

The XXV International Workshop-School
High Energy Physics and Quantum Field Theory

June 30 – July 5, 2025

Moscow, Russia

QFTHEP'270

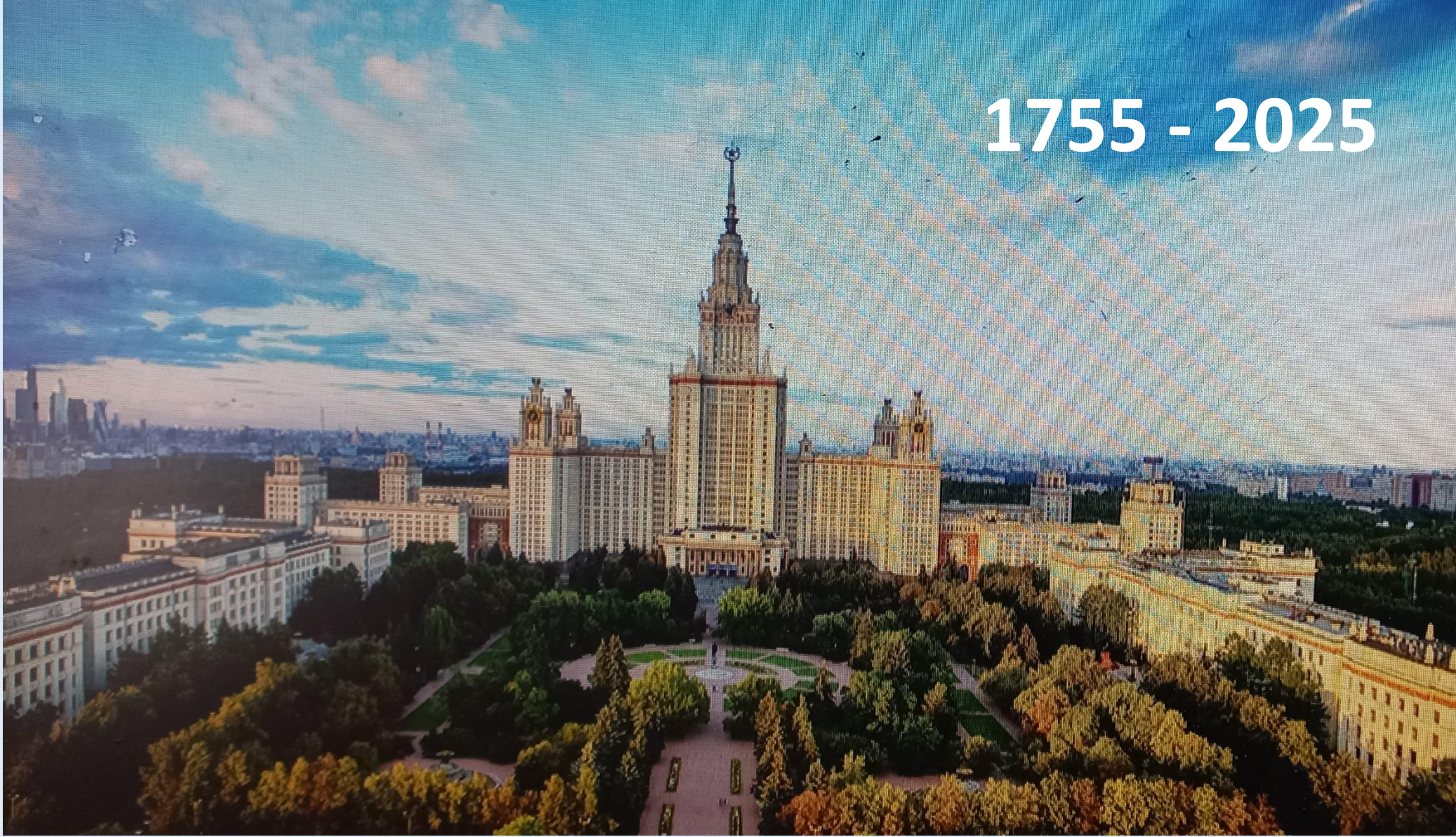
**Measurement of the neutron electromagnetic timelike
formfactor near the threshold**

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Novosibirsk State University





1755 - 2025

$e^+e^- \rightarrow n\bar{n}$ annihilation

$$\sigma(e^+e^- \rightarrow B\bar{B}) = \frac{\alpha^2 \beta C^2}{4m^2} \left(|G_M|^2 (1 + \cos^2 \theta) + \frac{4m_B^2}{m^2} |G_E|^2 (1 - \cos^2 \theta) \right)$$

$$J^{PC} = 1^{--}, \quad J = L+S,$$

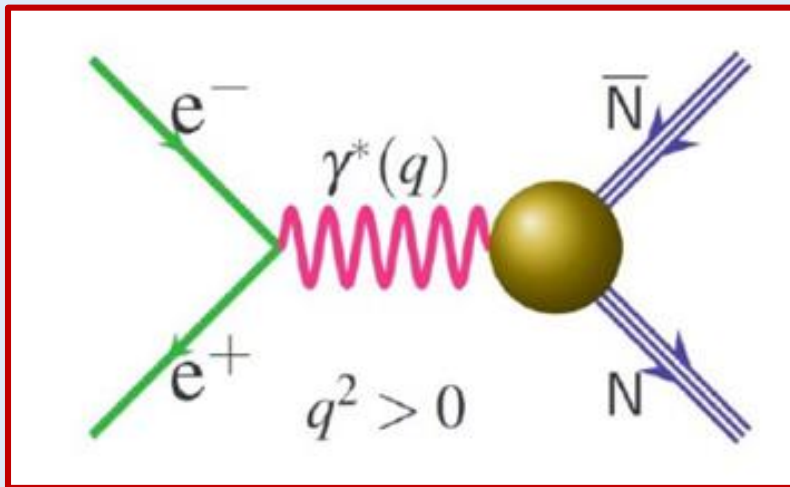
$$P = (-1)^{L+1} = -1, \quad L=0,2$$

$$C = (-1)^{L+S} = -1, \quad S=1,$$

S, D – waves,

two form factors

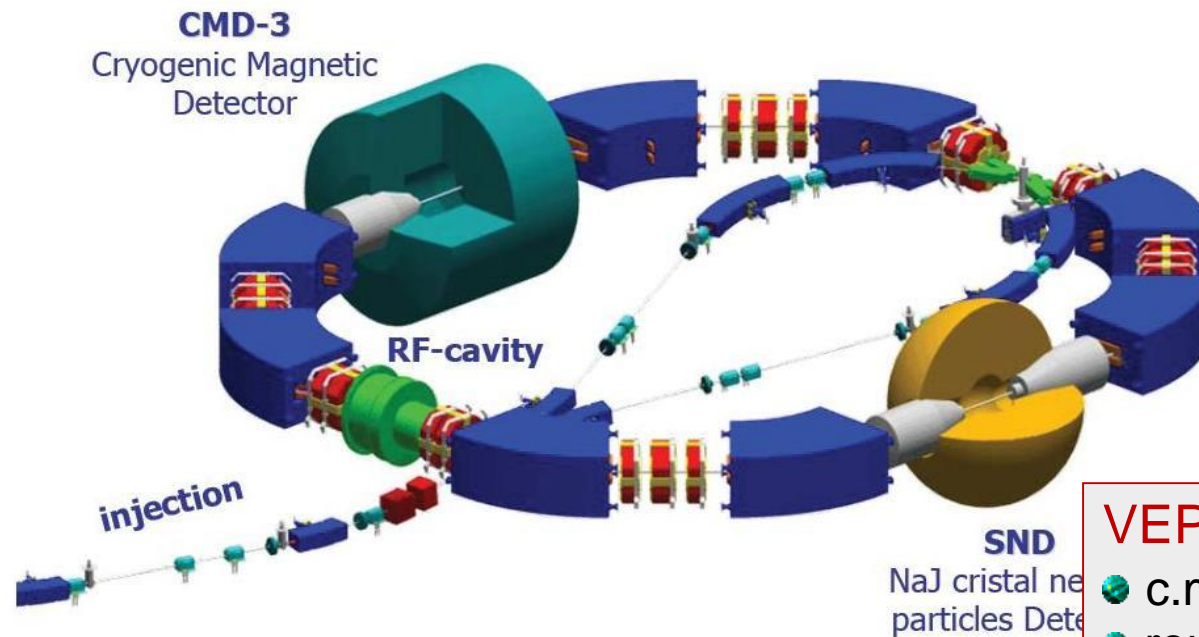
e.g. G_E, G_M



B – baryon = p, n ;
 $m = 2E_b$ – cms energy ;
 β – nucleon velocity,
 θ – polar angle;
 m_b – nucleon mass ;
 G_E, G_M - form factors

