LXXV Международная конференция «ЯДРО-2025. Физика атомного ядра и элементарных частиц. Ядерно-физические технологии»

Измерение электромагнитных временноподобных формфакторов нейтрона и протона на e+e- коллайдере ВЭПП-2000 с детектором СНД

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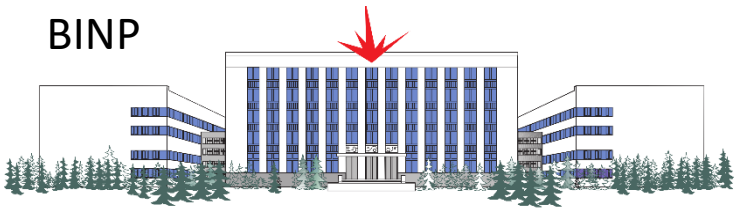
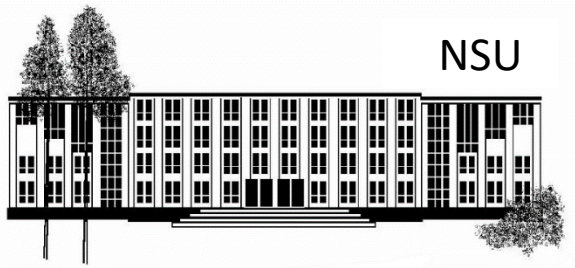
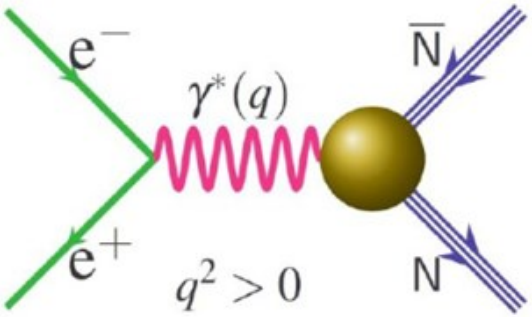




$e^+e^- \to n\bar{n}/p\bar{p}$ annihilation



$N = n, p$: $I(J^p) = 1/2\,(1/2^+)$

$N\bar{N}$: $J^{PC} = 1^{--} \implies S, D$

A spin-$\frac{1}{2}$ particle $\implies$ two EM FFs $G_E(q^2)$ and $G_M(q^2)$

$$\sigma(e^+e^- \to n\bar{n}) = \frac{4\pi\alpha^2\beta C}{3s}\left(|G_M|^2 + \frac{2m_n^2}{s}|G_E|^2\right)$$

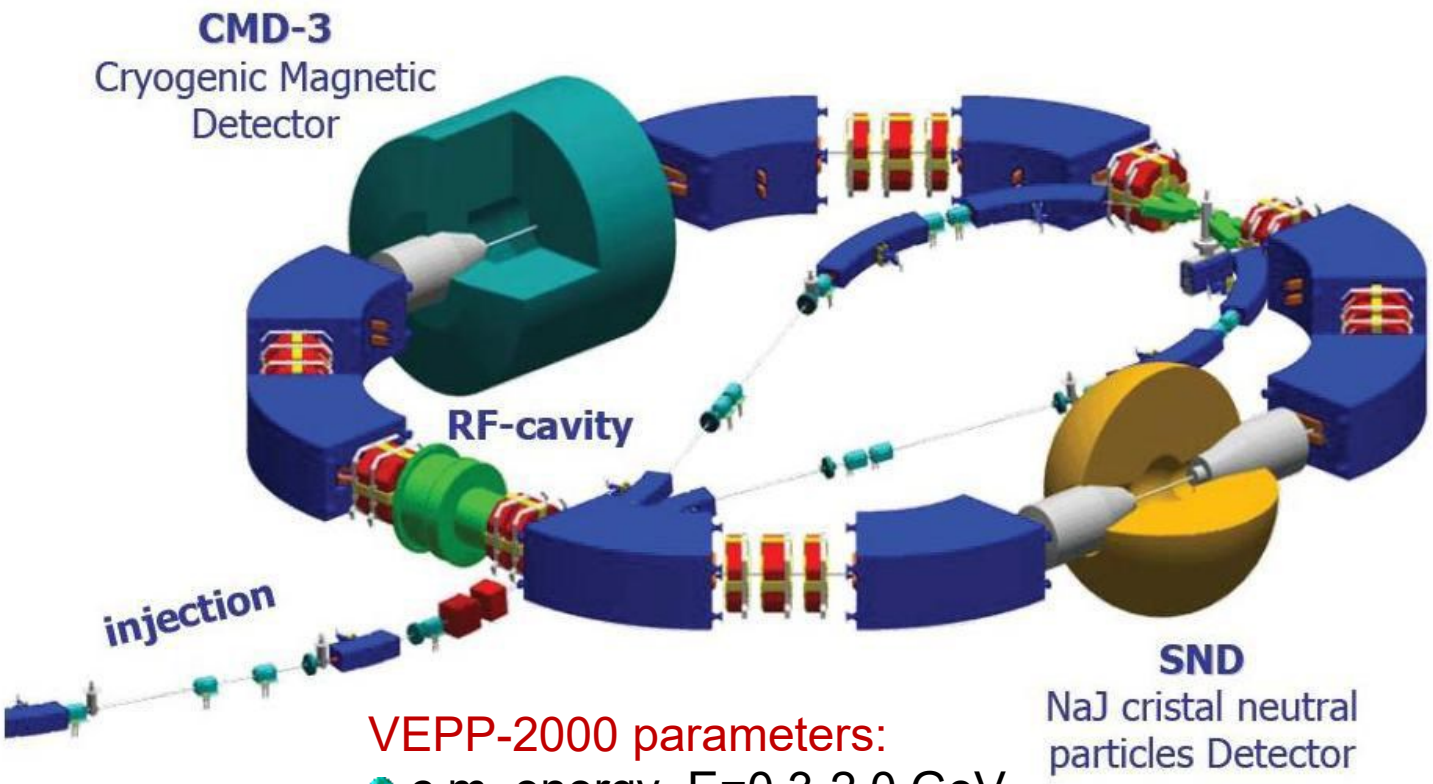
$e^+e^- \to N\bar{N}$:

- *A study the reactions near threshold and up to 2 GeV*
- *A measurement of the cross sections*
- *A measurement of the EM FFs*

BaBar BESIII CMD BINP @ Novosibirsk, Russia VEPP2000 Collider SND

VEPP-2000 e^+-e^- collider

(2 x 1000 MeV)



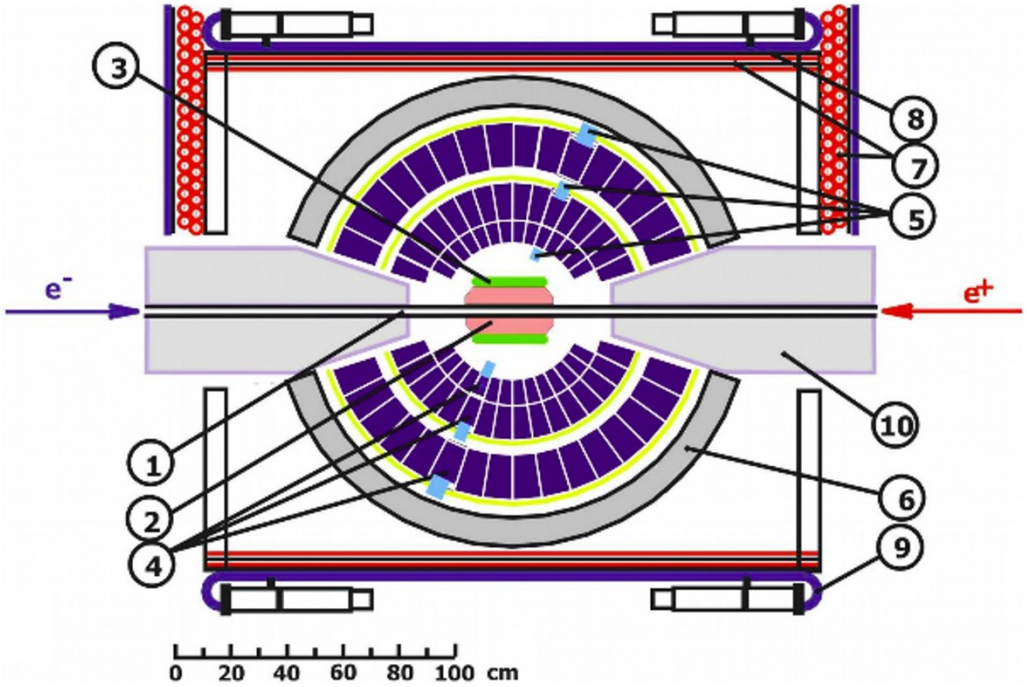
VEPP-2000 parameters:

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

1.10^{32} cm^{-2} sec^{-1} (project),

7.10^{31} cm^{-2} sec^{-1} (achieved)

Spherical Neutral 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*.

