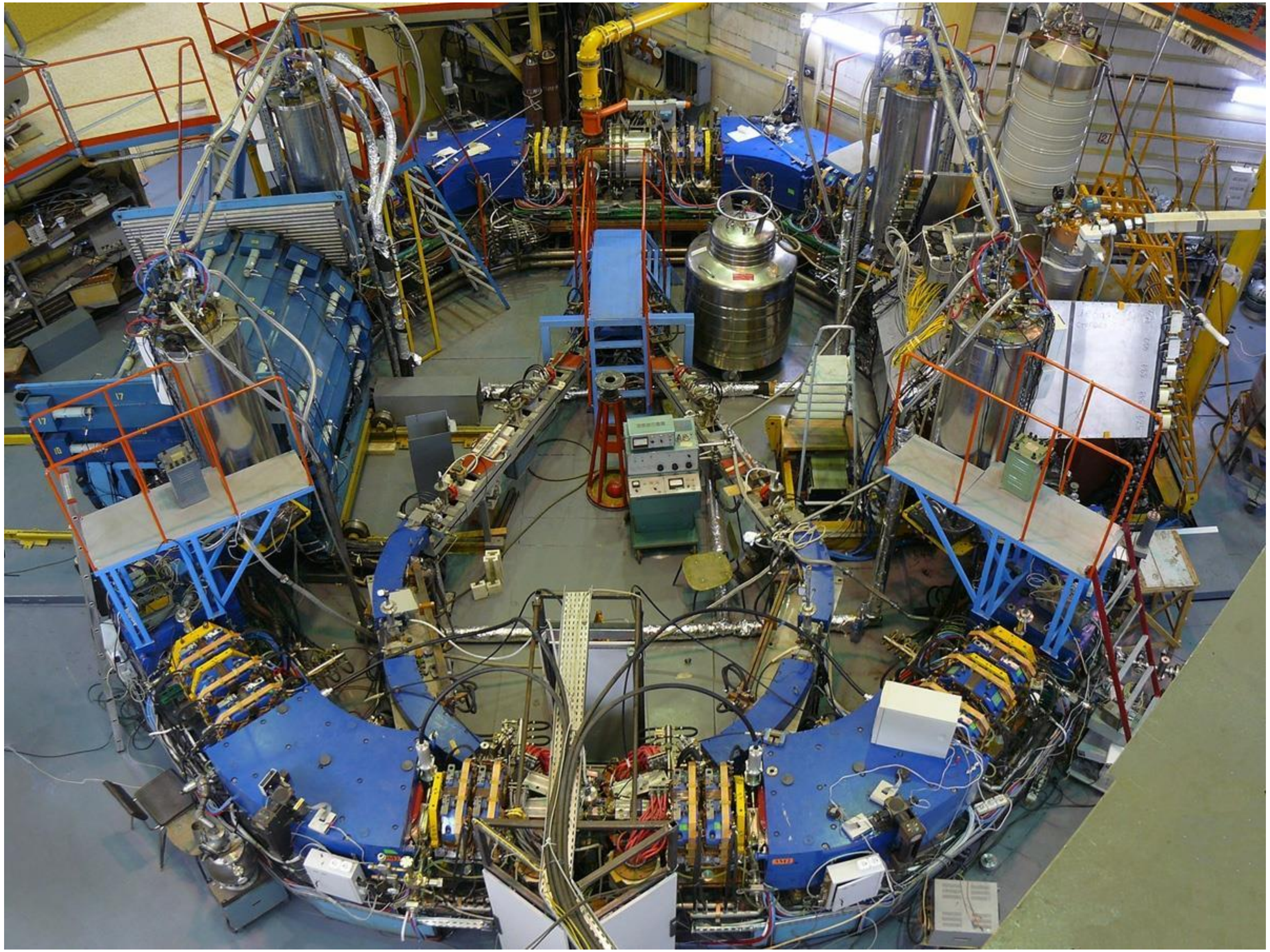
✓The preliminary results on the $e^+e^- \to p\bar{p}$ cross section has been obtained.

