

# Сессия-конференция СЯФ ОФН РАН

10-13 March 2026

**Измерение отношения  $|GE|/|GM|$  электрического и магнитного временеподобных формфакторов нейтрона на  $e+e$ - коллайдере ВЭПП-2000**

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**СО РАН**



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

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

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

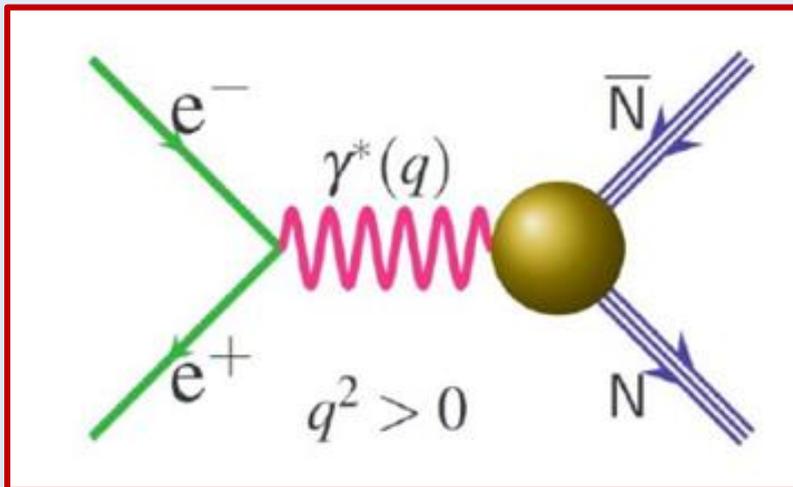
$$P = (-1)^{L+1} = -1, \quad L=0,2$$

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

S, D – waves,

two form factors

e.g.  $G_E, G_M$

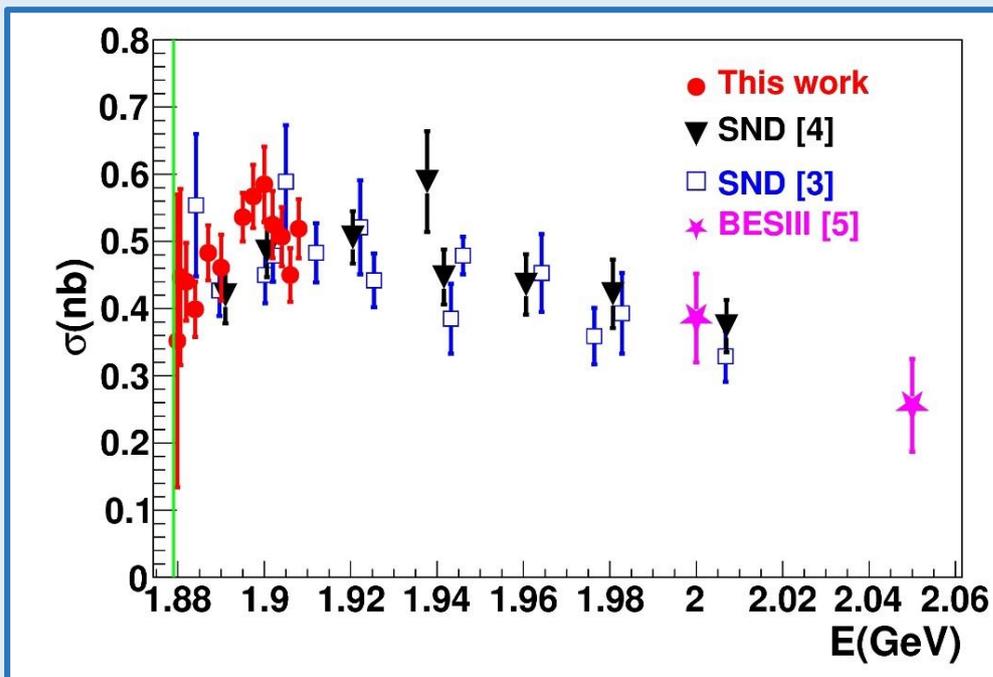


$B$  – baryon =  $p, n$  ;  
 $m = 2E_b$  – cms energy ;  
 $\beta$  – nucleon velocity,  
 $\theta$  – polar angle;  
 $m_b$  – nucleon mass ;  
 $G_E, G_M$  - form factors

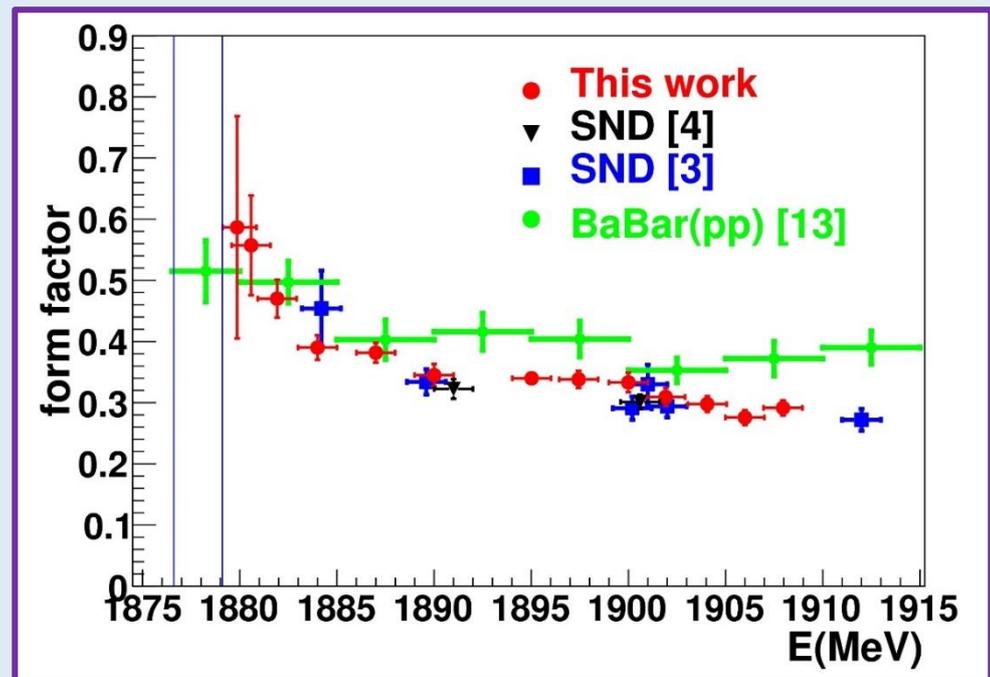
$G_E, G_M$  = электрический и магнитный формфакторы нейтрона

# Recent SND $n\bar{n}$ measurements

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



## Neutron timelike eff. formfactor

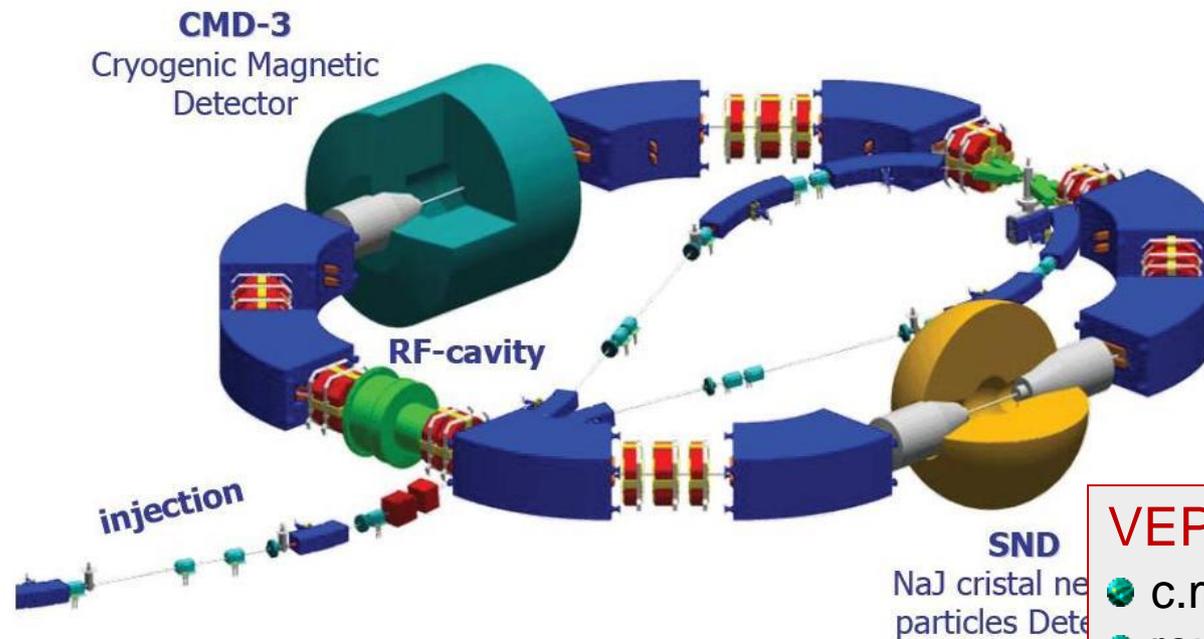


$$|F|^2 = \frac{|G_M|^2 + |G_E|^2 / 2\tau}{1 + 1/2\tau}, \quad \tau = \frac{m^2}{4m_B^2}$$