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

Experiment of 2022 г.
threshold region of e^+e^- -> n anti-n

E_{beam} =

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

ΔL = 100 1/pb

13 energy points

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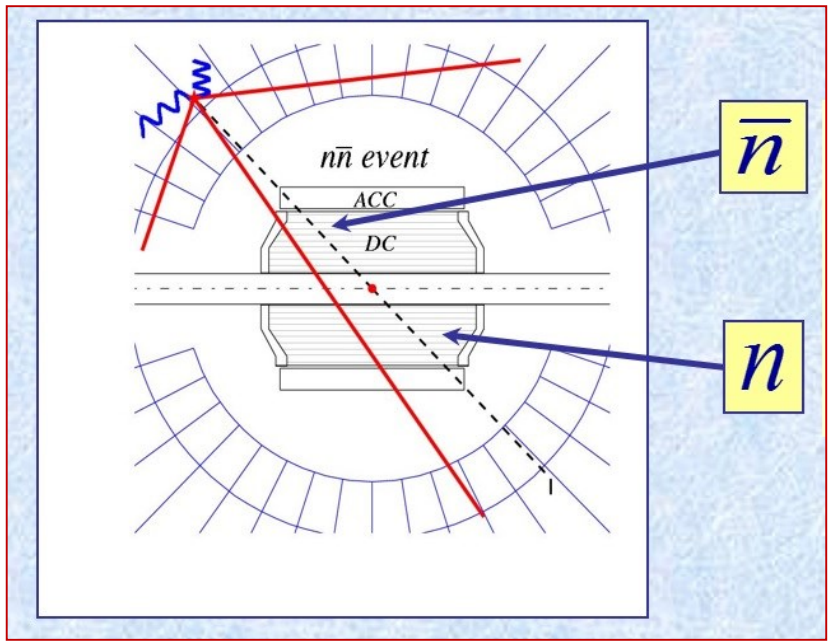
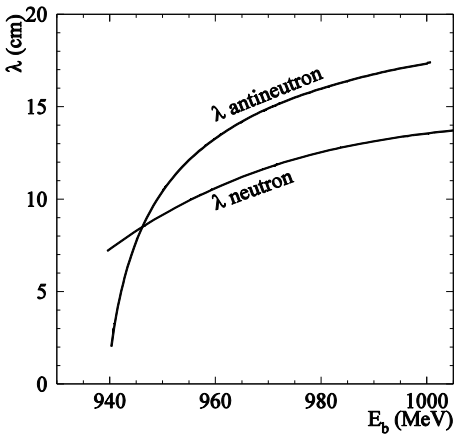
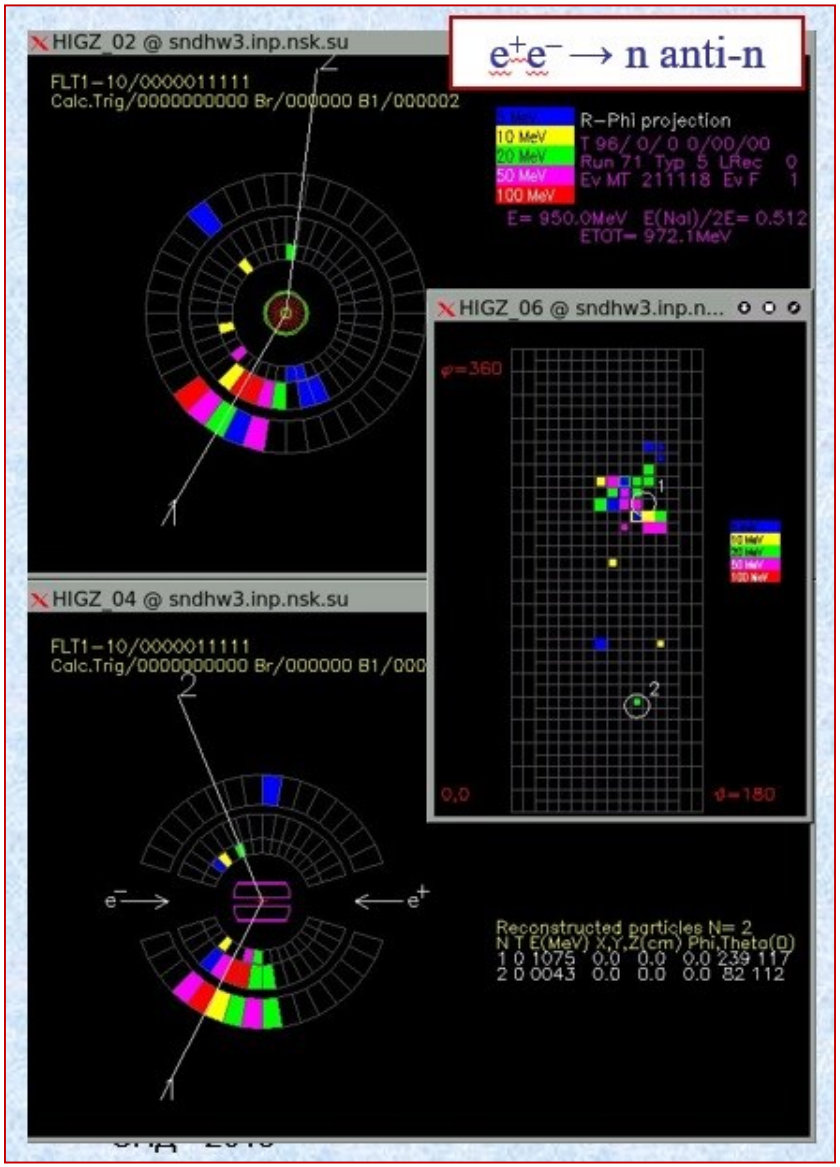
Grant RHF: No. 23-22-00011

Typical view of $n\bar{n}$ event







$n\bar{n}$ events selection

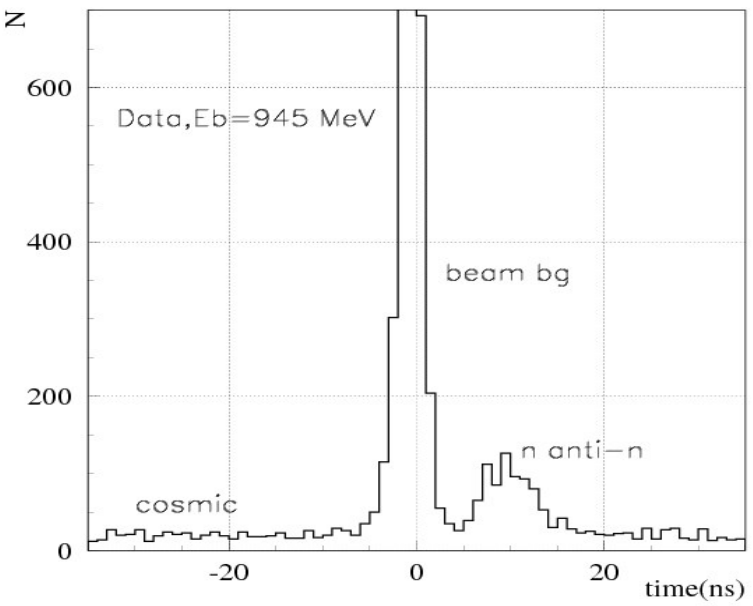
Event selection

(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 : $P>0.2E_{beam}$
5 - EMC energy : $E_{tot} > E_{beam}$
6 - photon χ^2 : >-2.5