Коллайдер ВЭПП-2000

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



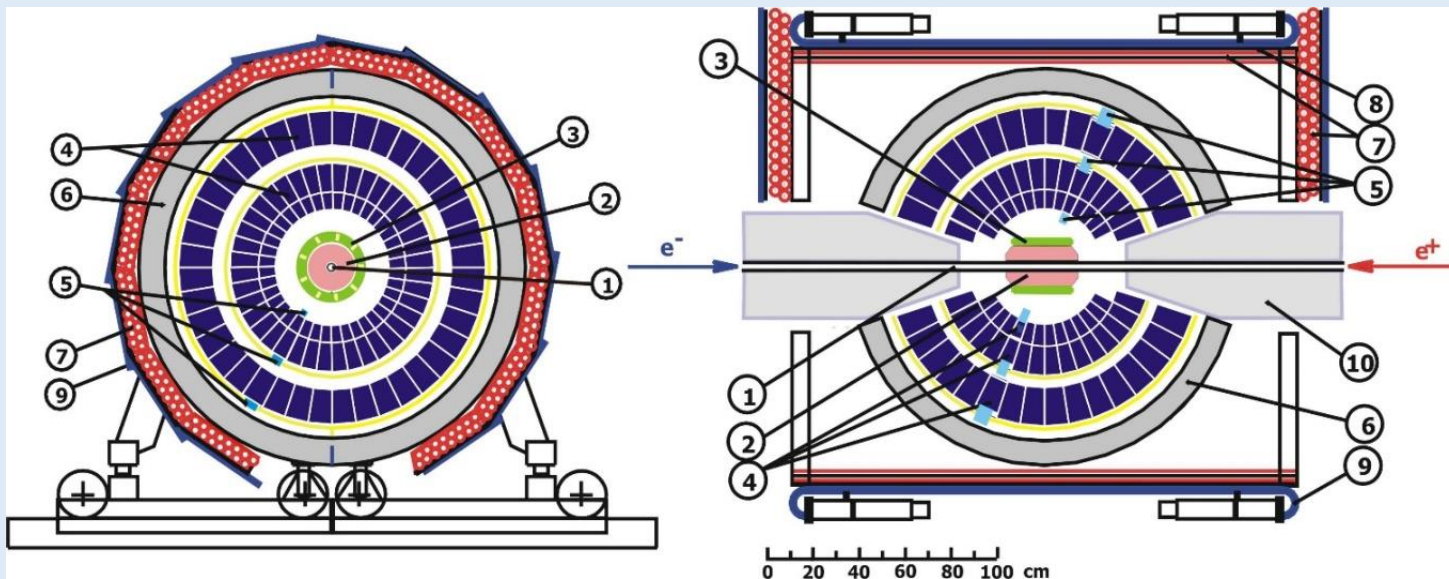
VEPP-2000 parameters:

- c.m. energy $E=0.3-2.0$ GeV
- round beam optics
- Luminosity at $E=1.8$ GeV
 $1 \cdot 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ (project),
 $7 \cdot 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$ (achieved)

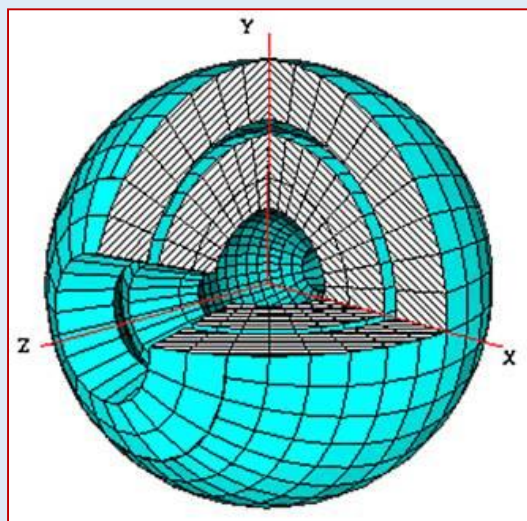
**В работе – с 2010 года
(since 2010)**



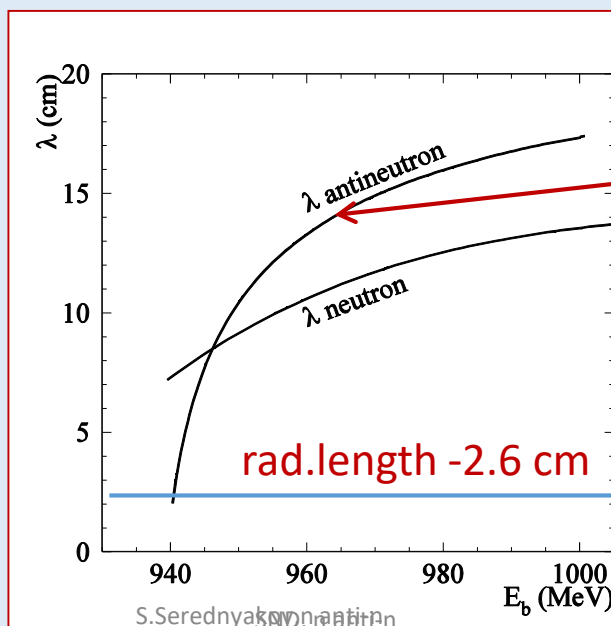
SND detector (since 1995)



- 1 – vacuum chamber,
- 2 – tracking DC,
- 3 – aerogel $n=1.13, 1.05$
- 4 – NaI(Tl) crystals,
- 5 – phototriodes,
- 6 – absorber,
- 7–9 – muon detector,
- 10 – SC solenoids



Solid angle - 95% 4π



Attenuation length

SND – good antineutron detector

Экспериментальные данные (experimental data)

Эксперимент 2022 г.

область порога $e^+e^- \rightarrow n \text{ anti-n}$

$E_{\text{beam}} =$

939.6, 940, 941, 942, 943.5, 945, 947.5, 949, 950, 951, 952, 953, 854 MeV

↑
порог

$\Delta L = 100 \text{ 1/pb}$

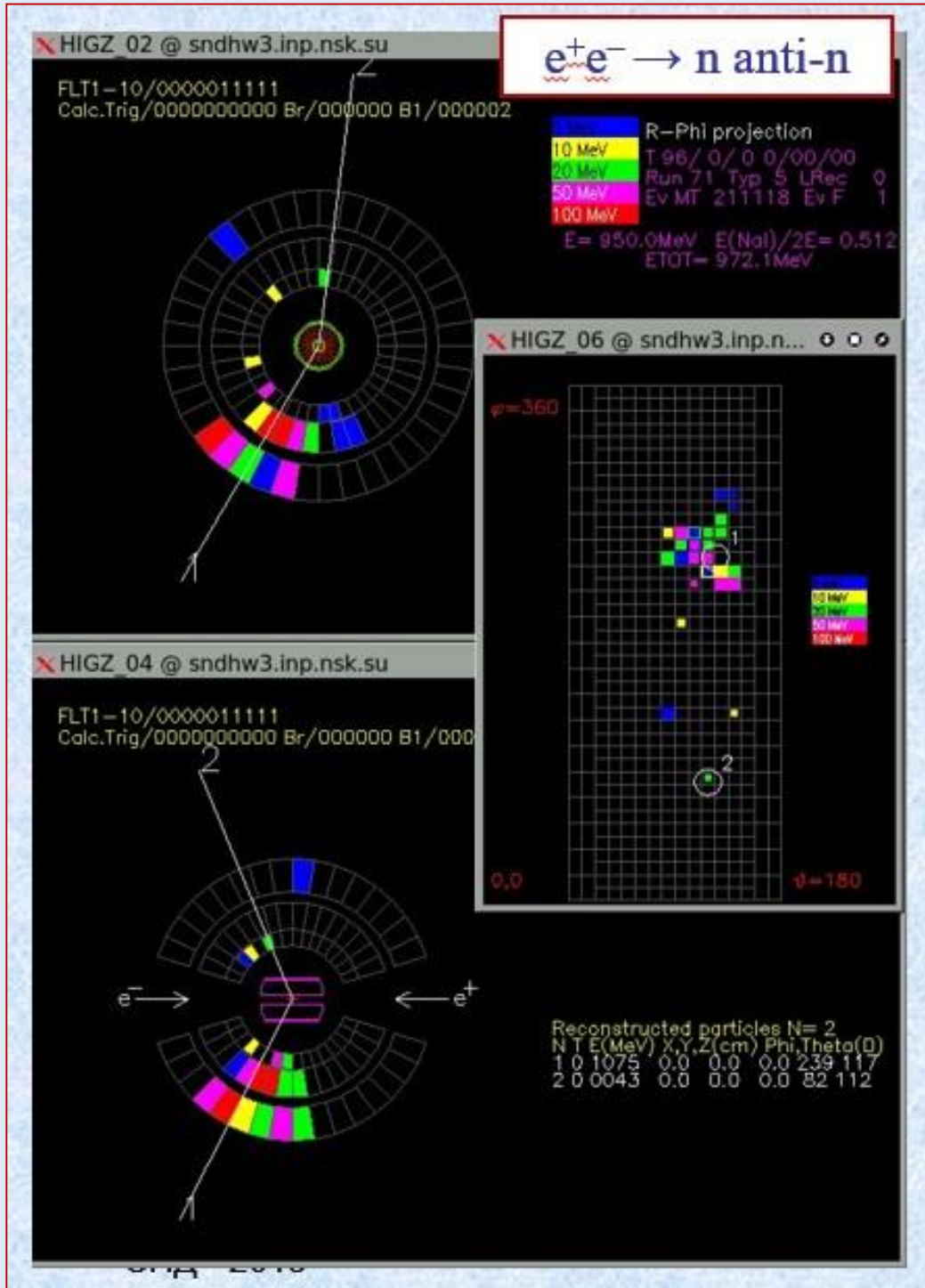
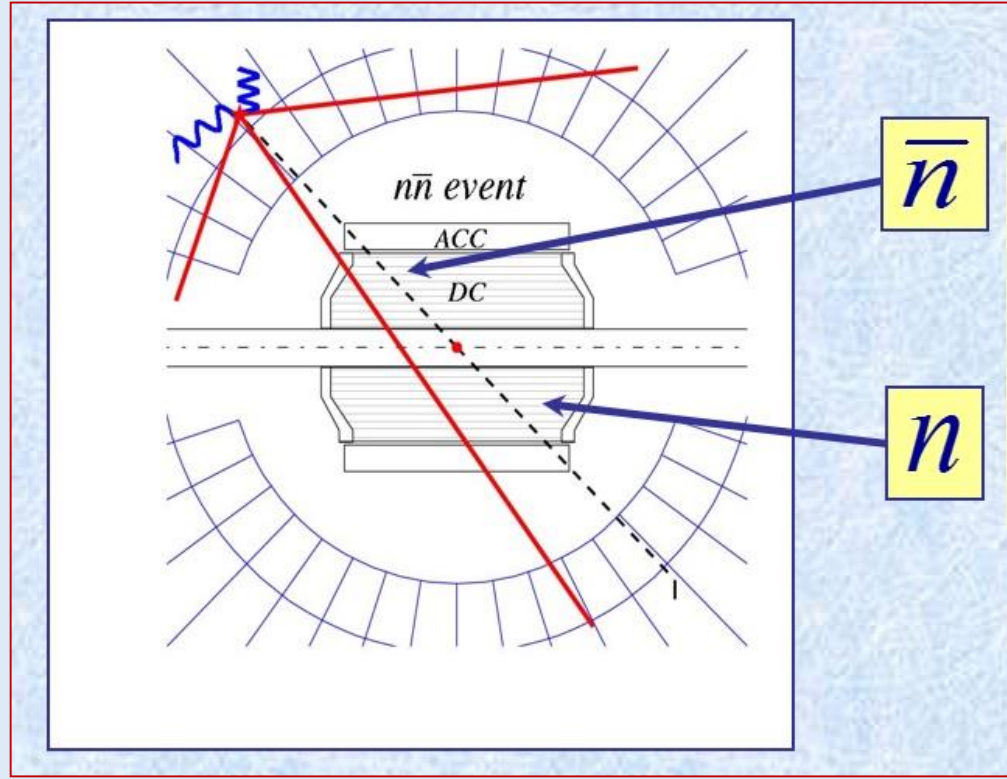
13 точек по энергии