F - effective formfactor

## Коллайдер ВЭПП-2000

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



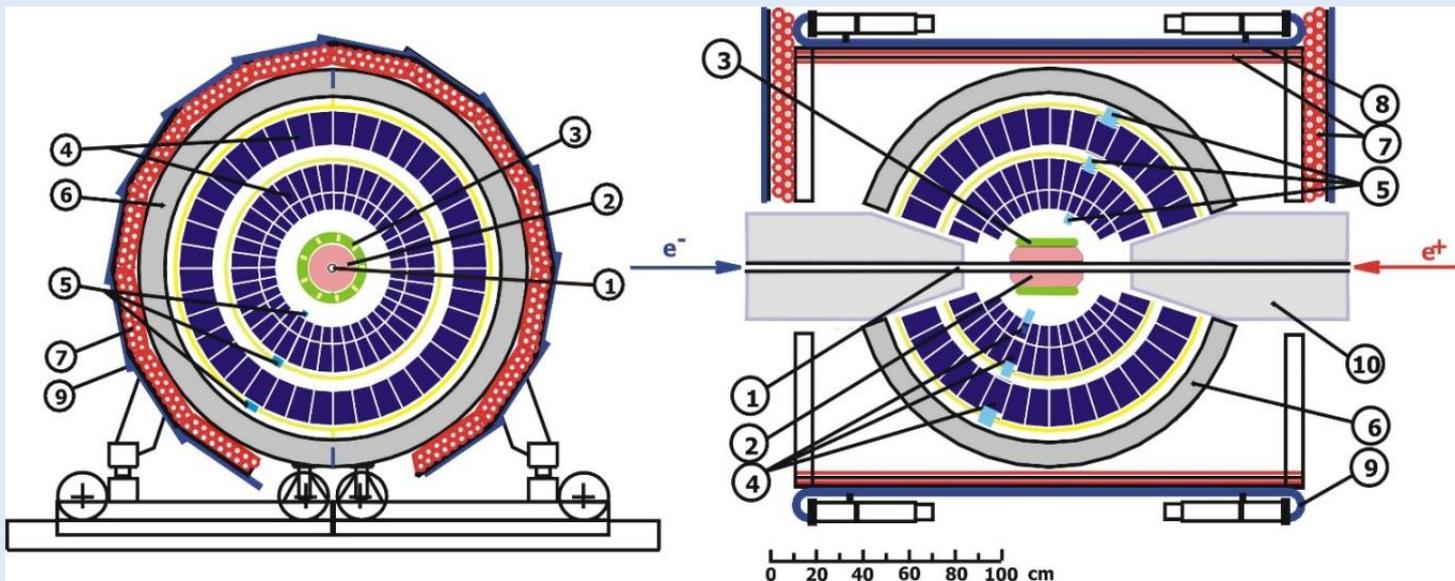
#### VEPP-2000 parameters:

- 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)

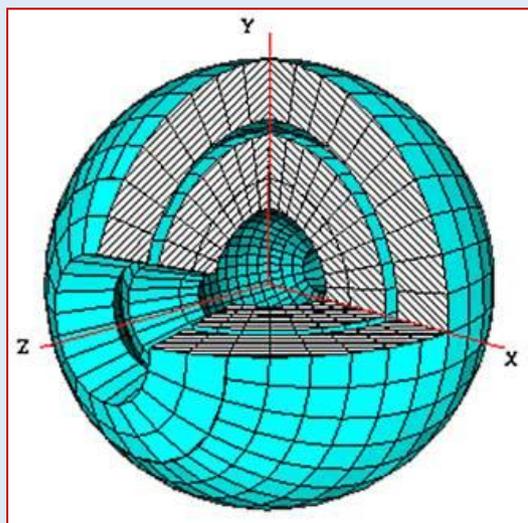
**В работе – с 2010 года  
(since 2010)**



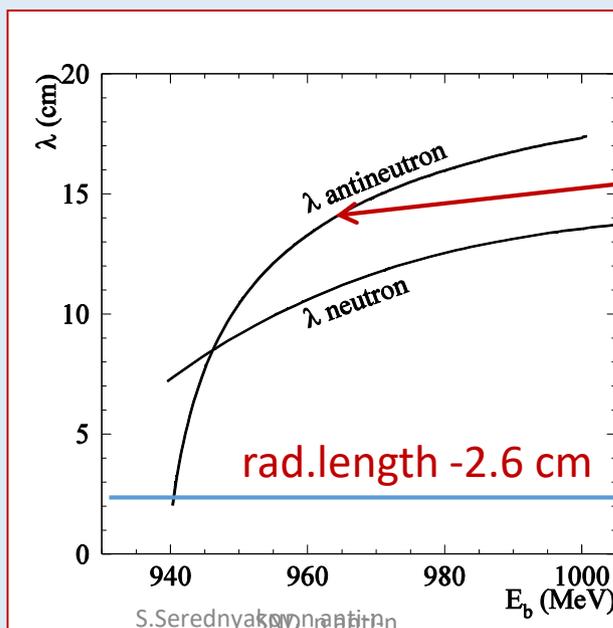
# SND detector (since 1995)