Registration efficiency: ε_{MC} ~20 %

time spectra

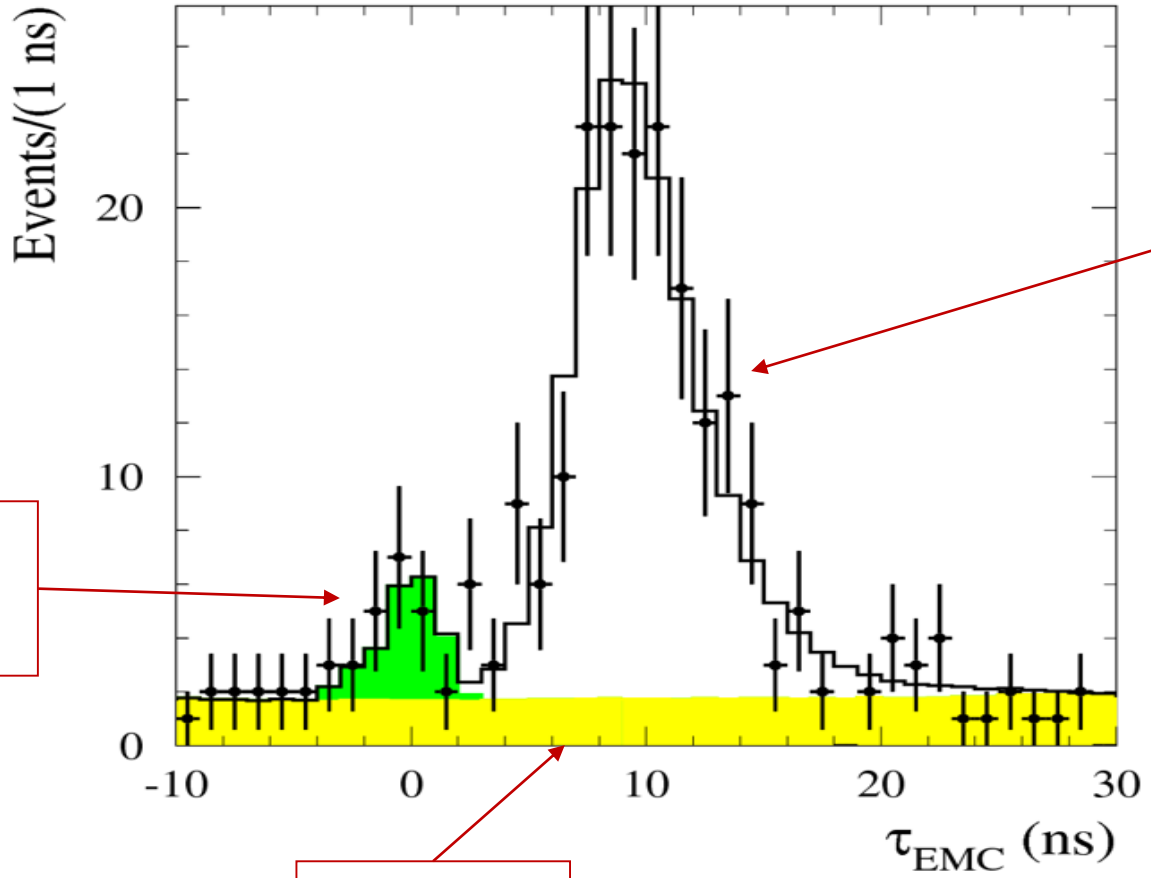


Background:

1 – cosmic bkg – flat,
2 -- beam bkg - peak at t=0;
3 – physical bkg - e+e-> ng(QED), $\pi 0$, η , .

Time spectra fit

$$N(\tau) = N_{csm} \cdot S(\tau)_{csm} + N_{bg} \cdot S(\tau)_{bg} + N_{n\bar{n}} \cdot S(\tau)_{n\bar{n}}$$



Delayed anti-n signal

t=0, beam and phys. bkg

Cosmic bkg

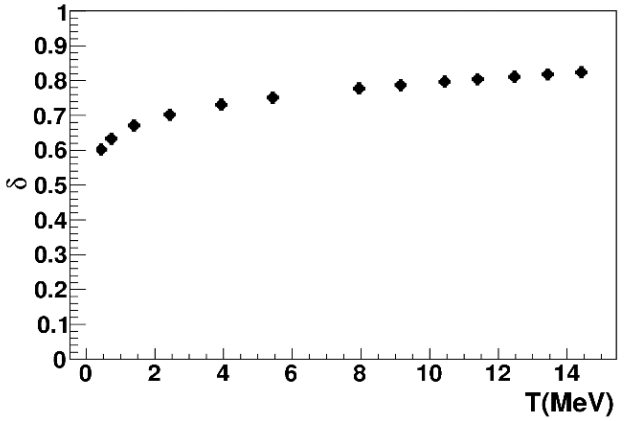
Measured e^+e^- -> n anti-n cross section

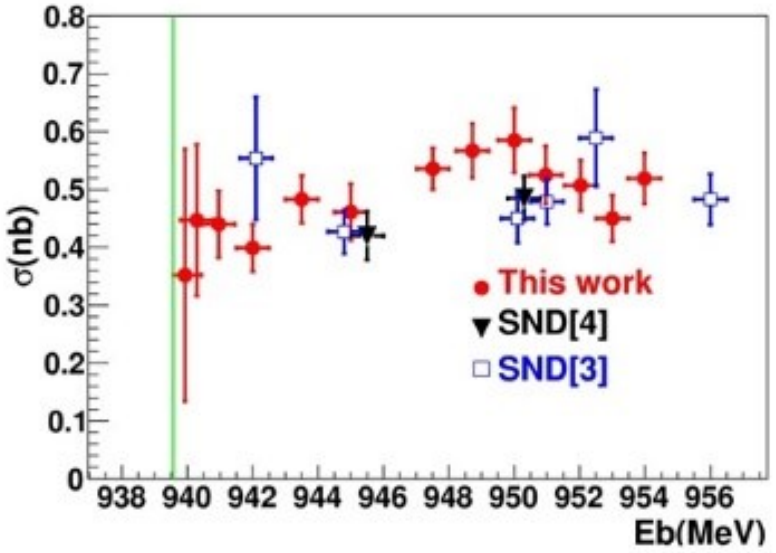
Вычисление сечения

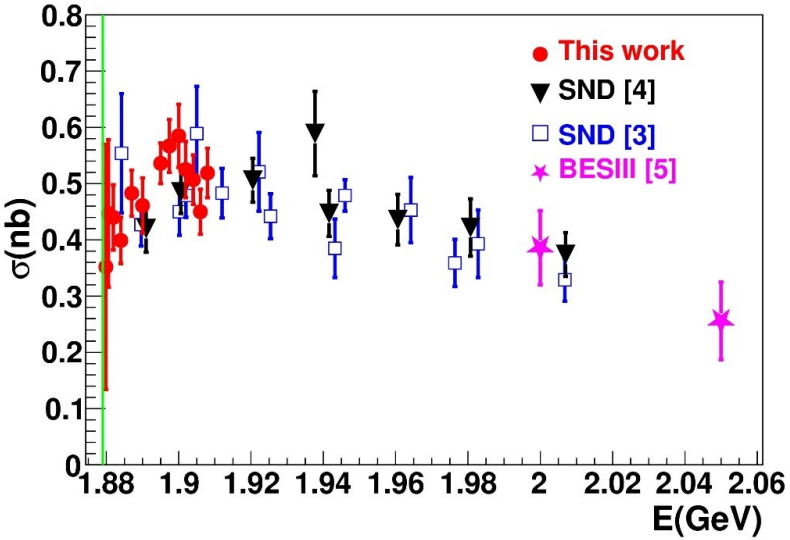
$\sigma_B = N_{nn} / \varepsilon (1+\delta) L$

Example :

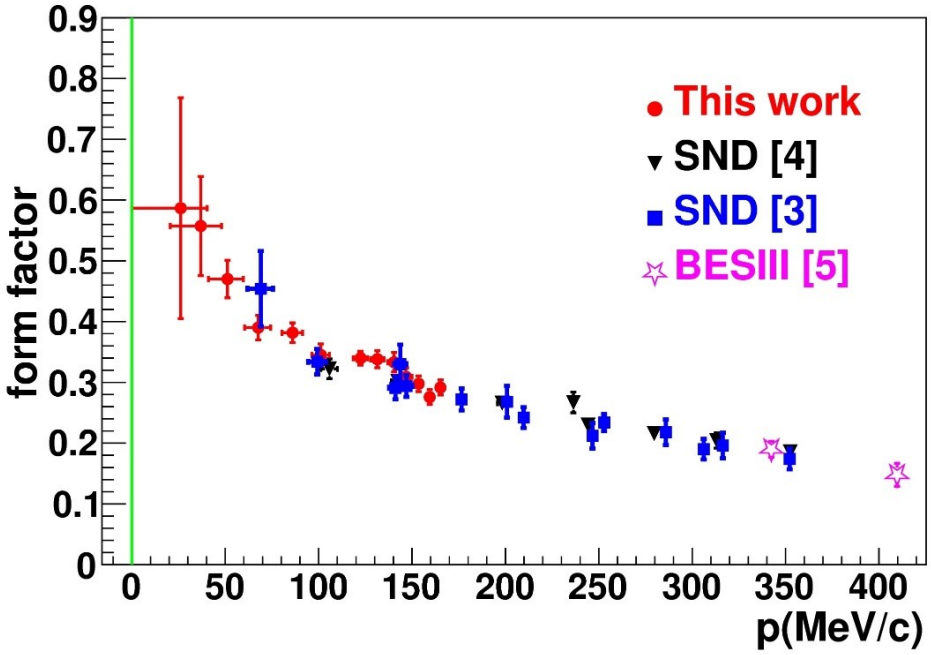
N_{nn} – detected events number, ~300,
L - integrated luminosity, ~ 5 pb^{-1},
ε - MC detection efficiency, ~ 0.2,
$1+\delta$ - radiative correction, ~ 0.8,
σ_B - total cross section ~ 0.4-0.6 nb,
σ_{vis} - visible cross section,
err(stat) ~5%,
err(syst) ~ 10%,
both errs are shown.