Публикация:

Ядерная физика, 2024, т.87, N5, с.400-413

Грант РФФ : No. 23-22-00011

Typical view
nn - events

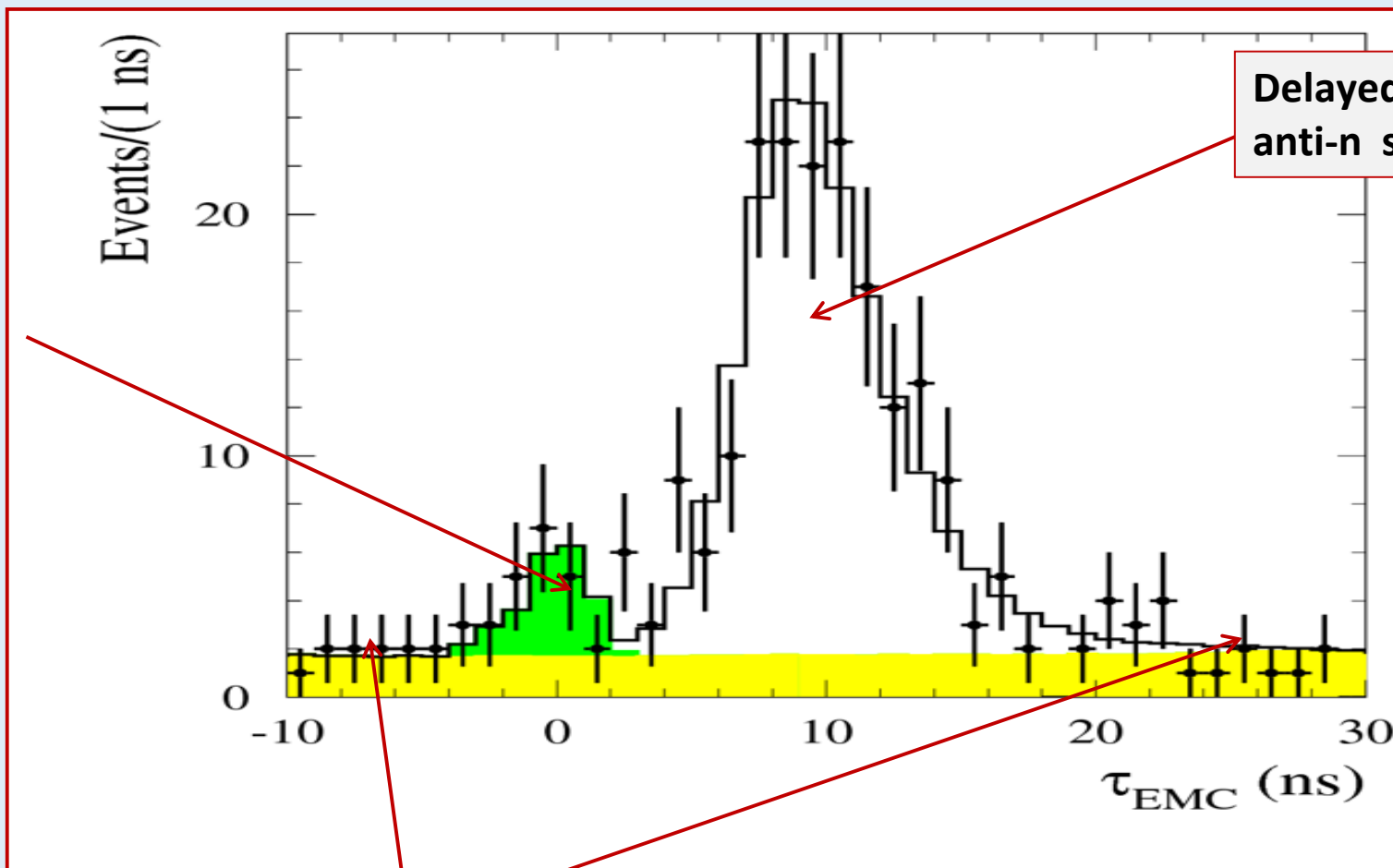


Временные спектры (Time spectra)

Фит временного спектра (time fit):

$$N(t) = N_{\text{csm}} * H(t)_{\text{csm}} + N_{\text{bg}} * H(t)_{\text{bg}} + N_{\text{nn}} * H(t)_{\text{nn}}$$

$t=0$,
beam and
phys. bkg

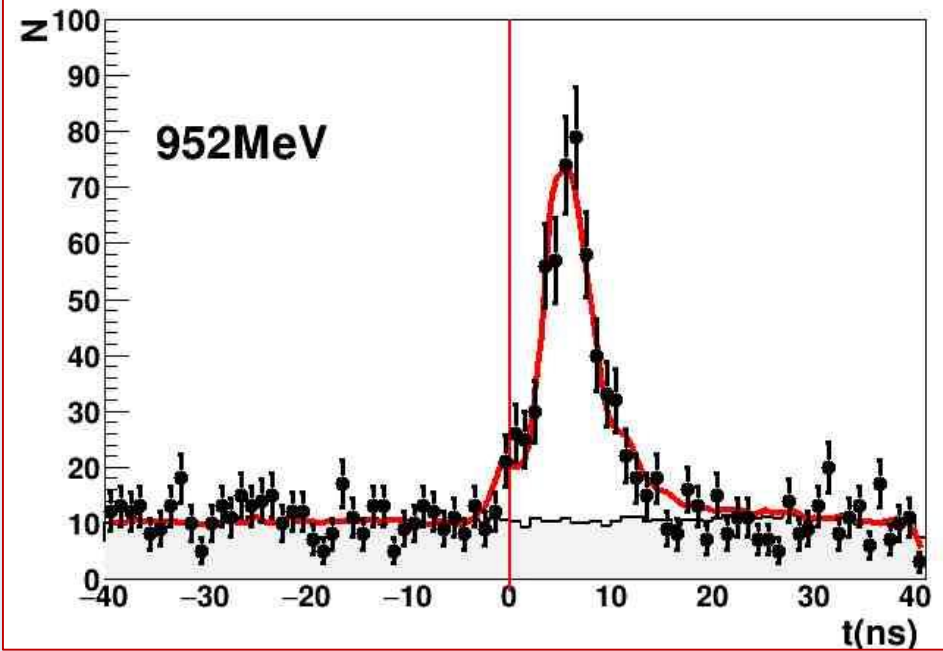
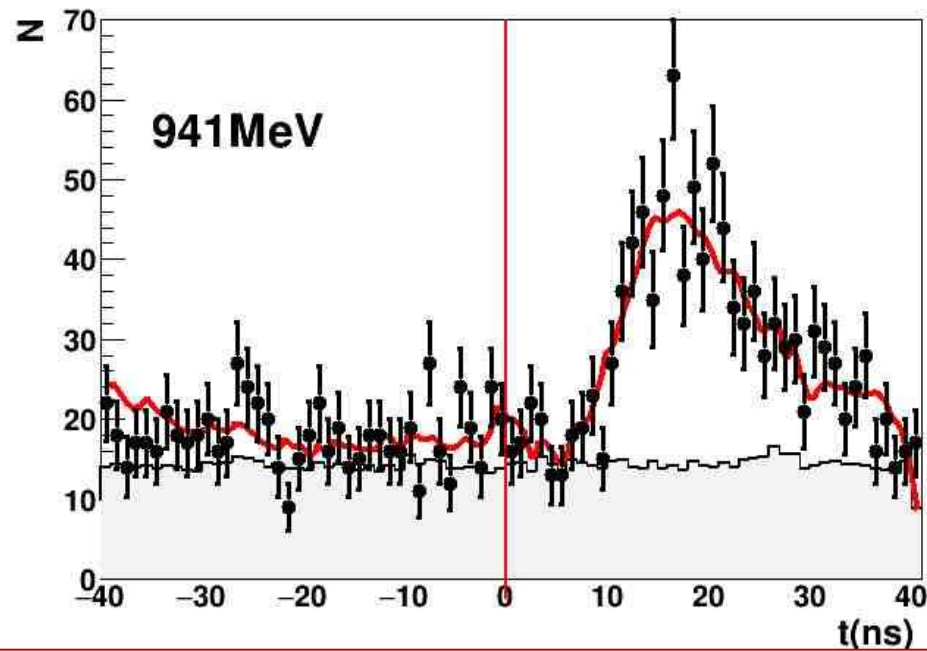


Delayed
anti-n signal

Cosmic bkg

Временные спектры МНAD2022, станд.отбор (Time spectra , stand. Selection)

n+anti-n



MC simulation $e^+e^- \rightarrow n + \text{anti-}n$

GEANT-4, V.10.5 package is used

+

Emission of photons by initial e^+ , e^- (ISR)

+

Beam energy spread $\sigma E \sim 0.7$ MeV

+

Dead detector channels

+

Beam background pileups

+

Corrections data/MC

Detection efficiency MC $\sim 20\%$

Measured $e^+e^- \rightarrow n \text{ anti-n}$ cross section

Вычисление сечения

$$\sigma_B = N_{nn} / \varepsilon (1+\delta) L$$

Example :