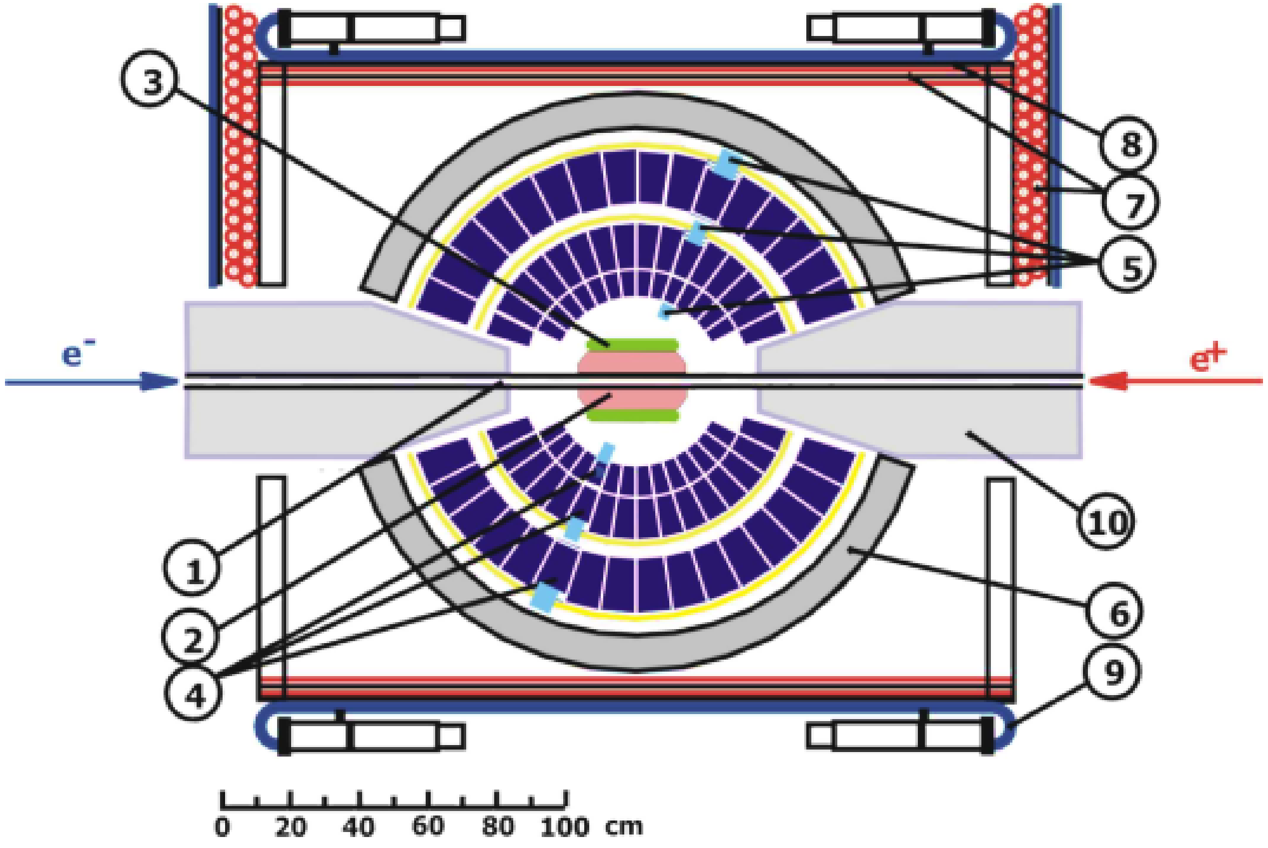
✓The dynamics of the process $e^+e^- \to \pi^+\pi^-\pi^0$ has been studied in the energy range 1.15-2.0 GeV.