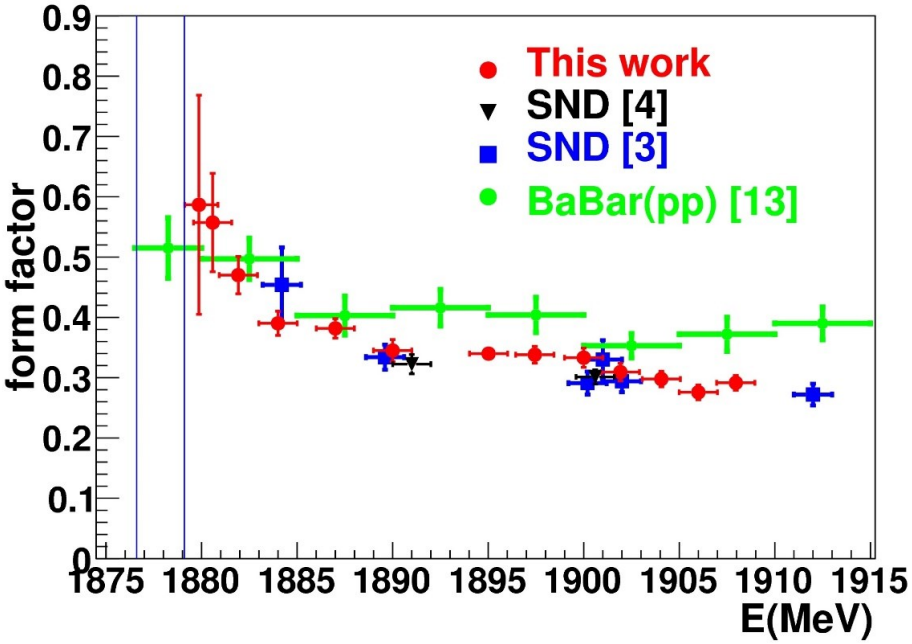






Measured effective timelike neutron formfactor





$$\sigma(e^+e^- \to n\bar{n}) = \frac{4\pi\alpha^2\beta C}{3s}(1 + 1/2\tau)\left|G_{eff}\right|^2$$

Effictive formfactor

$$\left|G_{eff}\right|^2 = \frac{|G_M|^2 + |G_E|^2/2\tau}{1 + 1/2\tau}, \qquad \tau = \frac{s}{4m_n^2}$$

Calculation of GE/GM using angular distribution

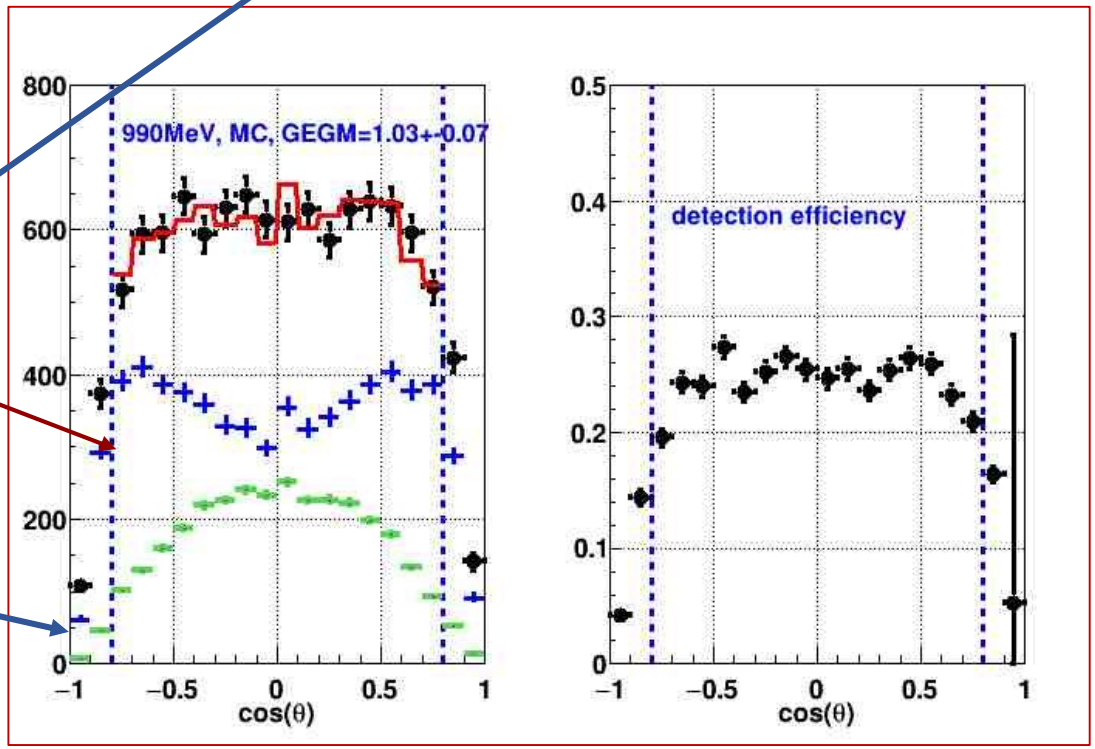
$$\frac{d\sigma_{n\bar{n}}(s)}{d\cos\theta} = \frac{\alpha^2\beta C}{2s}\left(|G_M|^2(1+\cos^2\theta) + \frac{4m_n^2}{s}|G_E|^2\sin^2\theta\right)$$

At threshold
|GE|=|GM|

GM

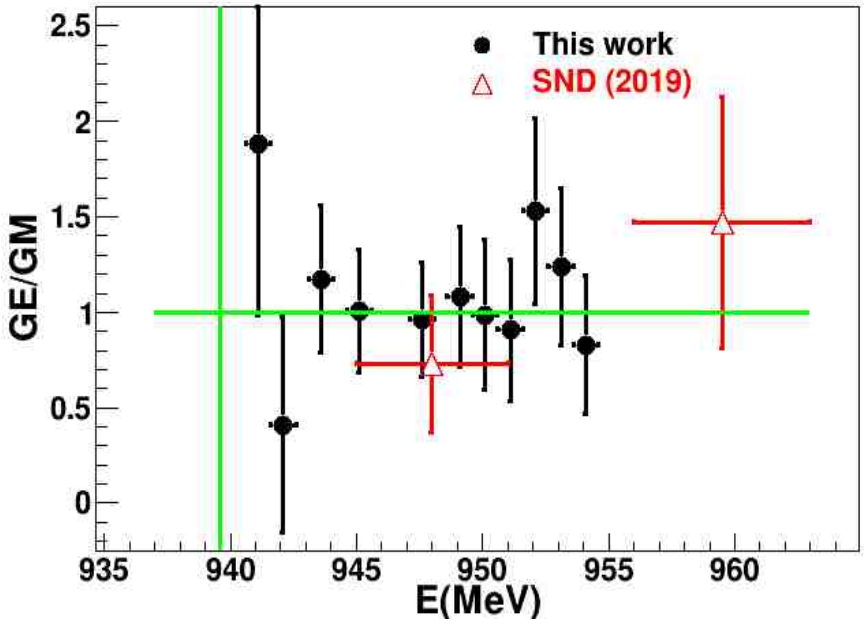
GE

N(GM) = 2 N(GE) !