N_{nn} – detected events number, ~ 300 ,

L - integrated luminosity, $\sim 5 \text{ pb}^{-1}$,

ε - MC detection efficiency, ~ 0.2 ,

$1+\delta$ - radiative correction, ~ 0.8 ,

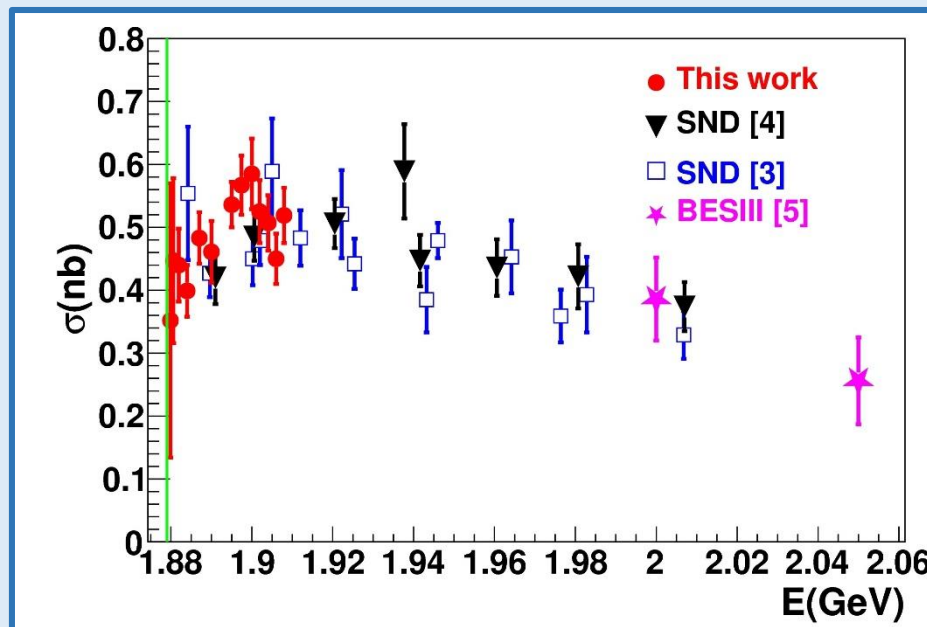
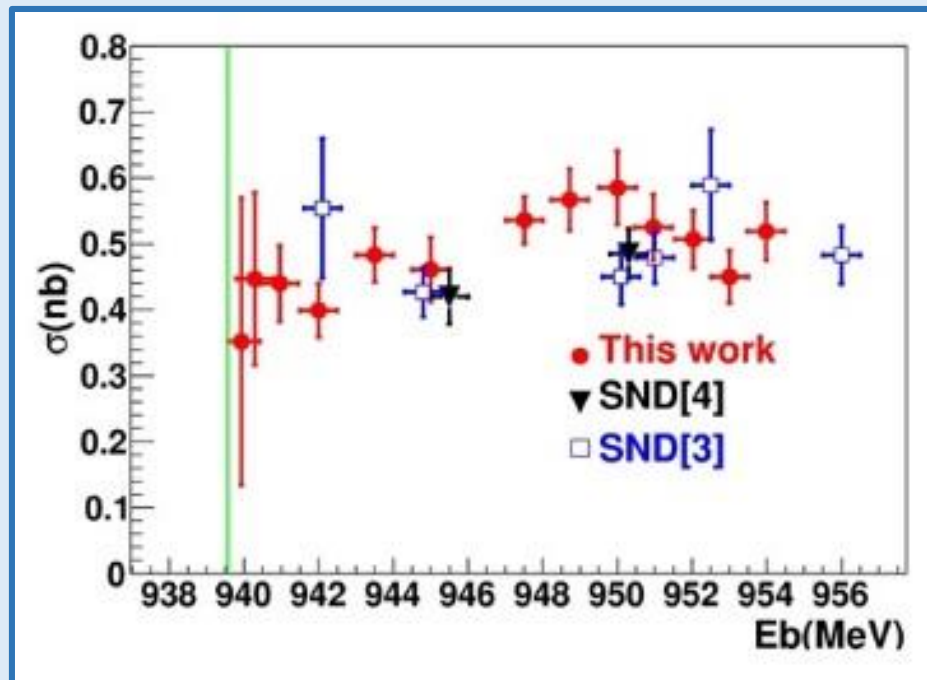
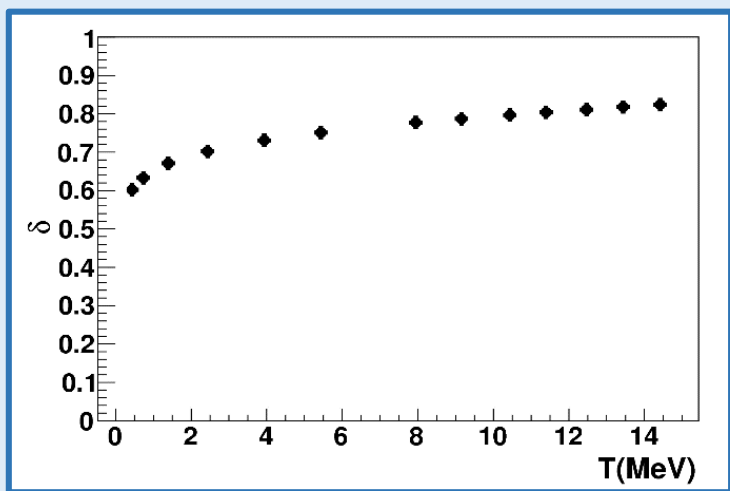
σ_B - total cross section $\sim 0.4\text{-}0.6 \text{ nb}$,

σ_{vis} - visible cross section,

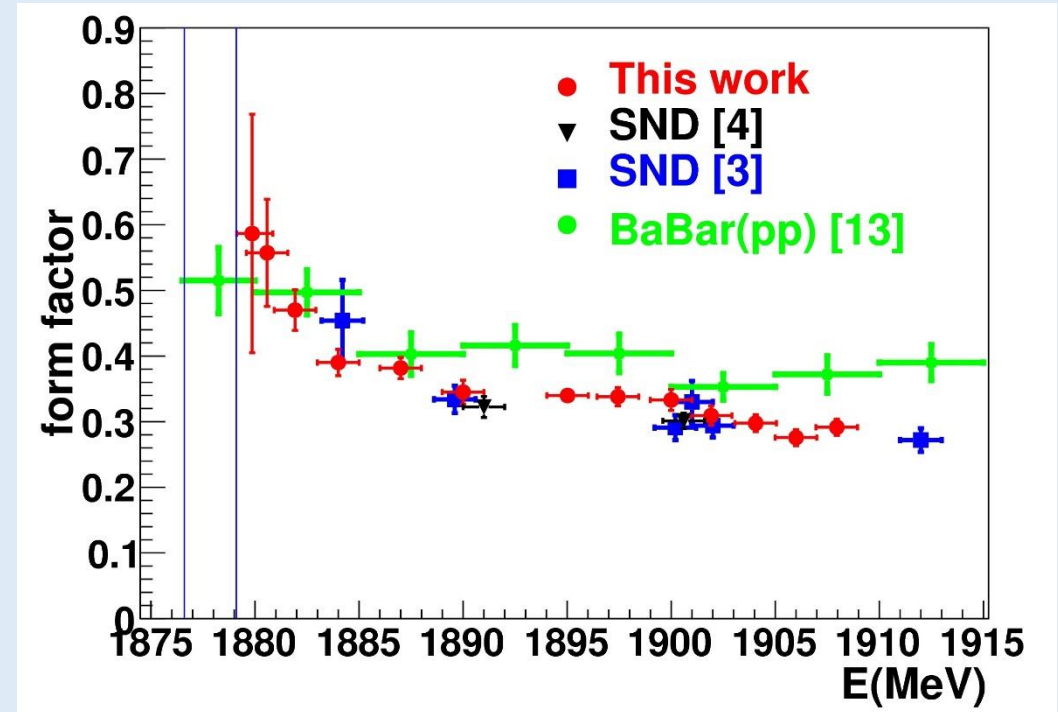
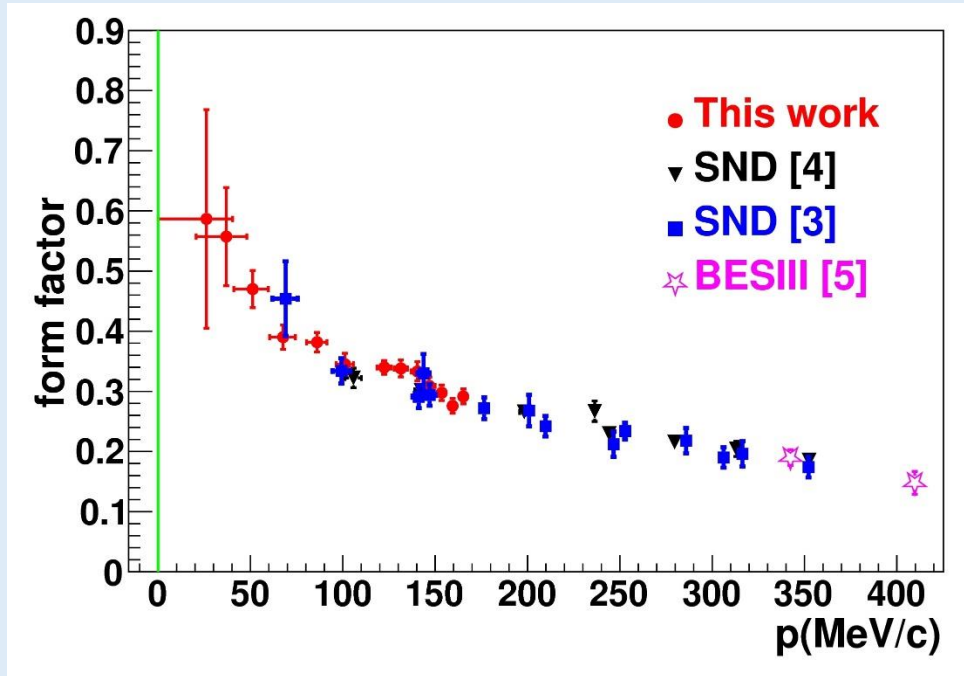
$\text{err}(\text{stat}) \sim 5\%$,

$\text{err}(\text{syst}) \sim 10\%$,

both errs are shown.