- 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



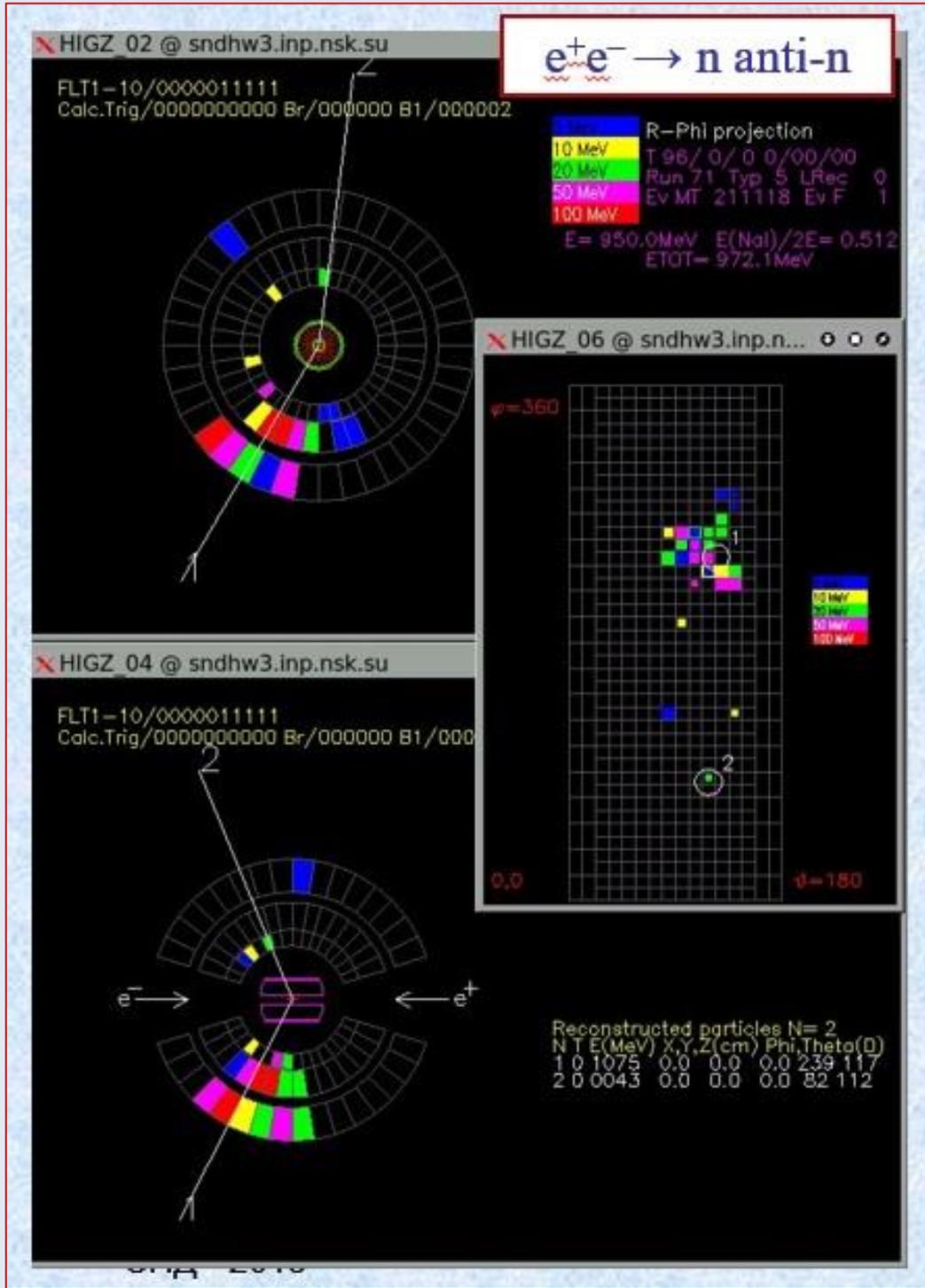
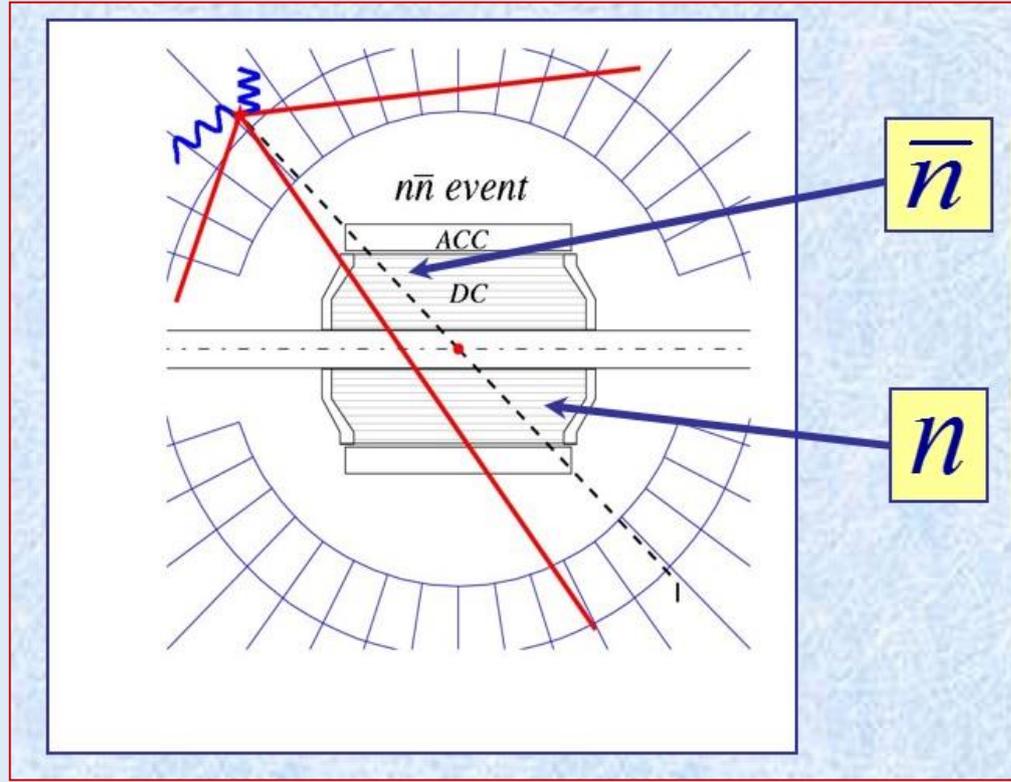
Solid angle - 95%  $4\pi$



Attenuation length

**SND – good antineutron detector**

# Typical view nn - events



## Экспериментальные данные (experimental data)

Эксперимент 2020 - 2021 гг.  
область выше порога  $e^+e^- \rightarrow n \text{ anti-n}$

$$E_{\text{beam}} =$$

**939.6**, 945.5, 950.3, 960.3, 968.8, 970.8, 980.3, 990.4, 1003.5 MeV

  
порог

$$\Delta L = 83 \text{ 1/pb}$$

8 точек по энергии

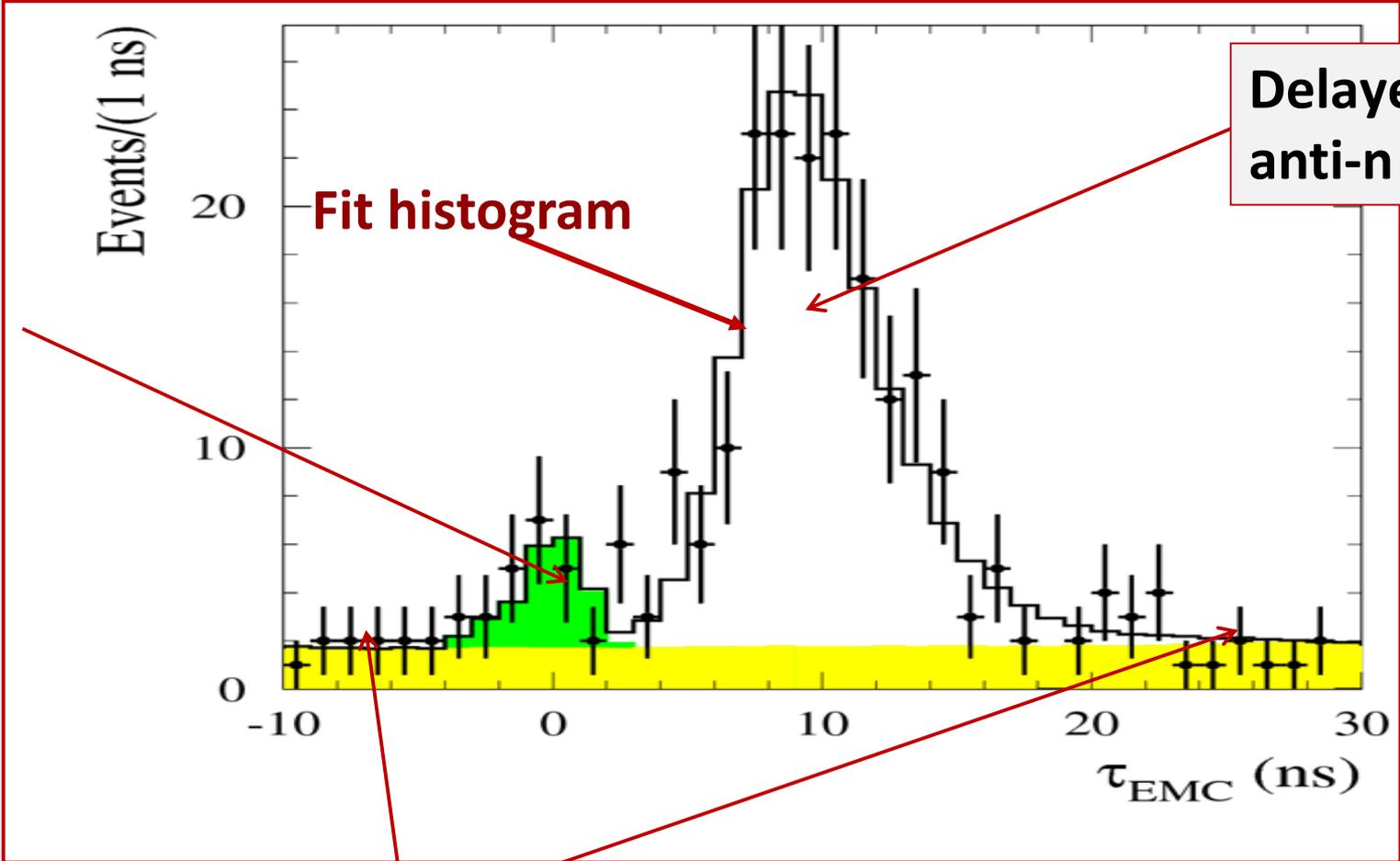
Публикация по измерению сечения:  
Ядерная физика, 2023, т.86, N6, с.664-671  
Грант РФФ : No. 23-22-00011