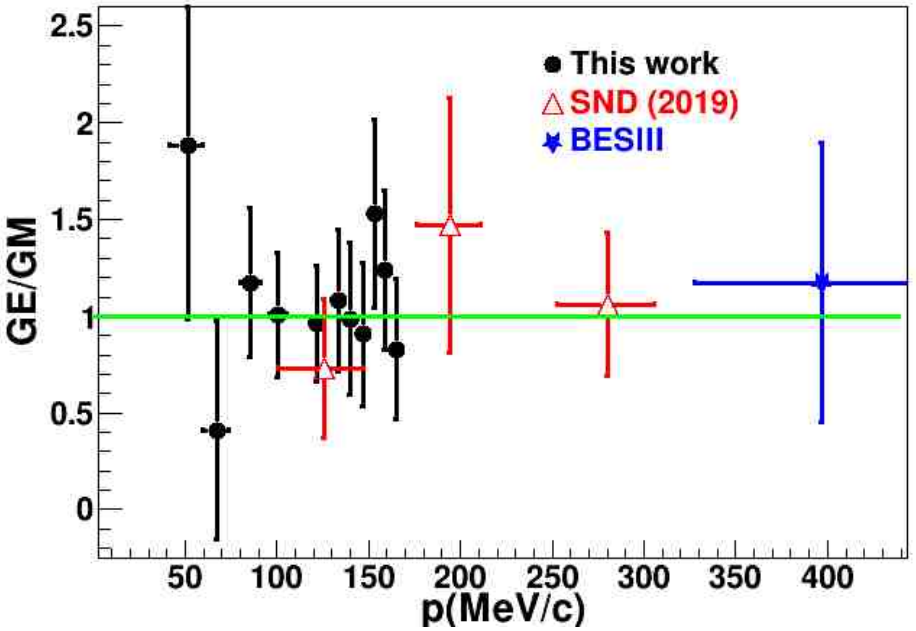


Measured GE/GM

GE/GM VS energy

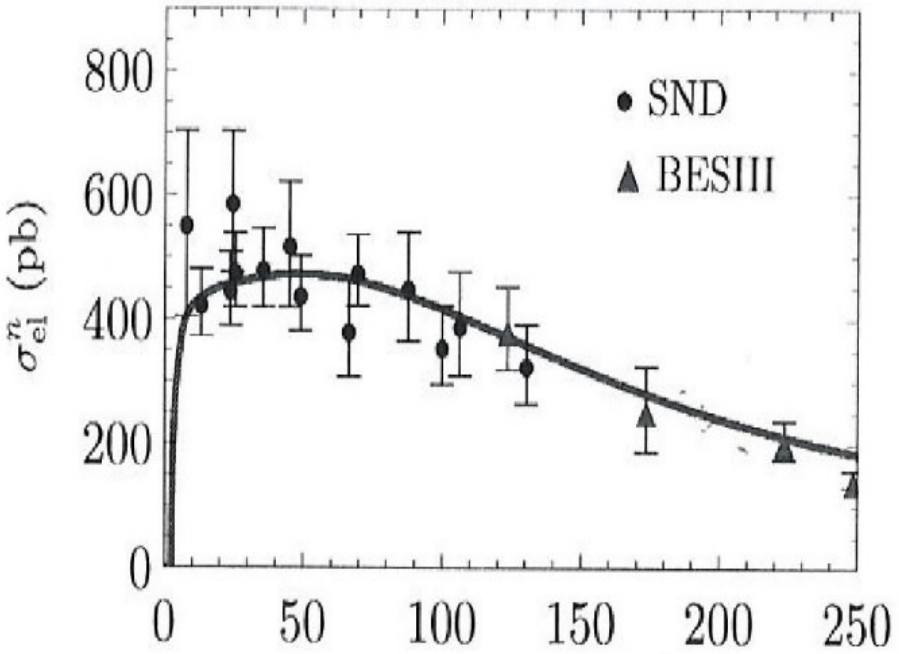


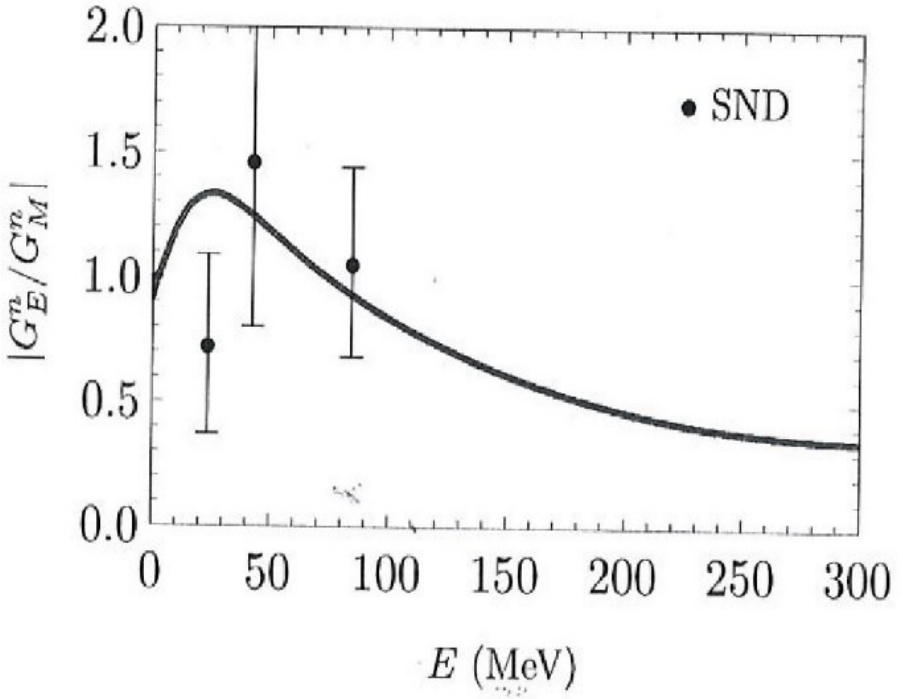
GE/GM VS momentum



Aver. |GE/GM|=1.028+-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)

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

Two strategies for the $e^+e^- \to p\bar{p}$ events selection:

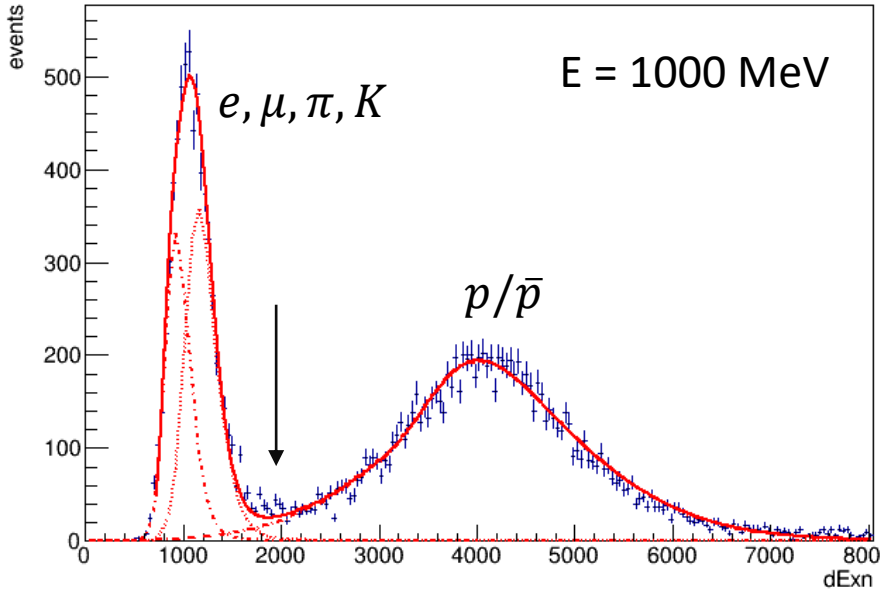
1. By the annihilation of an antiproton on the DC: $M_p < E_b < 960$ МэВ
2. By a pair of collinear charged tracks with high energy deposition in DC: $960 < E_b < 1000$ МэВ