✓The process $e^+e^- \to K^+K^-\pi^0$ has been studied in the $K^{*\pm}K^{\mp}$ and $\phi\pi^0$ intermediate states.

✓Rare radiative processes $e^+e^- \to \eta\pi^0\gamma$ and $\eta\eta\gamma$ have been measured in the energy range 1.05-2 GeV.

✓ The most precise measurement of the $e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$ cross section has been performed.





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.

[NIM A449 (2000) 125-139]

Calorimeter

- $13.5X_0, 0.95 \times 4\pi$
- Energy resolution

$$\frac{\sigma_E}{E} = \frac{0.042}{\sqrt[4]{E[GeV]}}$$

- Angular resolution

$$\sigma_\varphi = \frac{0.82^\circ}{\sqrt{E[GeV]}} \oplus 0.63^\circ$$

Tracking system

- 9 layers, $0.94 \times 4\pi$
- Angular resolution

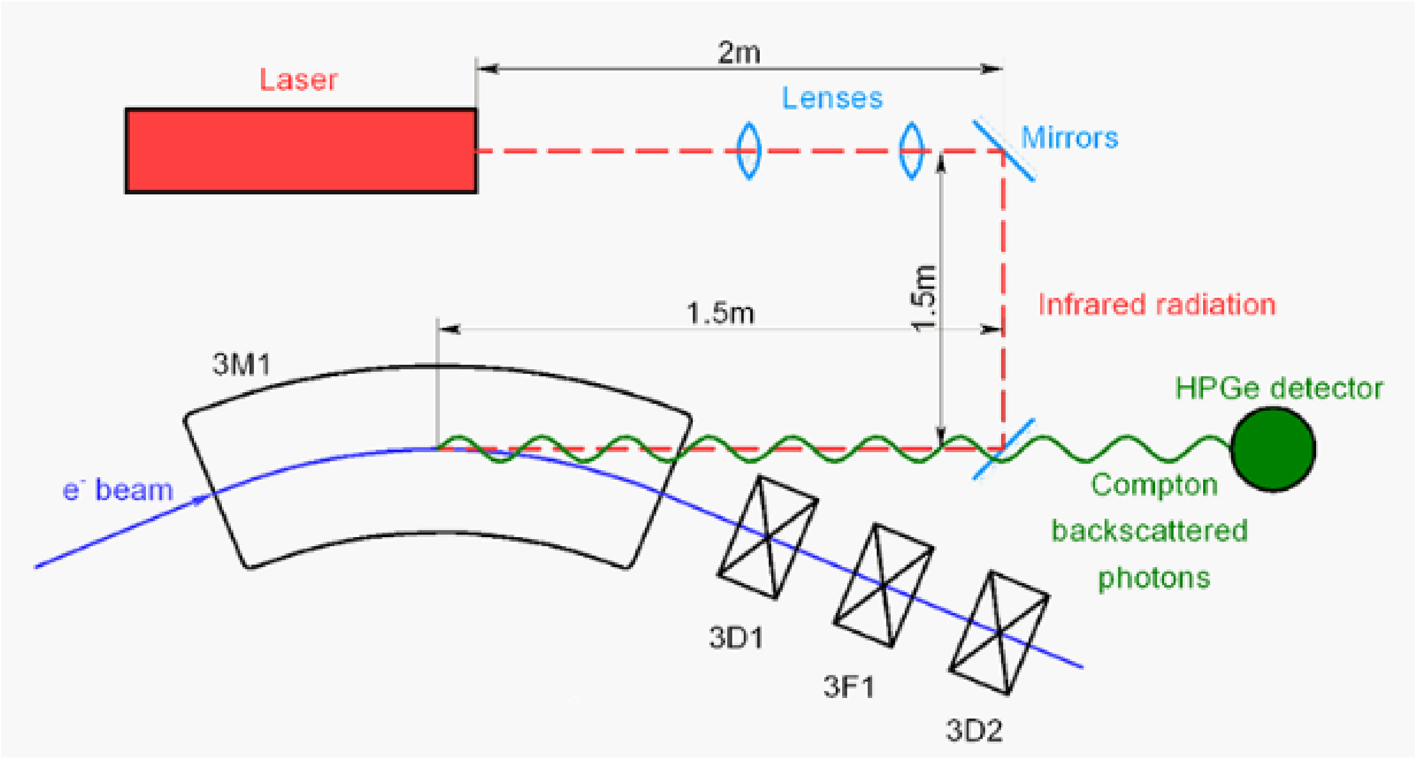
$$\sigma_\varphi = 0.55^\circ, \sigma_\theta = 1.2^\circ$$