# Выделение нейтронов по задержке времени

## 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

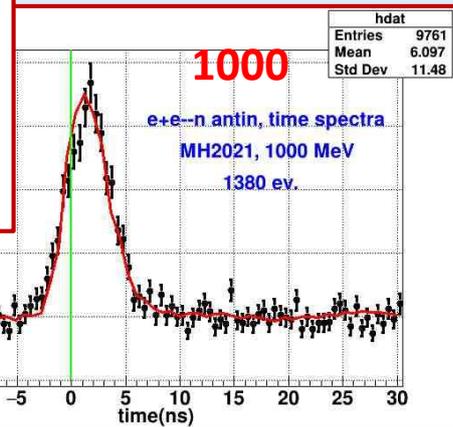
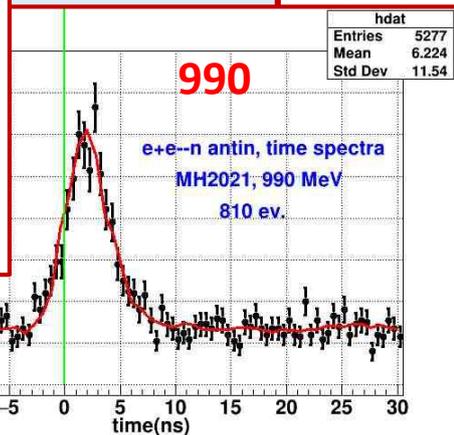
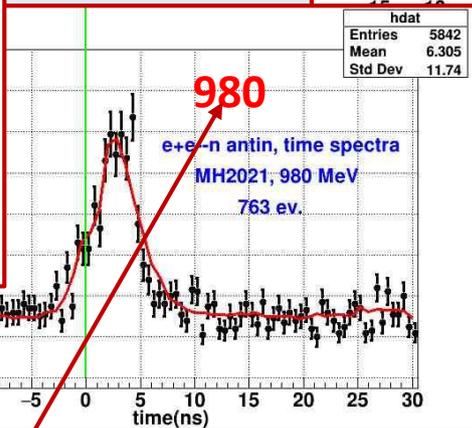
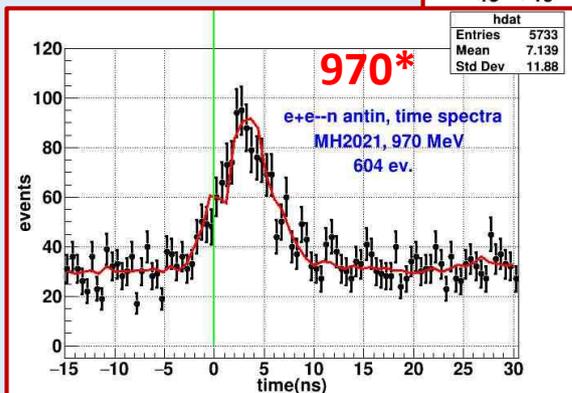
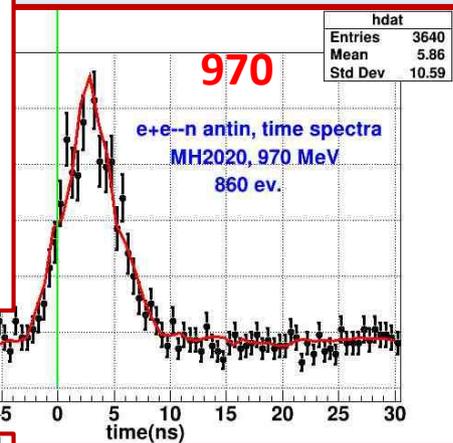
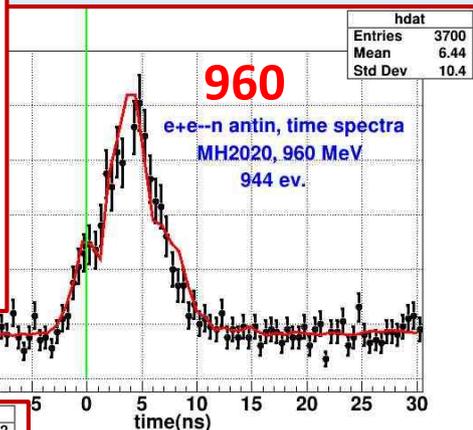
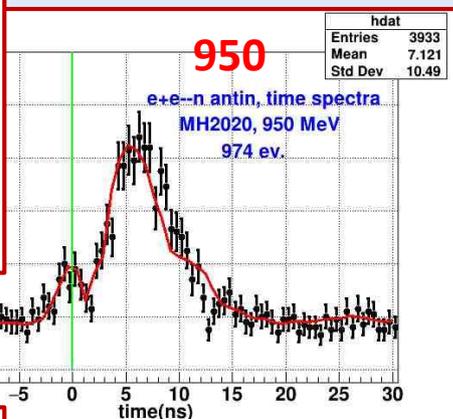
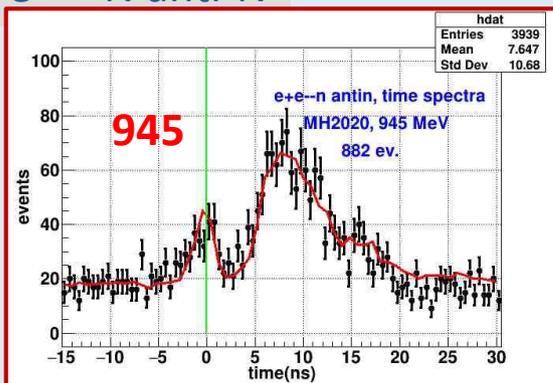


Delayed  
anti-n signal

Cosmic bkg

# Time spectra n+anti-n MHAD2020,-2021

Fit shown by red line

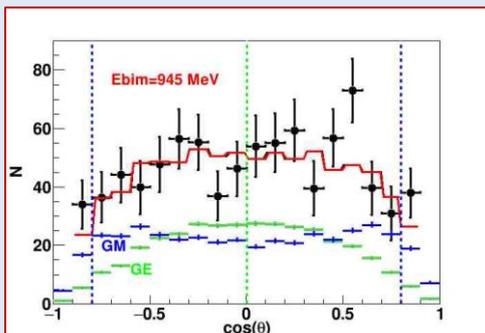


Beam energy (MeV)

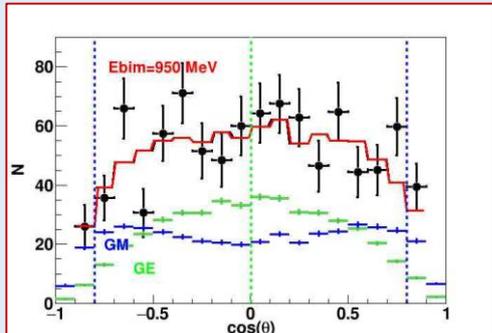
# Угловые распределения $n+\text{anti-n}$ по $\cos \theta$