In this analysis, the second type of events will be analyzed

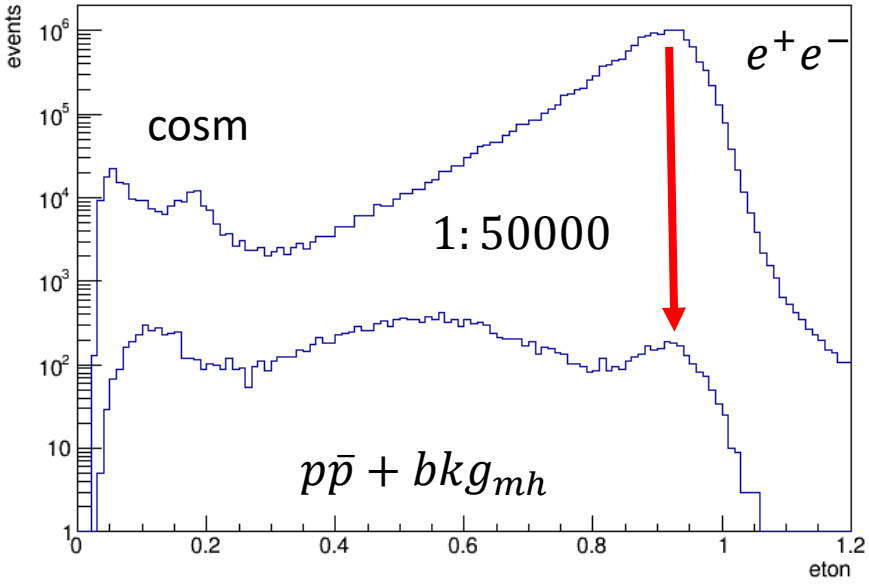
1.	Trigger:	trin > 0
2.	Number of charge particles:	nc ≥ 2
3.	Collinearity:	$\lvert\Delta\varphi\rvert < 10^o$
		$\lvert\Delta\theta\rvert < 20^o$
7.	Пучковость:	$\lvert z_{0,i}\rvert < 15\ cm$
		$\lvert\Delta z_0\rvert < 10\ cm$
		$\lvert d_{0,i}\rvert < 2\ cm$
8.	High energy deposition in the DC:	$dExn_i > dEdx_{cut}$

$p\bar{p}$ events selection dy dEdx

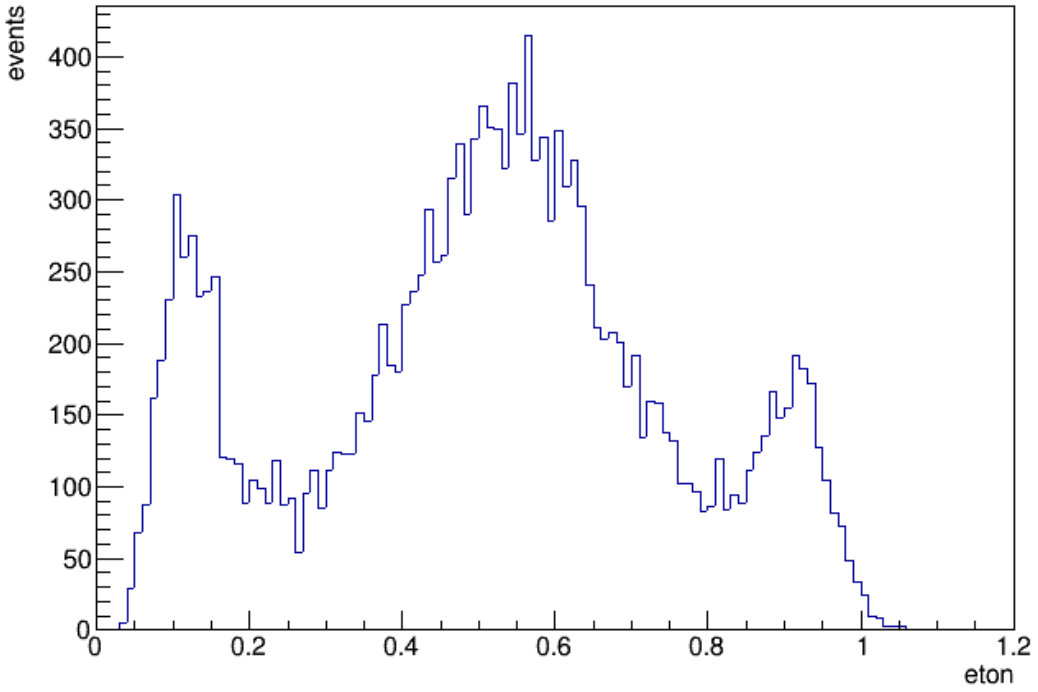
Energy deposition in DC



Energy deposition in CAL of collinear events

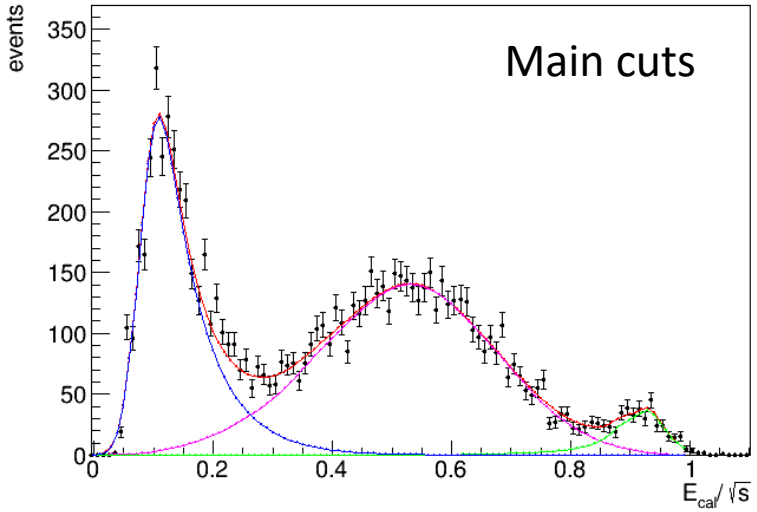


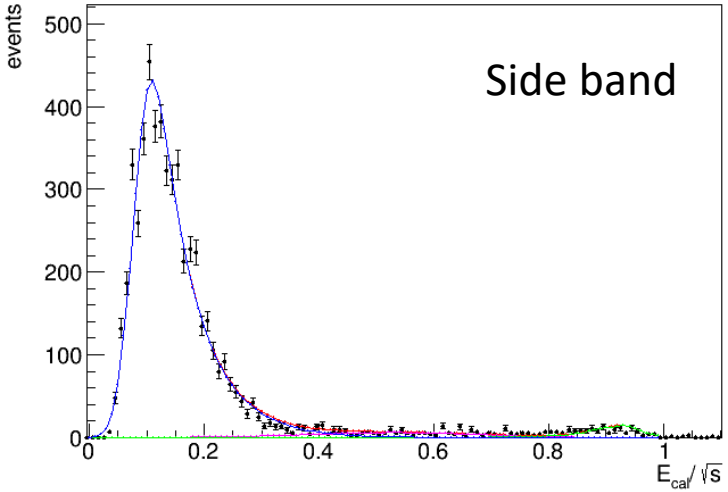
Backgrounds



1. Collinear processes:
   1. $e^+e^- \to e^+e^-$
   2. $e^+e^- \to \mu^+\mu^-$
   3. $e^+e^- \to \pi^+\pi^-$
   4. $e^+e^- \to K^+K^-$
   5. Cosmics
2. Multi-hadron processes:
   1. $e^+e^- \to \pi^+\pi^-\pi^0$
   2. $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$
   3. $e^+e^- \to KK\pi$
   4. etc
3. Other processes:
   1. Two-photon
   2. etc