- Vertex position resolution

$$\sigma_R = 0.12cm, \sigma_Z = 0.45cm$$

Aerogel counters

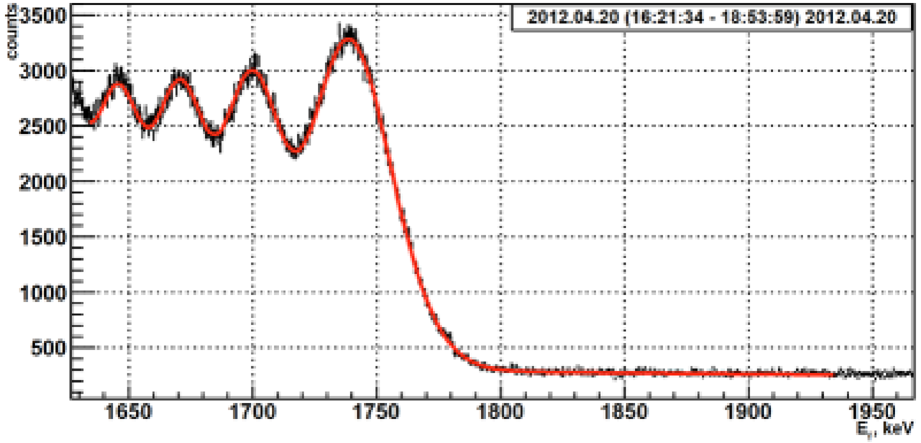
- K/π separation E < 1 GeV



Backscattered photons spectrum edge:
parameters B, S, E

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

E.V. Abakumova et al., PRL 110 2013 140402



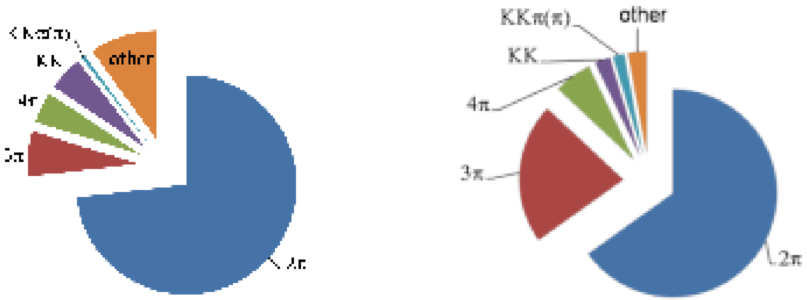
$$a_\mu^{EXP} - a_\mu^{SM} = 3.6\sigma$$