Fit shown by red line

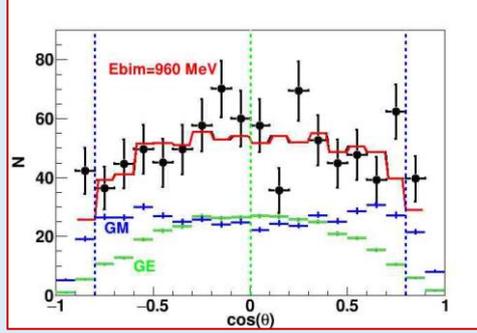
**Eb=945**



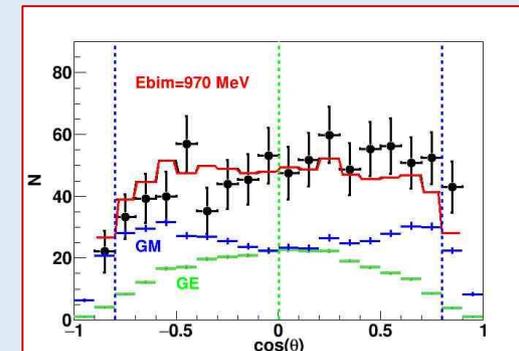
**Eb=950**



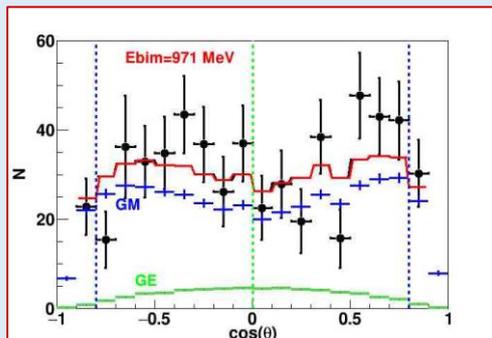
**Eb=960**



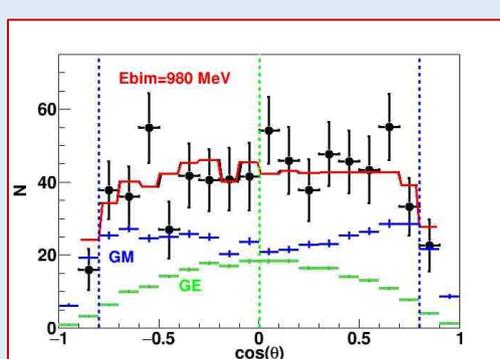
**Eb=970**



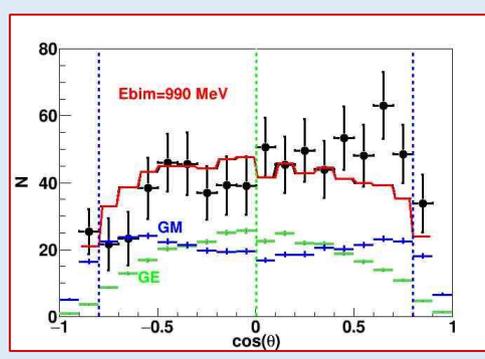
**Eb=970**



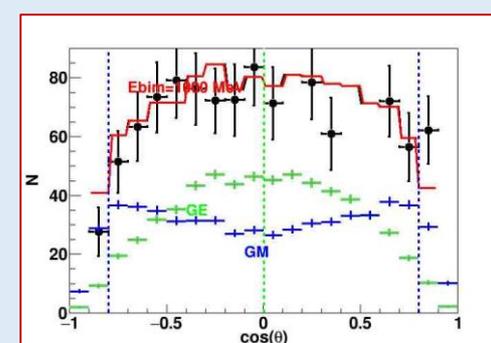
**Eb=980**



**Eb=990**



**Eb=1009**



# Определение GE/GM из углового распределения вылета нейтронов

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

На пороге  
 $|G_E| = |G_M|$

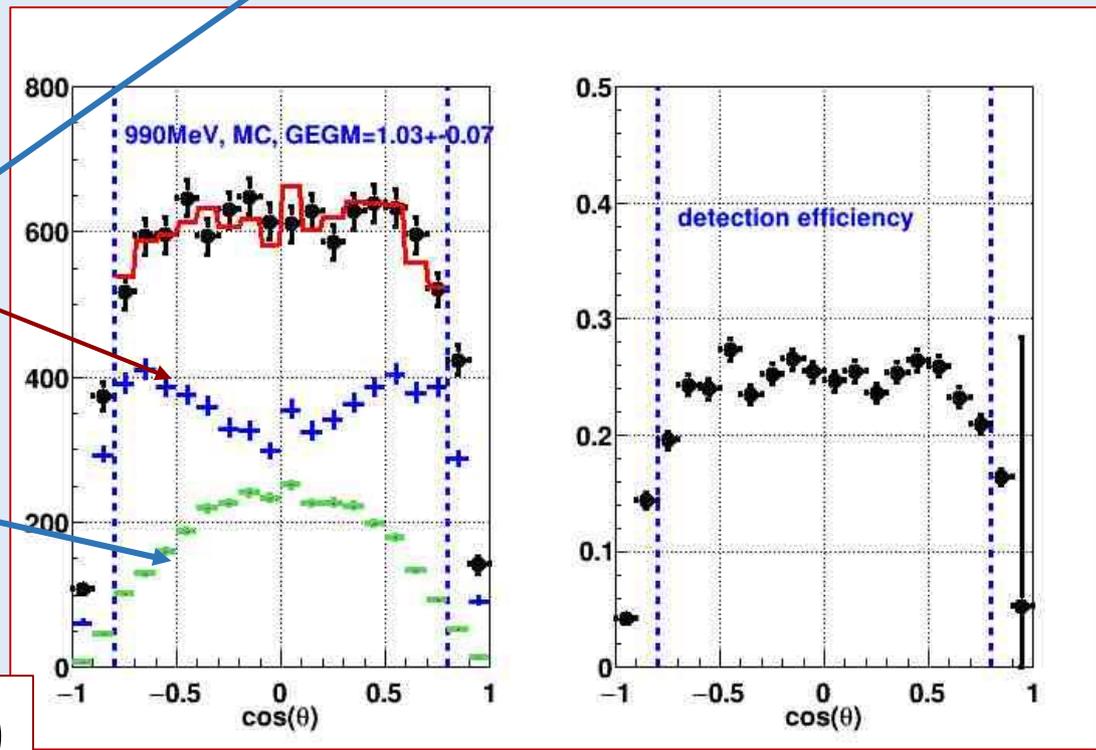
$N(GM) = 2 N(GE) !$

$H_{GM}$

$H_{GE}$

**Fit function  $H(x)$ : ( $x = \cos\theta$ )**  
 $H(x) = \text{par}[0] (H_{GM} + \text{par}[1] H_{GE})$

$\text{par}[1] \sim |GE/GM|^2$



## Таблица результатов

$N$	$E_b$	$p$	$L$	$N_{nn}$	$ G_E / G_M $
1	945.5	51	9.38	882+-41	1.321+-0.401+-0.099
2	950.3	67	9.44	978+-40	1.473+-0.388+-0.184
3	960.3	86	9.17	962+-38	1.371+-0.332+-0.225
4	968.8	101	8.78	909+-38	1.122+-0.293+-0.139
5	970.8	122	5.99	625+-37	0.523+-0.440+-0.203
6	980.3	133	8.17	764+-37	1.064+-0.337+-0.151
7	990.4	140	9.40	811+-39	1.352+-0.398+-0.306
8	1003.5	147	22.5	1562+-61	1.530+-0.340+-0.115

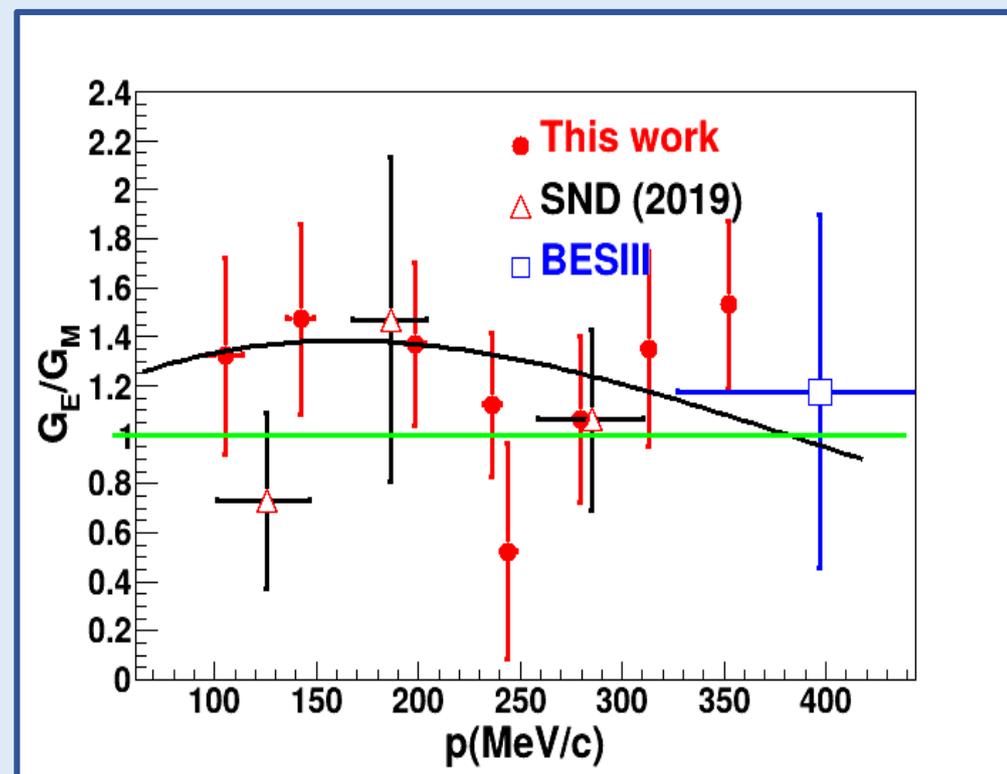
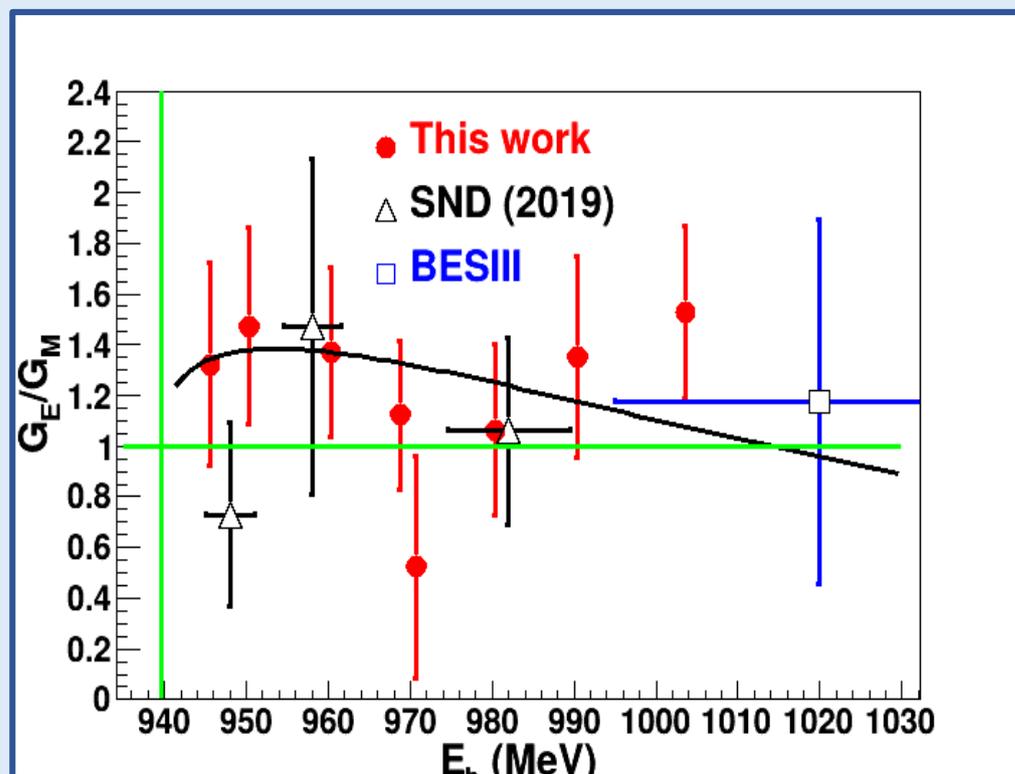
Энергия  
(МэВ)