Measured effective timelike neutron formfactor



$$\sigma(e^+e^- \rightarrow B\bar{B}) = \frac{4\pi\alpha^2\beta C}{3m^2} \left(|G_M|^2 + \frac{2m_B^2}{m^2} |G_E|^2 \right)$$

$$|F|^2 = \frac{|G_M|^2 + |G_E|^2 / 2\tau}{1 + 1/2\tau}, \quad \tau = \frac{m^2}{4m_B^2}$$

← Эффективный формфактор

Calculation of GE/GM using angular distribution

$$\sigma(e^+e^- \rightarrow B\bar{B}) = \frac{\alpha^2 \beta C^2}{4m^2} \left(|G_M|^2 (1 + \cos^2 \theta) + \frac{4m_B^2}{m^2} |G_E|^2 (1 - \cos^2 \theta) \right)$$

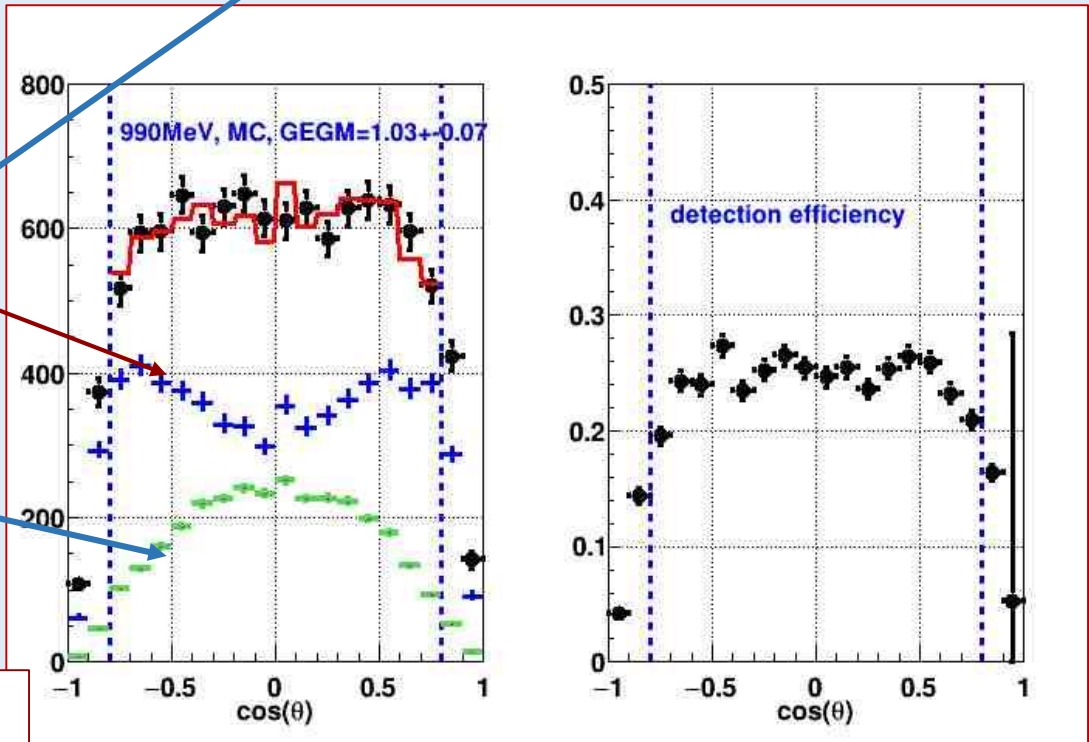
At threshold
 $|G_E| = |G_M|$

GM

$N(GM) = 2 N(GE) !$

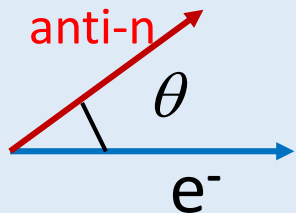
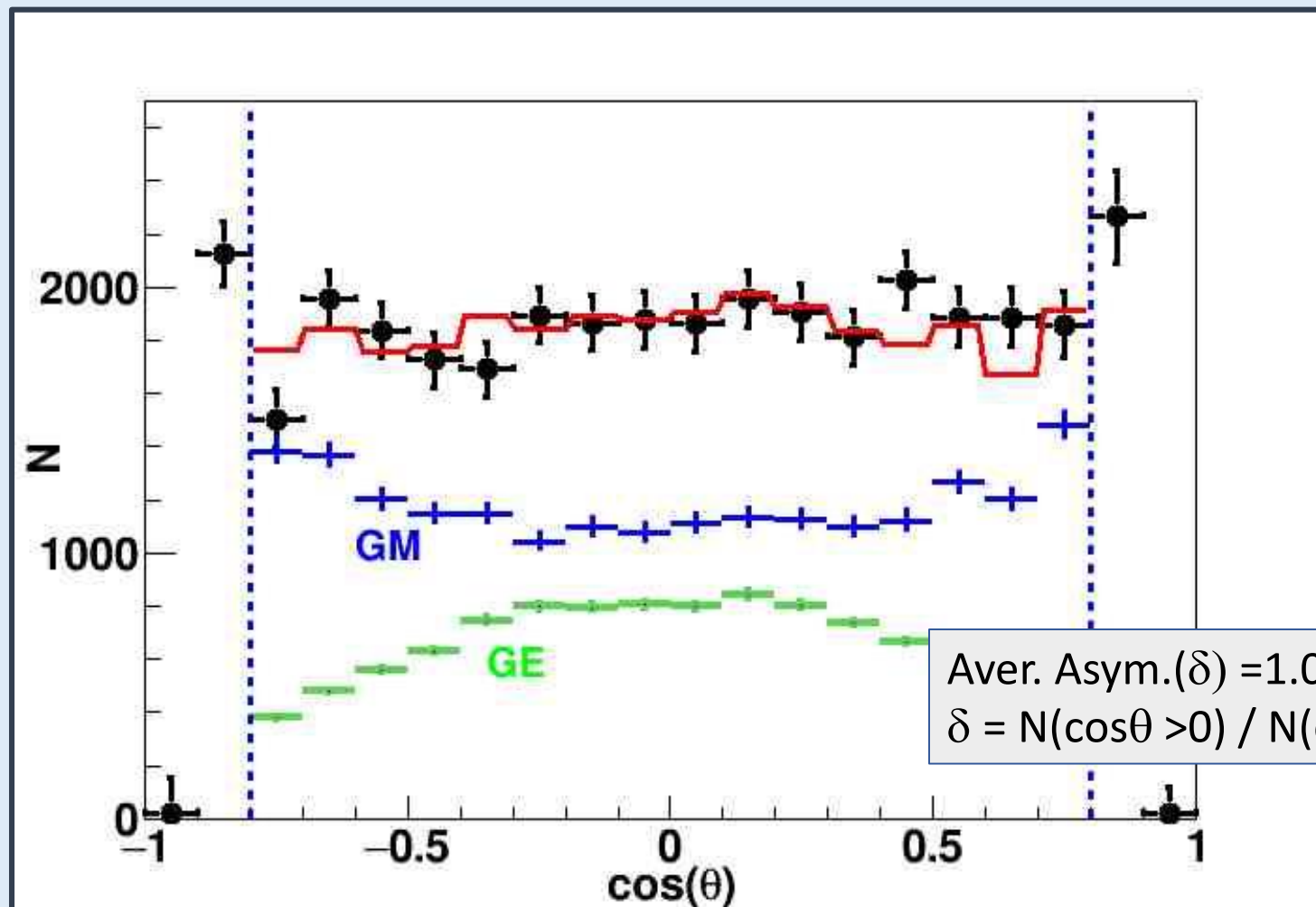
GE