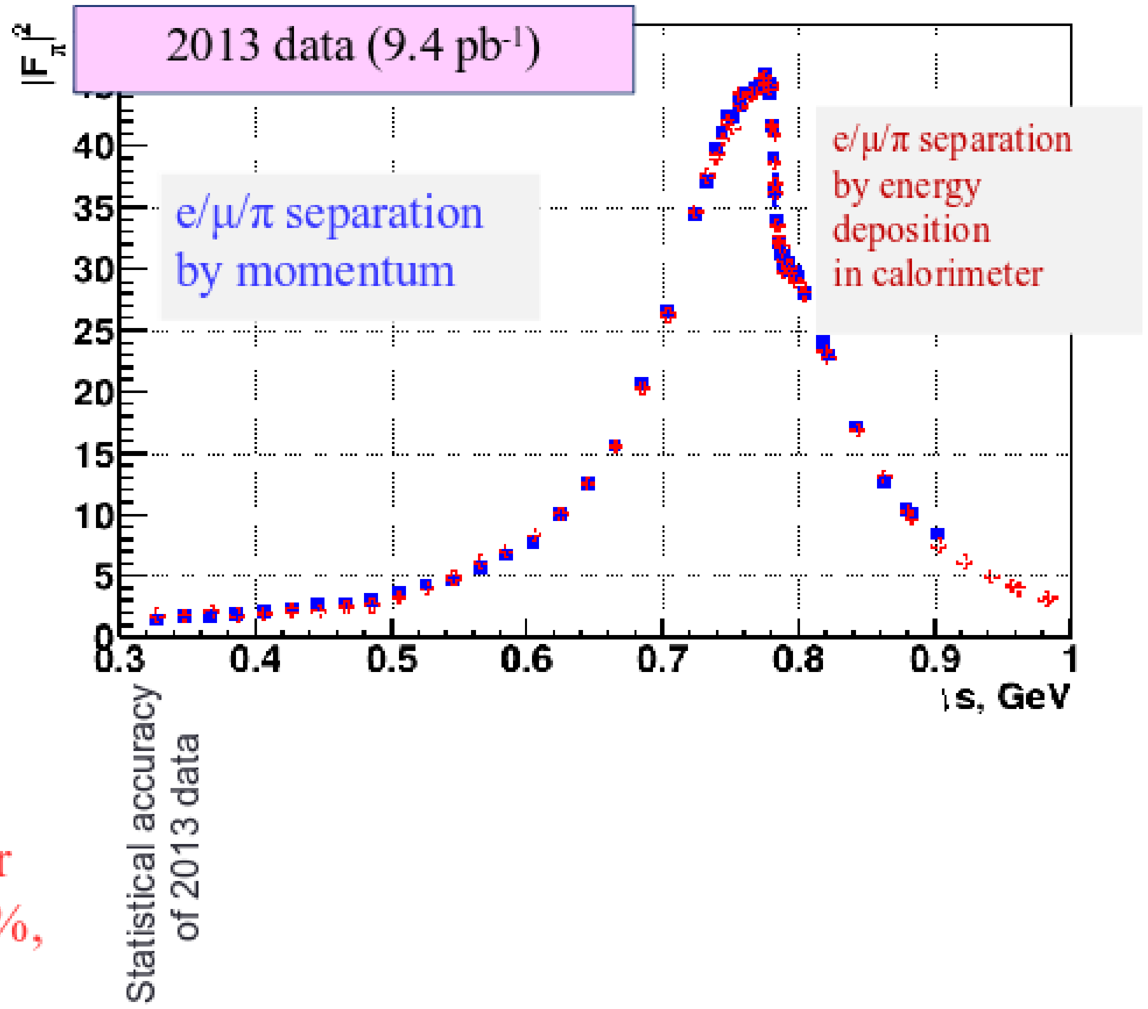
$$a_\mu^{\text{had, LO-VP}} = \frac{\alpha^2 m_\mu^2}{9\pi^2} \int_{m_\pi^2}^{\infty} ds \frac{\hat{K}(s)}{s^2} R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to \gamma^* \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

Contribution to the hadronic part of $(g\text{-}2)_\mu$ value from the VEPP-2000 energy region is about 92%:

Contribution and squared error fraction:





The goal is to reach systematic error under 0.36% (now radiative correction to 0.2-0.4%, e/μ/π separation 0.1-0.5%, 0.3-0.6% pion decay and nuclear interaction).