Импульс  
(МэВ/с)

Светимость  
1/pb

Число  
событий

$G_E/G_M$  – stat – syst err

Результаты измерения  $G_E/G_M$ 

Среднее значение  $G_E/G_M = 1.21 \pm 0.13$

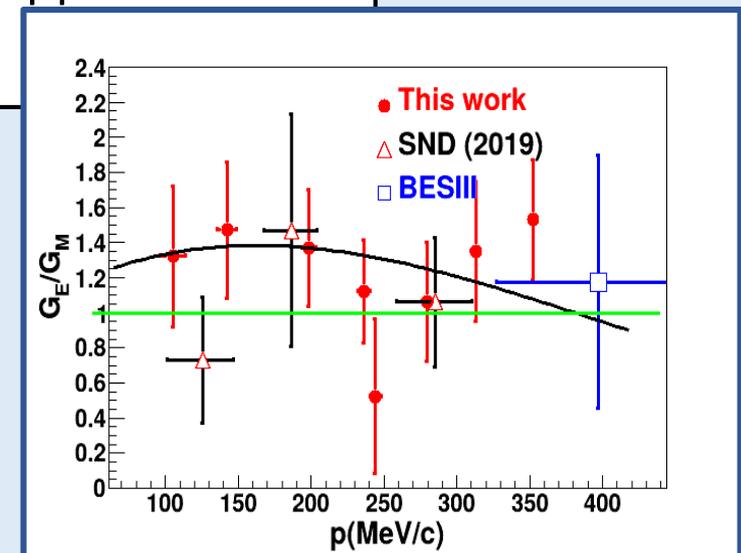
Сравнение с моделью: Milstein, Salnikov *Phys.Rev.D*, 106 (2022) 7, 074012

## Систематические неточности

1. Условие отсутствия треков в дрейфовой камере  $\sim 0.06$
  2. Условие на поперечный размер кластера в калориметре  $\sim 0.11$
  3. Вариации временного спектра физического фона  $\sim 0.08$
  4. Влияние асимметрии в угловом распределении  $\sim 0.11$
- Total : 0.10 – 0.30

# Заключение

1. Проведен эксперимент на коллайдере ВЭПП-2000 в 2020-2021 гг. по изучению процесса  $e^+e^- \rightarrow n \text{ anti-n}$
2. Измерения проводились вблизи порога процесса в 8 точках по энергии с интегральной светимостью 83 1/пб. Зарегистрировано около 10 тыс. событий  $n \text{ anti-n}$
3. По распределению  $\cos\theta$  антинейтронов определялась величина  $|G_E|/|G_M|$  - отношение электр. и магн. формфакторов нейтрона.
4. Измеренная величина  $|G_E|/|G_M|$  находится в пределах 1.0 – 1.5, точность измерения  $\sim 0.3-0.4$ . Среднее  $1.21 \pm 0.13$ .



**Спасибо за внимание !**

# Backups

## $e^+e^- \rightarrow N\bar{N}$ 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:  $F(+\infty) = -F(-\infty) \sim 1/s^2$

# Выделение $n$ anti- $n$ событий

## Условия отбора

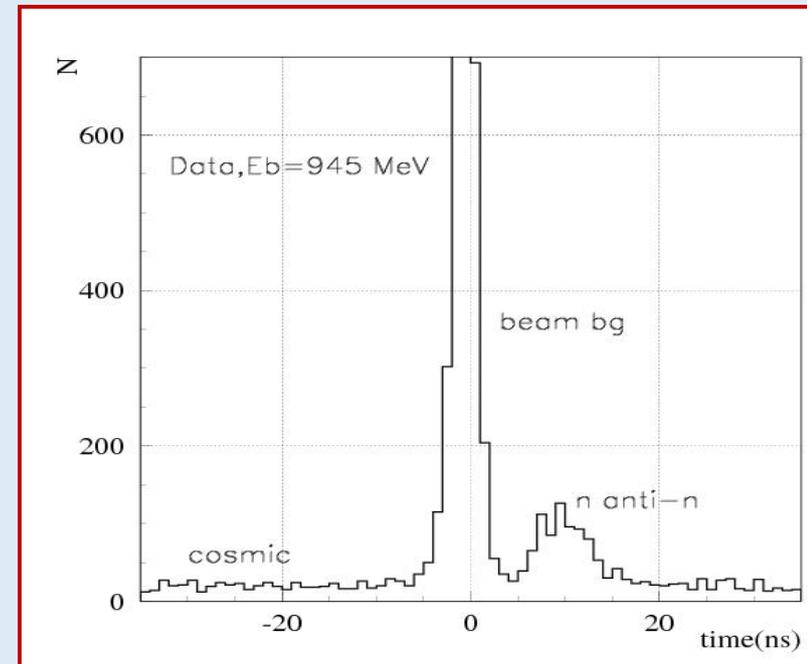
(No tracks\*, no photons\*, no kinematic  $\chi^2$ )

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

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Эффективность регтстрации :  $\epsilon_{MC} \sim 20\%$