$$H(x) = \text{par}[0] (H_{GM} + \text{par}[1] H_{GE})$$



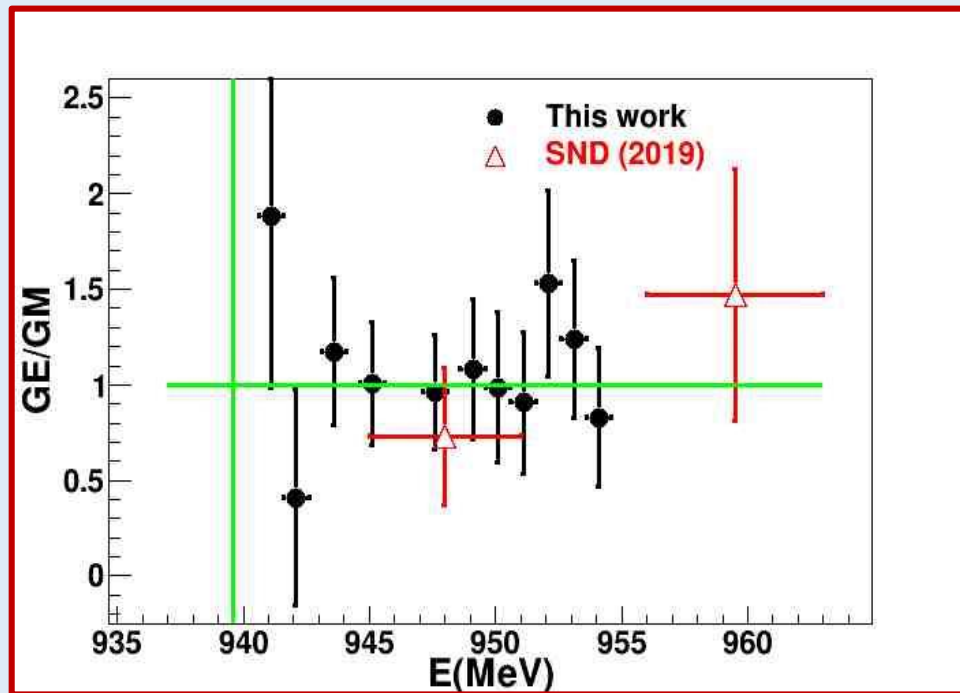
Summary fit by $\cos\theta$ for GE/GM

$E_{\text{beam}} = 941 \rightarrow 954 \text{ MeV}$, 11 energy points

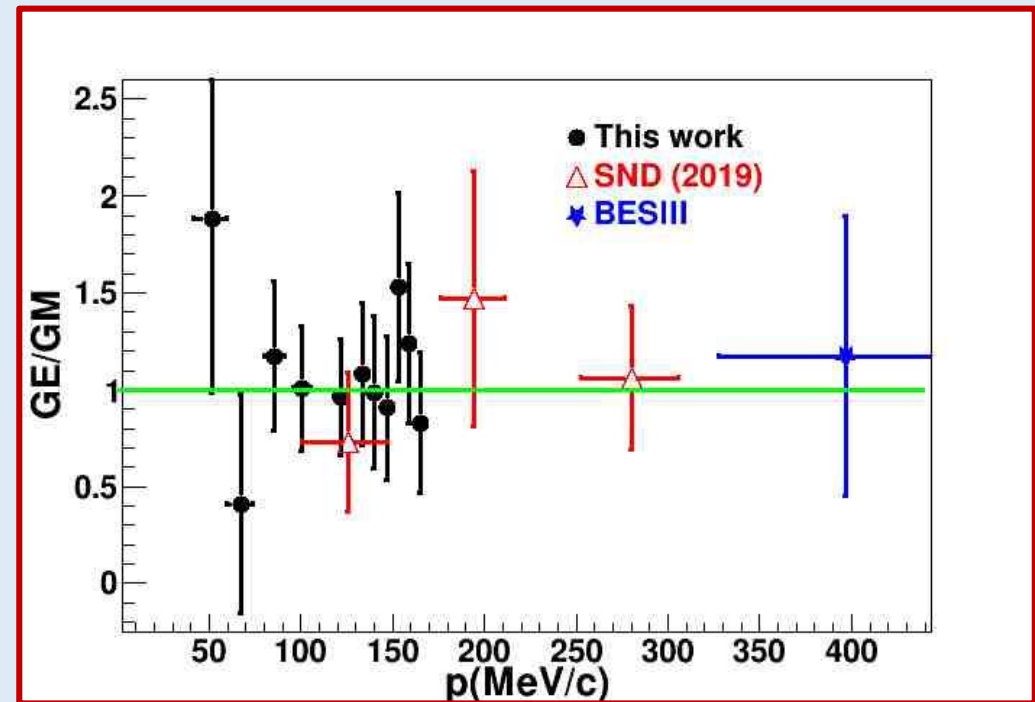


Measured GE/GM

GE/GM VS energy

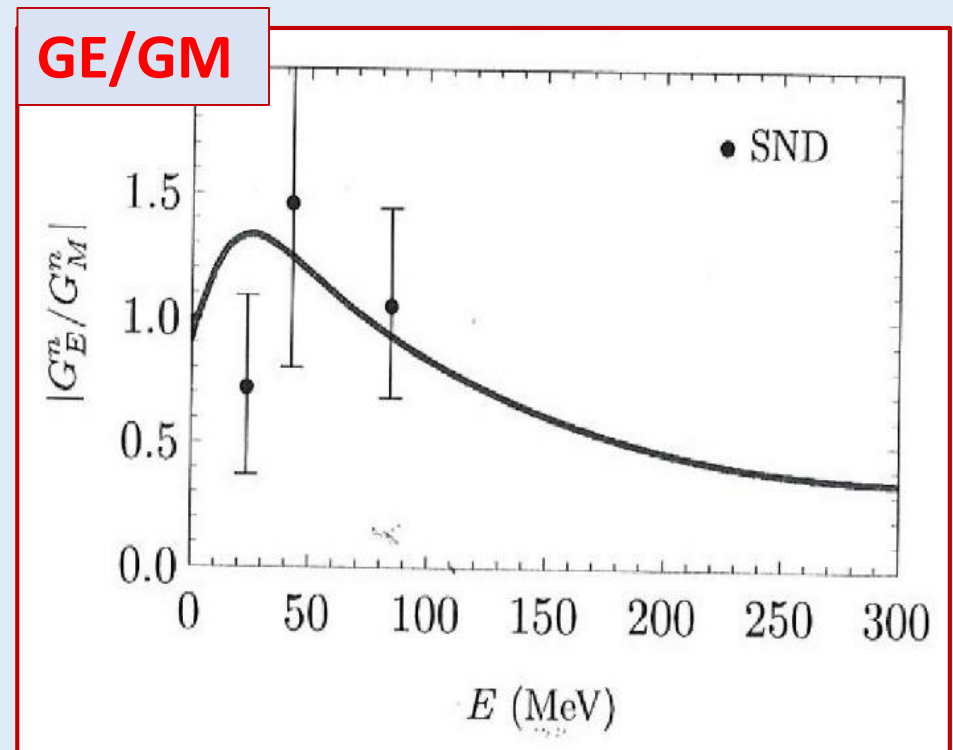
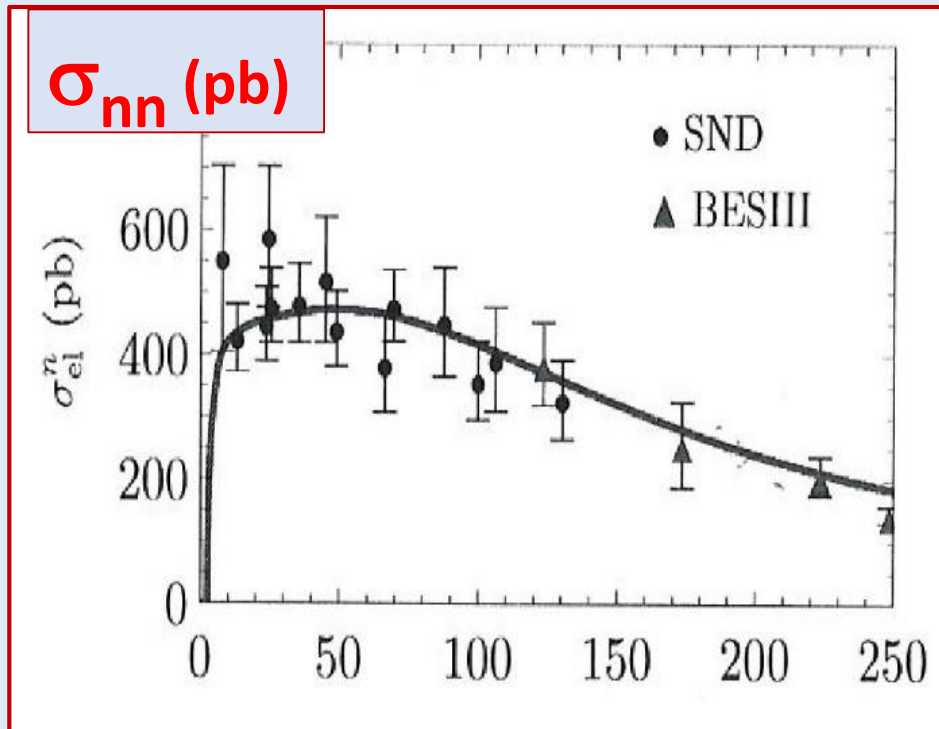


GE/GM VS momentum



Aver. $|GE/GM| = 1.028 \pm 0.114$ (stat)

Theoretical predictions - σ_{nn} , GE/GM



NN production in e^+e^- annihilation near the threshold
A. I. Milstein and S. G. Salnikov
Phys.Rev. D, 106, 074012 (2022)

Conclusions

1. Experiments are carried out at the VEPP-2000 e^+e^- collider to measure time like nucleon form factors at energies from the threshold to 2 GeV
2. At present, data have been accumulated with an integrated luminosity of about 180 pb^{-1} , about 10^4 $n+\text{anti-}n$ events have been registered, and 4 articles have been published.
3. The presented report presents the latest data on the study of the $e^+e^- \rightarrow n+\text{anti-}n$ process at energies from the threshold to $E=1910 \text{ MeV}$
4. The measured cross-section changes with energy within 0.4-0.6 nb. At the point closest to the threshold, the cross-section is about 0.4 nb.
5. The effective time-like form factor of the neutron decreases with energy. Its value at the threshold is about 0.5, at an energy of 2000 MeV – 0.15.
6. Preliminary results are presented on the ratio $|GE/GM|$ of the electric and magnetic timelike form factors of the neutron.

The work is supported by RNF grant : No. 23-22-00011 (PHΦ)

Thank you for hearing !

Spare slides

$e^+e^- \rightarrow N\bar{N}$ cross section

Differential cross section:

$$\sigma(e^+e^- \rightarrow B\bar{B}) = \frac{\alpha^2 \beta C^2}{4m^2} \left(|G_M|^2 (1 + \cos^2 \theta) + \frac{4m_B^2}{m^2} |G_E|^2 (1 - \cos^2 \theta) \right)$$

Total cross section:

$$\sigma(e^+e^- \rightarrow B\bar{B}) = \frac{4\pi \alpha^2 \beta C}{3m^2} \left(|G_M|^2 + \frac{2m_B^2}{m^2} |G_E|^2 \right)$$

Effective form factor

$$|F|^2 = \frac{|G_M|^2 + |G_E|^2 / 2\tau}{1 + 1/2\tau}, \quad \tau = \frac{m^2}{4m_B^2}$$

Two measurable values:

1 - effective FF,

2 - G_E/G_M

$C=1$ for neutrons

At threshold : $s=4m_B^2 \rightarrow |G_E| = |G_M| = |F|$

$F_n = -F_p / 2$

Asymptotic prediction: $F(+\infty) = -F(-\infty) \sim 1/s^2$

Selection of $n+\text{anti-}n$ events

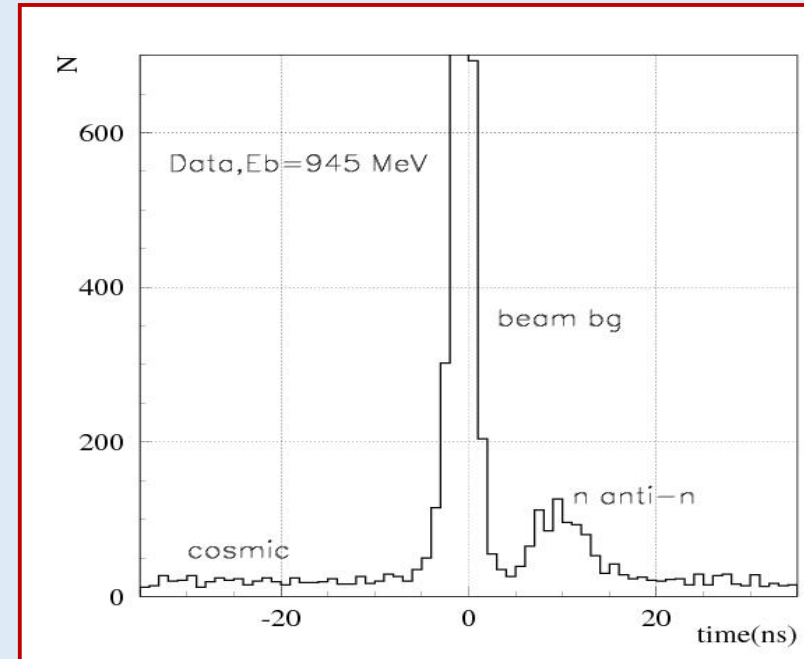
Selection conditions

(No tracks*, no photons*, no kinematic χ^2)

- 1 - veto μ system
- 2 - no cosmic track in EMC, incl. cosm. showers
- 3 - no charged tracks
- 4 - event momentum : $P > 0.2 E_{\text{beam}}$
- 5 - EMC energy : $E_{\text{tot}} > E_{\text{beam}}$
- 6 - photon χ^2 : > -2.5

Эффективность регистрации : $\varepsilon_{\text{EMC}} \sim 20\%$

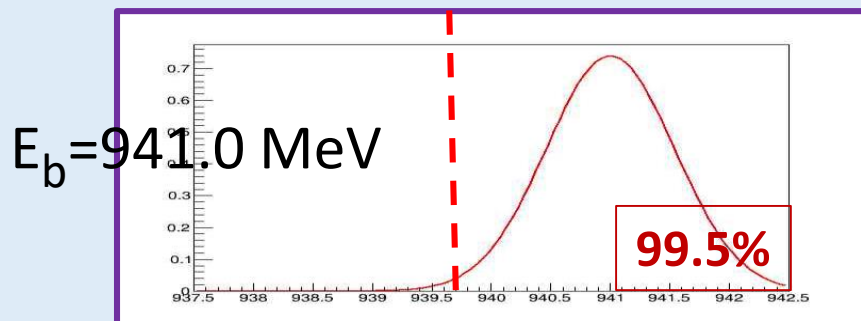
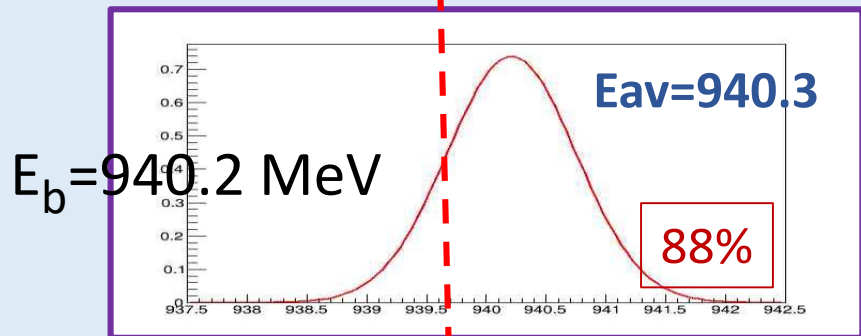
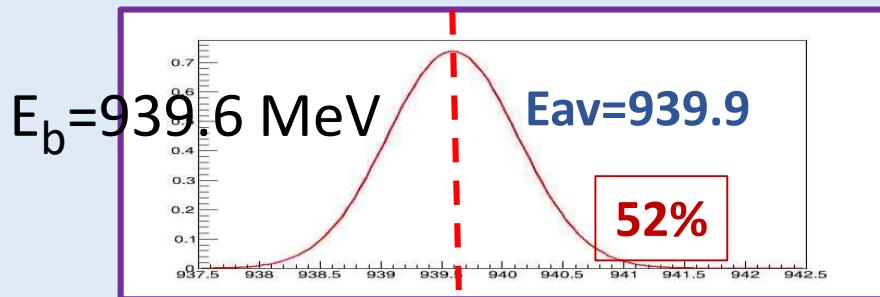
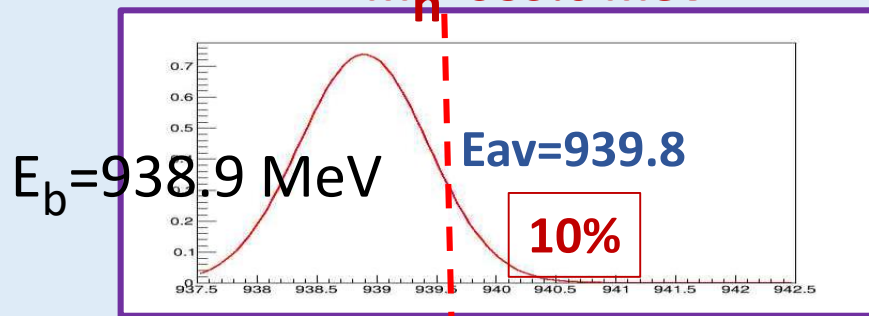
Time spectrum



Background:

- 1 – **КОСМ. ФОН** – плоский по времени,
- 2 -- **пучковый фон** - пик при $t=0$;
- 3 -- **физический фон** - $e+e- \rightarrow n\gamma(\text{QED}), \pi^0, \eta^0, \dots$

$M_n = 939.6 \text{ MeV}$



→ $E_b(\text{MeV})$

Пересечение нейтронного порога
при энергетическом разбросе
 $\sigma_E = 0.54 \text{ MeV}$

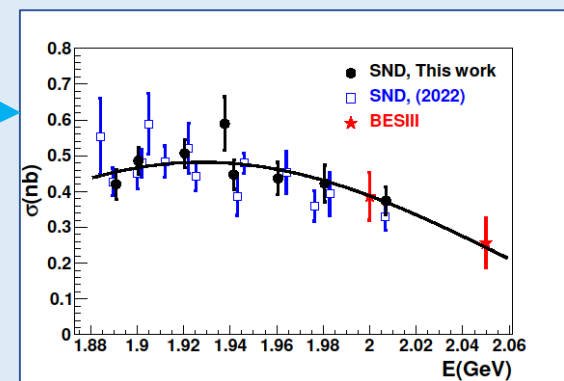
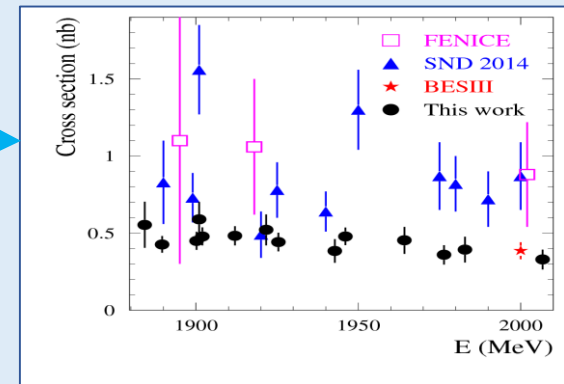
Предыдущие публикации по процессу $e^+e^- \rightarrow n \text{ anti-}n$

1. M.N. Achasov et al, European Physical Journal C 22, 761 (2022);
<https://doi.org/10.1140/epjc/s10052-022-10696-0>

----- Данные MHAD 2017, 2019 ----

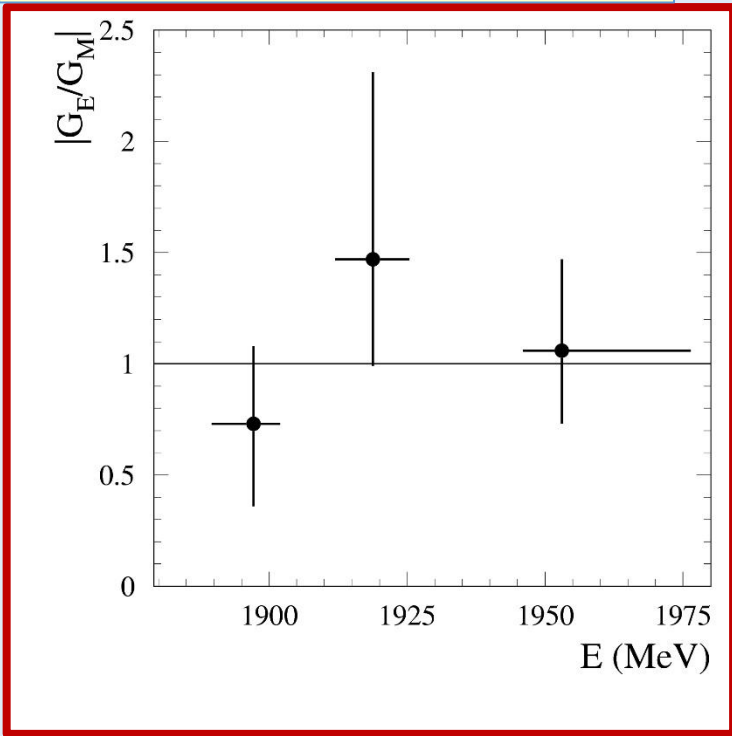
2. М.Н. Ачасов и др., Ядерная физика, 2023, т.86, No.6, с.672-680