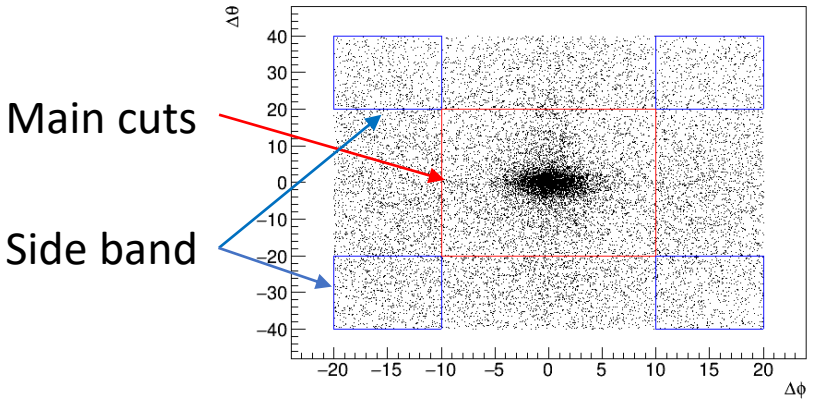
Number of events



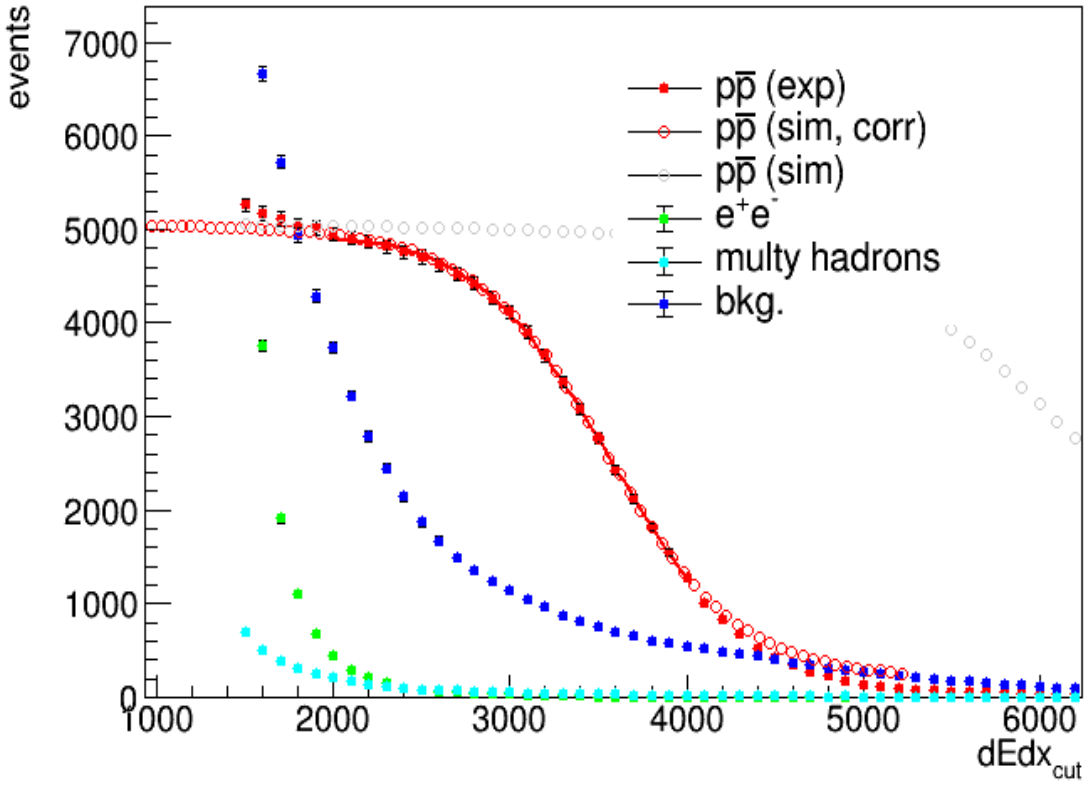


Fit model:

1. Simultaneous fitting of events in regions:
   1. Main cuts
   2. Sideband
2. Processes:
   1. $e^+e^- \to p\bar{p}$
   2. $e^+e^- \to e^+e^-$
   3. Low energy bkg
   4. Multi-hadron bkg



Scan by $dEdx_{cut}$



1. Components have different behavior depending on the parameter value $dEdx_{cut}$
2. Behavior is consistent with expectations
3. The proton part is clearly visible
4. Cut selection: $dEdx_{cut}$
5. The simulation after scale correction is in good agreement with the experiment:

   $\sigma/R = 0.244 \pm 0.005 \ \ (exp)$

   $\sigma/R = 0.230 \pm 0.001 \ \ (sim)$

Data

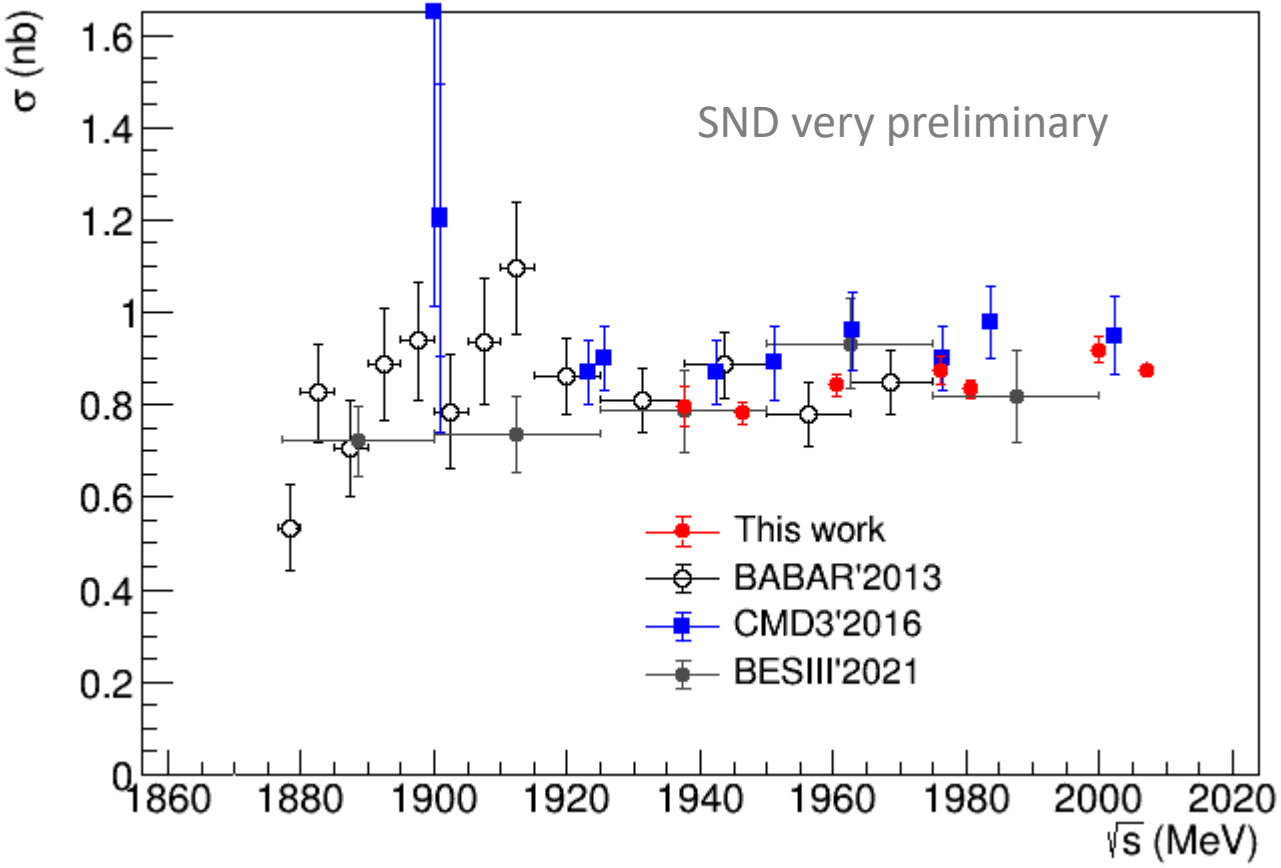
	scan	Beam, Mev	IL-1, pb	$N_{p\bar{p}}$	N_{mh}	$\xi_{e^+e^-}$	n_σ	ε
1	MHAD2017	1000.0	3.385	2070 ± 63	208 ± 32	$1.7 \cdot 10^{-4}$	1.56	0.986
2	MHAD2019	975.0	5.422	2558 ± 79	334 ± 47	$2.0 \cdot 10^{-5}$	2.06	0.998
3	MHAD2019	987.5	2.267	1260 ± 44	119 ± 22	$3.7 \cdot 10^{-5}$	2.48	0.9998
4	MHAD2021	970.0	5.981	2746 ± 150	416 ± 134	$2.8 \cdot 10^{-5}$	1.86	0.996
5	MHAD2021	980.0	8.293	4318 ± 130	676 ± 97	$1.9 \cdot 10^{-4}$	2.21	0.999
6	MHAD2021	990.0	9.717	5235 ± 122	948 ± 86	$7.2 \cdot 10^{-4}$	1.90	0.996
7	MHAD2021	1000.0	22.871	12864 ± 221	1887 ± 161	$2.4 \cdot 10^{-4}$	1.66	0.990