## Временной спектр

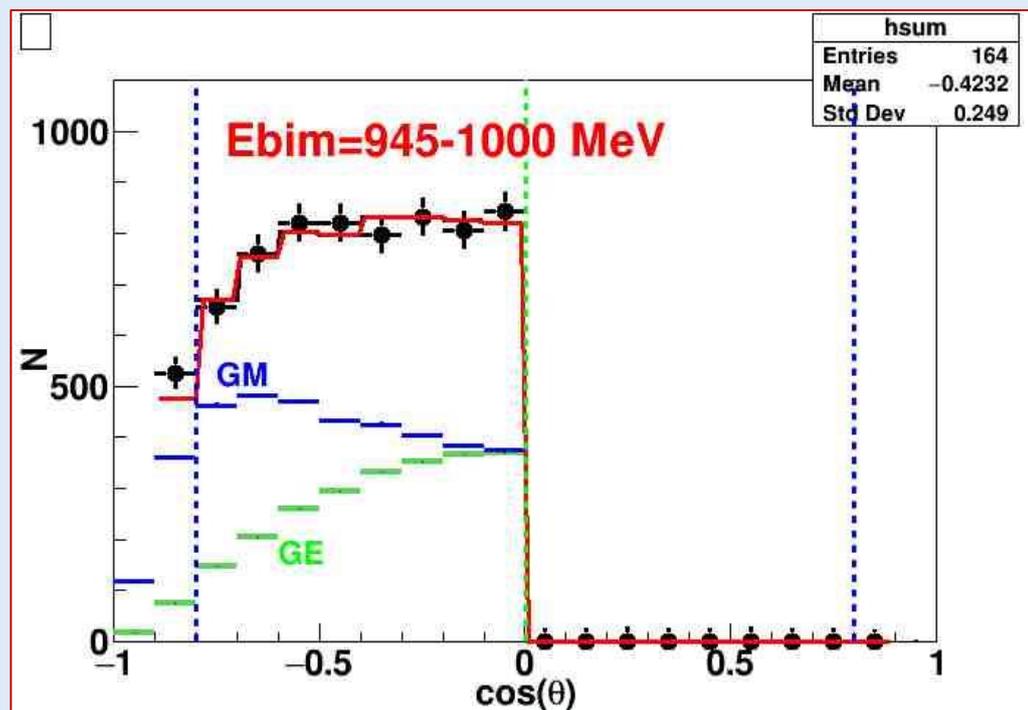
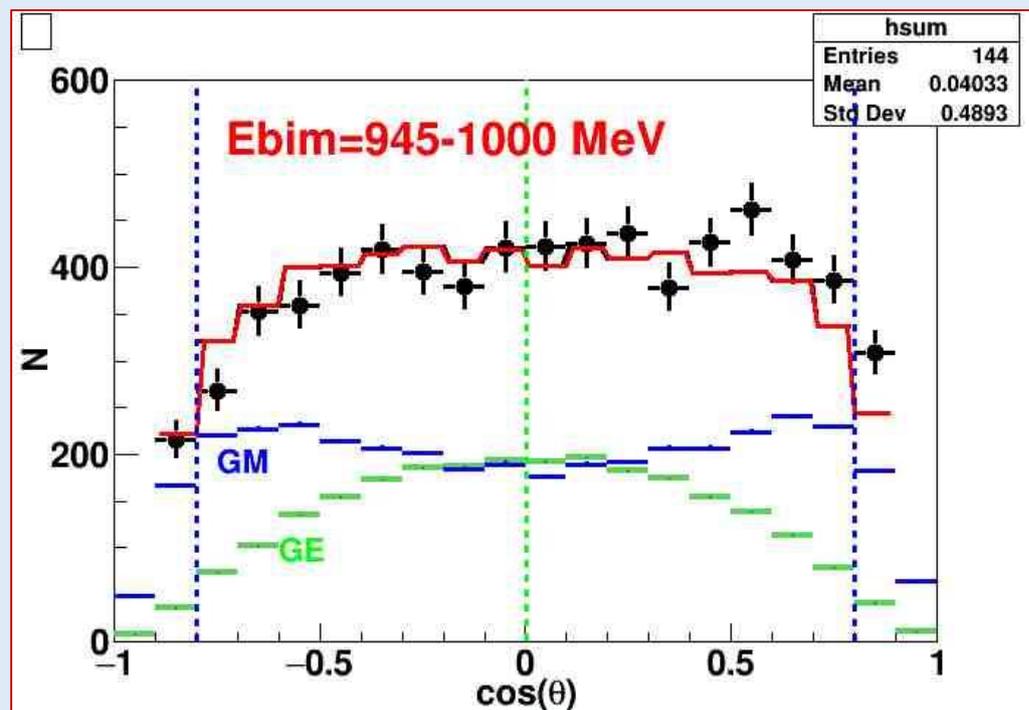


## Источники фона:

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

# Гистограммы по $\cos\theta$ для GE/GM по сумме всех энергий МНАД 2020,-2021

## Свернутая гистограмма

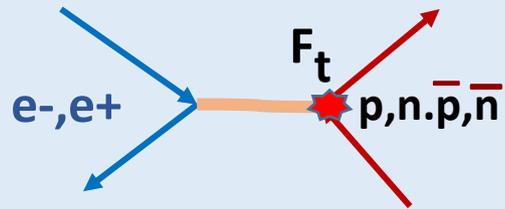


$$GE/GM = 1.221 \pm 0.118$$

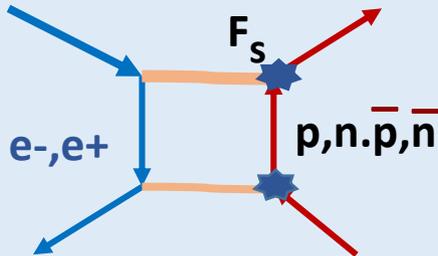
$$GE/GM = 1.184 \pm 0.116$$

$$\text{Syst. } \delta = -3.1\%$$

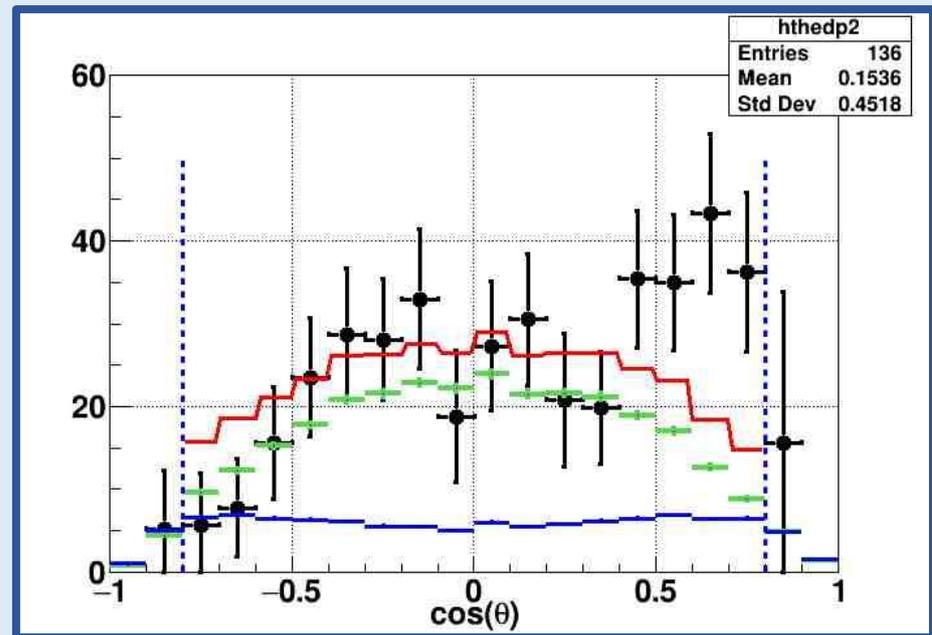
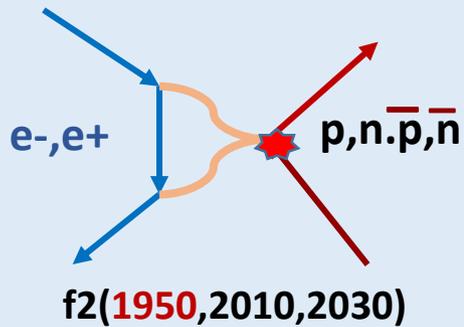
# Возникновение зарядовой асимметрии (В.Др.)



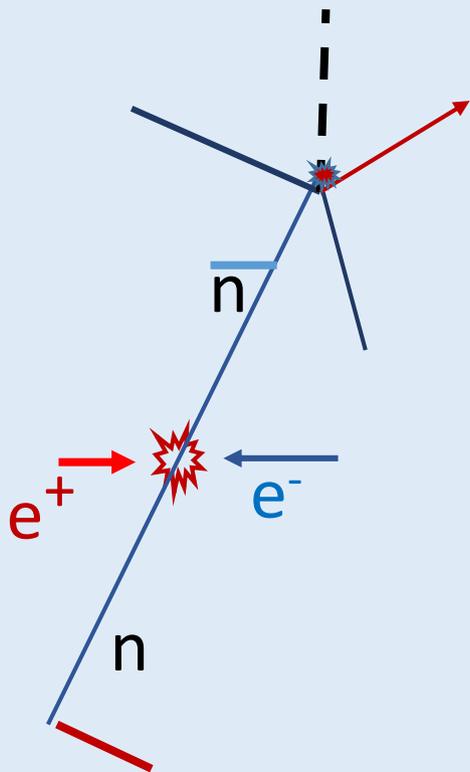
$$dN \sim A(1 + \alpha \cos \theta) d\cos \theta$$



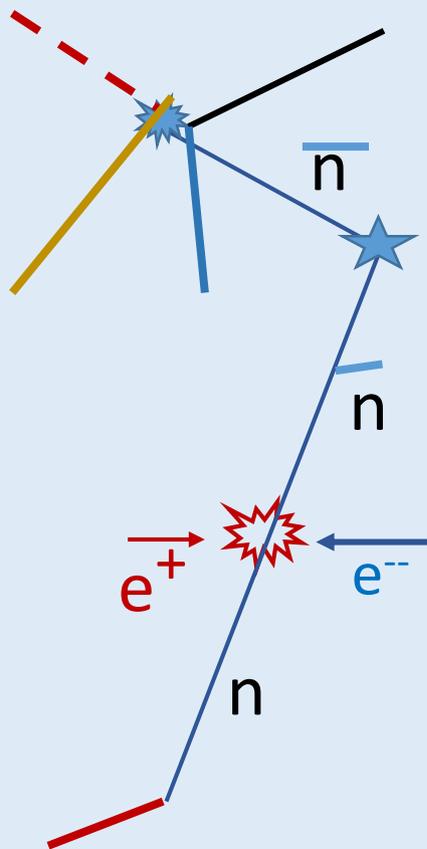
Угловое распределение антинейтронов,  
 $E_b = 990 \text{ MeV}$  (MHAD2021)