----- Данные MHAD 2020, 2021 ----

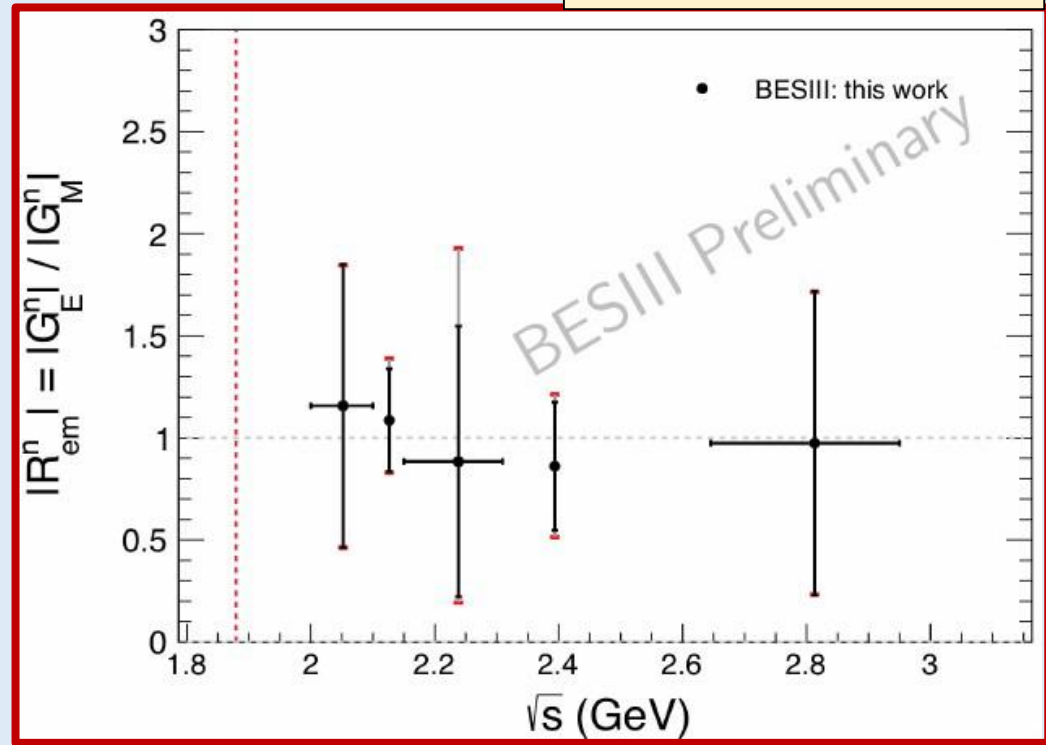


Existing data on timelike GE/GM

SND, 2023, 18 pb⁻¹, EPJC



BESIII, 355 pb⁻¹,



Предыдущие публикации по процессу $e^+e^- \rightarrow n \text{ anti-}n$

Совместная регистрации антинейтрона и нейтрона
в событиях $e^+e^- \rightarrow n + \text{anti-}n$ (MHAD 2017 data)

EPJ Web of Conferences 212 07007 (2019)

V.P. Druzhinin, S.I. Serednyakov

**Measurement of the $e^+e^- \rightarrow n \bar{n}$ cross section with the SND
detector at the VEPP-2000 collider**

<https://doi.org/10.1051/epjconf/201921207007>

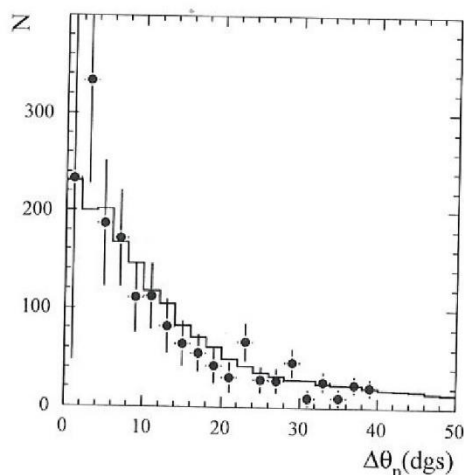
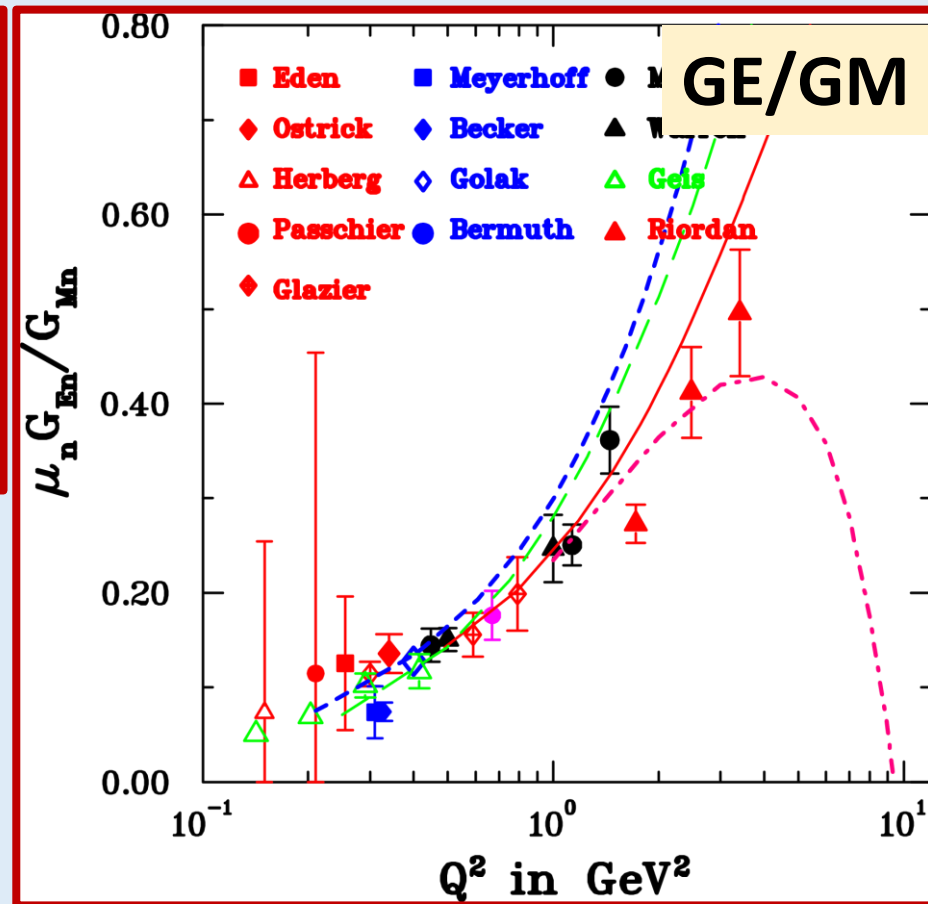
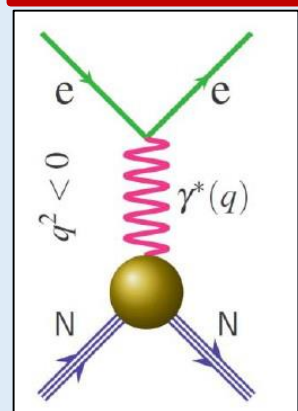
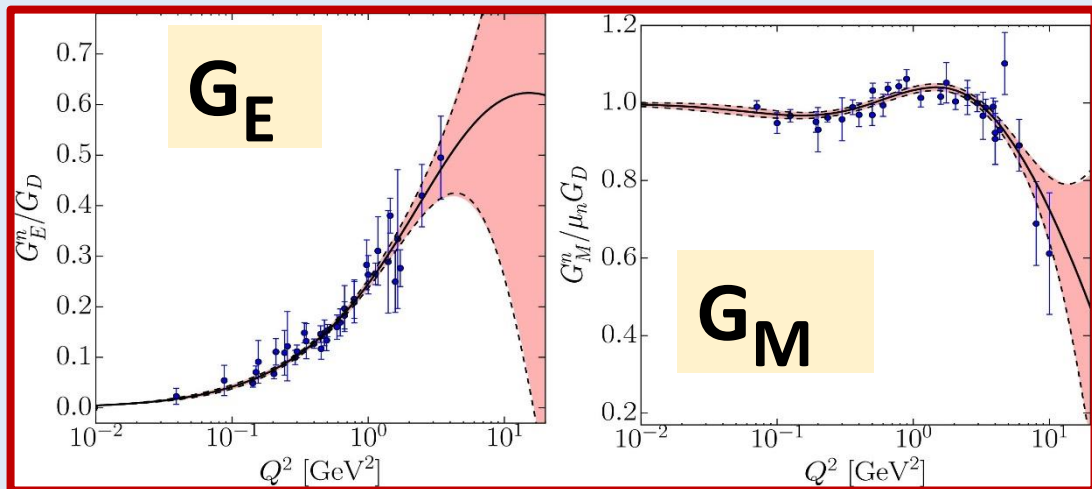


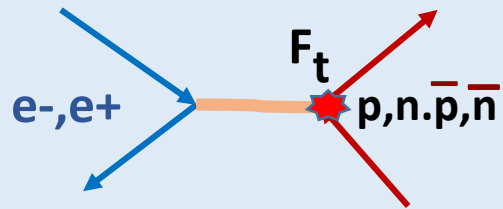
Figure 3. The distribution of the angle between the neutron-candidate direction and the reverse antineutron direction for data (points with error bars) and simulated (histogram) events.

The recoiled neutron can be also observed in EMC in the direction opposite to the antineutron direction as a photon or several photons. We construct the distribution of the angle between the photon direction and the expected neutron direction n for photons with energy greater than **20 MeV**. The n distribution for the energy range $E_b = 970-1000 \text{ MeV}$ is shown in Fig. 3. The peak in the distribution near zero is clearly seen. The data and simulated n distributions are in good agreement. The efficiency of the recoiled neutron detection is about **30%**.

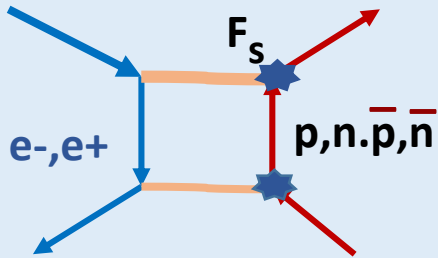
Существующие данные в пространственноподобной области



Возникновение зарядовой асимметрии



$$dN \sim A(1 + \alpha \cos \theta) d\cos \theta$$



Угловое распределение антинейтронов,
 $E_b = 990 \text{ MeV}$ (MHAD2021)