$N_{p\bar{p}}$ --- number of the $e^+e^- \to p\bar{p}$ events

N_{mh} --- number of multi-hadron background events estimated by sideband

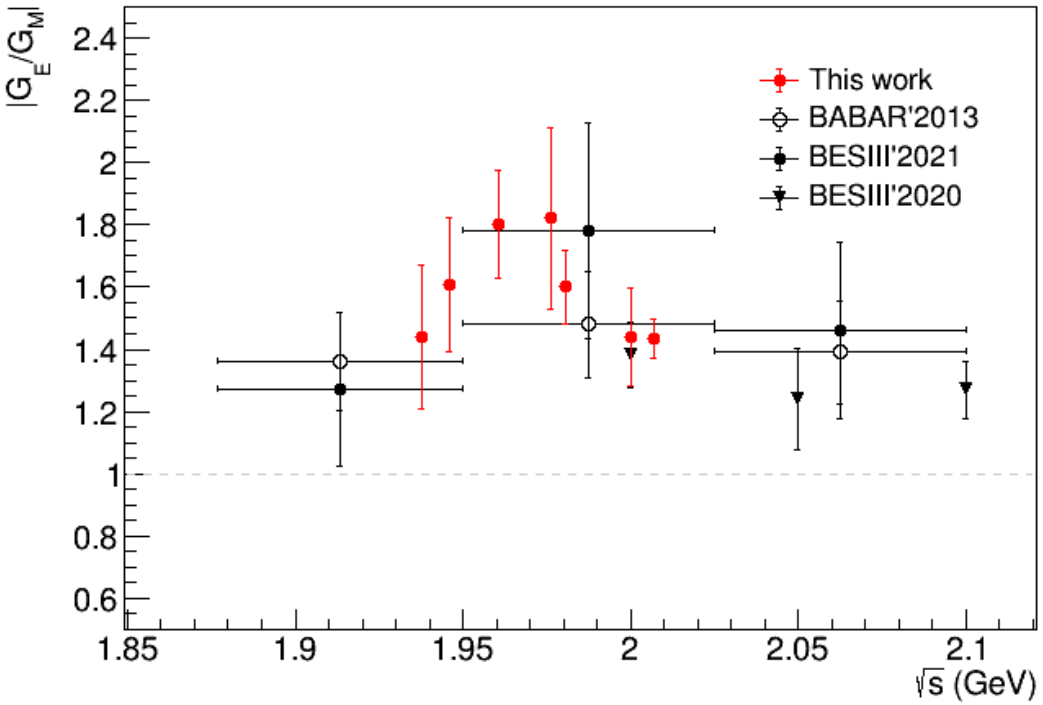
$\xi_{e^+e^-}$ --- the part of the $e^+e^- \to e^+e^-$ events

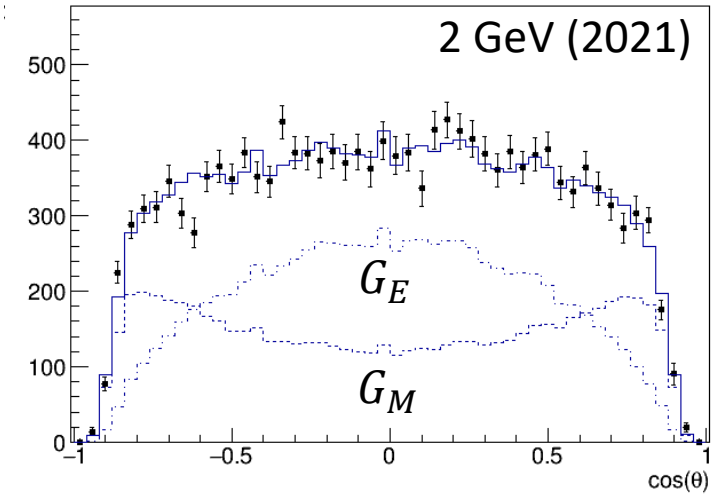
Cross section of $e^+e^- \to p\bar{p}$



Estimation of systematic error: <10 %

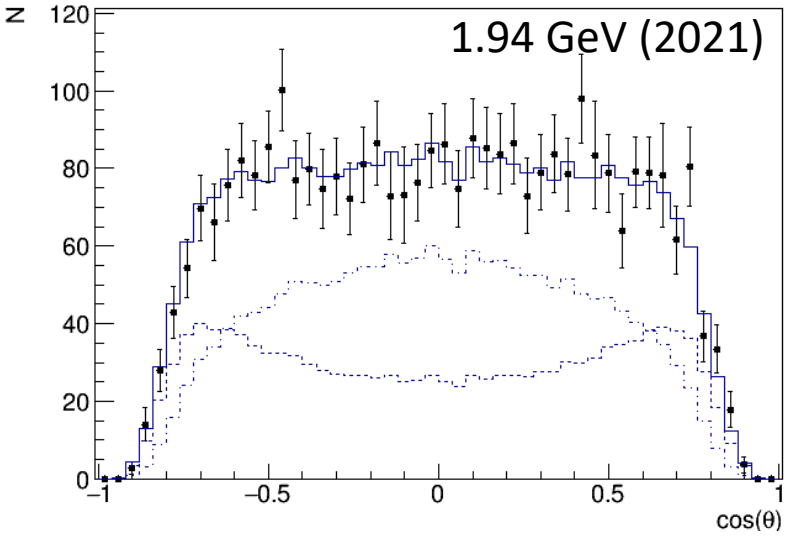
Measurement $|G_E/G_M|$ of proton

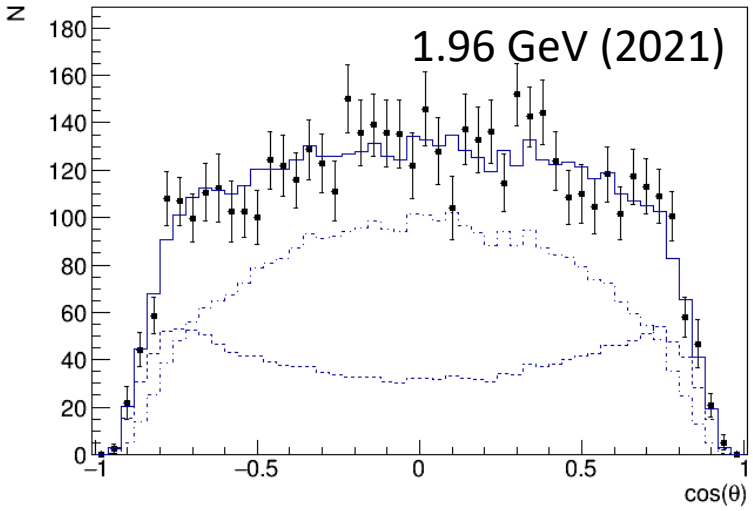


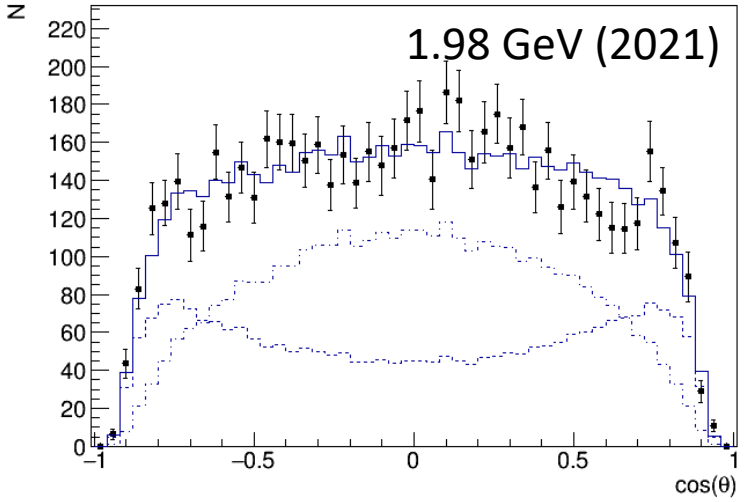


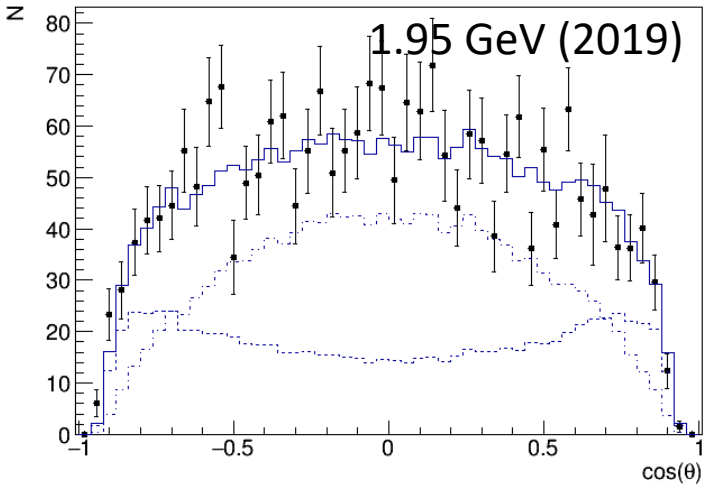
$$\frac{d\sigma_{p\bar{p}}(s)}{d\cos\theta} = \frac{\alpha^2\beta C}{2s}\left(|G_M|^2\left(1+\cos^2\theta\right) + \frac{4m_n^2}{s}|G_E|^2\sin^2\theta\right)$$

Measurement $|G_E/G_M|$: other points









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+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->n+anti-n process at energies from the threshold to E=1910 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 and proton.
7. The measured preliminary cross-section of the e+e->p+anti-p process

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

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