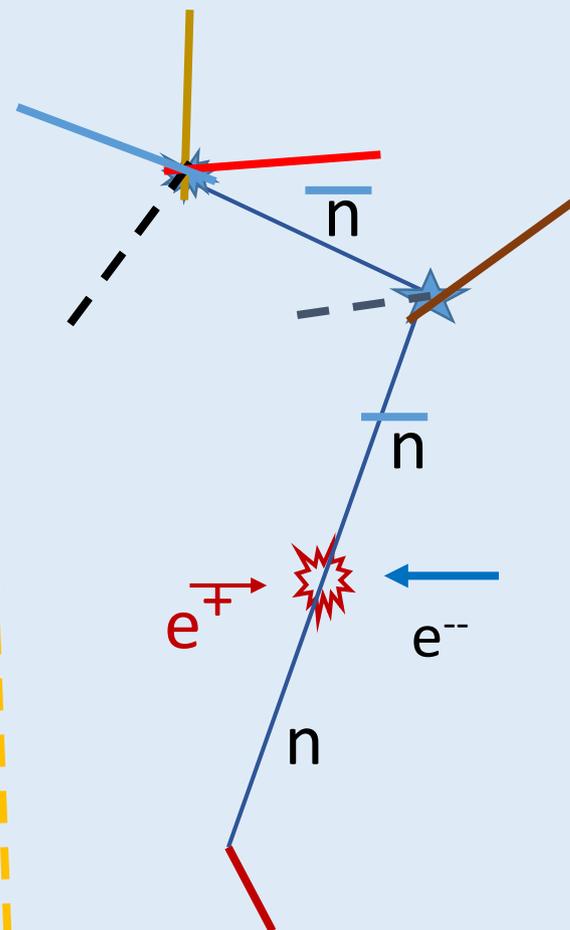
# Три вида первого взаимодействия антинейтрона в детекторе



1 - аннигиляция

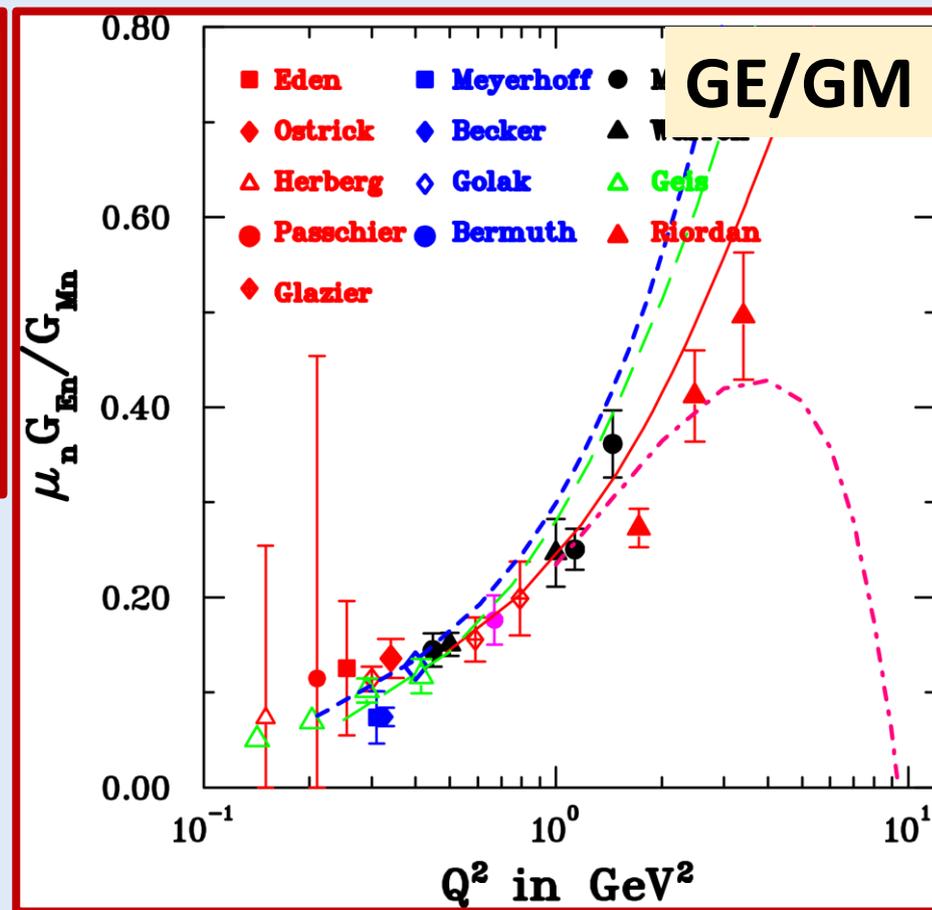
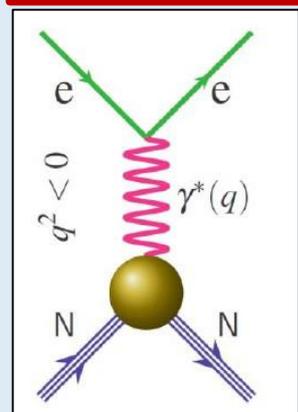
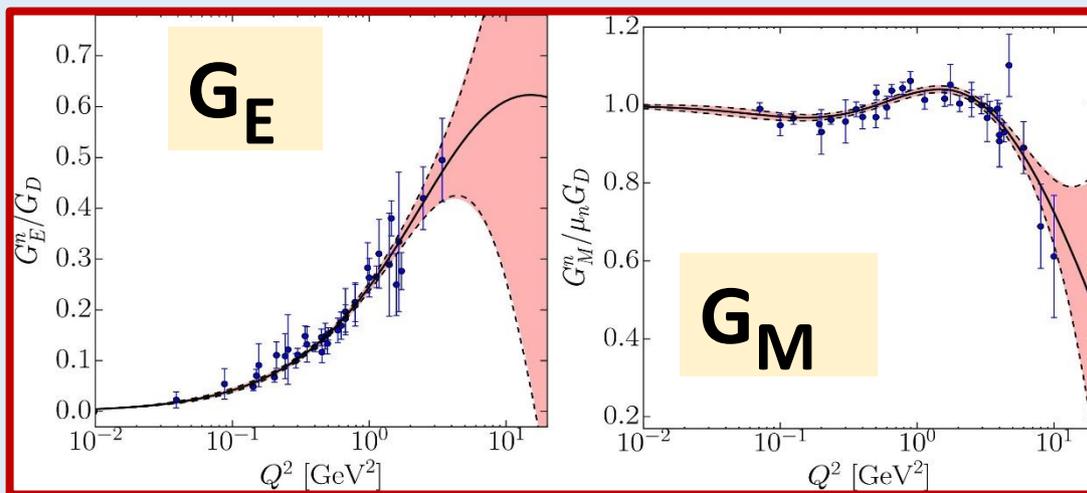


2 – упр. рассеяние + аннигиляция



3 – неупр. рассеяние + аннигиляция

# Экспериментальные данные для формфактора нейтрона в пространственно-подобной области



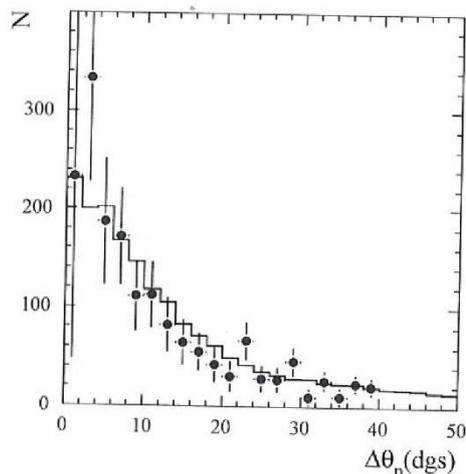
# Совместная регистрации антинейтрона и нейтрона в событиях $e^+e^- \rightarrow n + \text{anti-n}$ (Run 2017 data)

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%**.

## Недавние публикации СНД по процессу $e^+e^- \rightarrow n \text{ anti-n}$

[1] M. N. Achasov et al. (SND Collaboration), Eur. Phys. J. C (2022:82:761). <http://doi.org/10.1140/epjc/s10052-022-10696-0>, e-Print:2206.13047[hep-ex]

[2] M. N. Achasov et al. (SND Collaboration), Phys. Part Nucl. 54 No.4, 624 (2023)

[3] M. N. Achasov et al. (SND Collaboration), Phys. Atomic Nucl. 86 No.6, 1165 (2023). e-Print:2309.05241[hep-ex]

[4] M. N. Achasov et al. (SND Collaboration), Phys. Atomic Nucl. 87 No.5, 604 (2024) e-Print:2407.15308[hep-ex]

