PRECISION MEASUREMENTS IF THE NUCLEON FORM FACTOR IN THE TIME-LIKE REGION WITH FINUDA AT DAΦNE2

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Abstract

A first feasibility study of the measurement of nucleon Form Factors in the time-like region with the FINUDA apparatus is presented, in the perspective of an increase of DAΦNE energy to about 2 GeV.

INTRODUCTION

One of the still open problems in e^+e^- annihilation physics in the region around 2 GeV, close to the threshold for the production of a nucleon-antinucleon pair, is the precise measurement of the time-like nucleon electromagnetic Form Factors (FF); for these quantities very few data exist, collected mainly, in the last decade, by the FENICE Experiment operating on ADONE, LNF [1]. The interest of such measurements is discussed at length elsewhere in these proceedings [2]; it is here just worth to remind the anomalous behaviour of the magnetic neutron form factor close to the $\overline{\mathcal{N}}\mathcal{N}$ threshold, where one would expect it to vanish due to analiticity (which requires the magnetic and the electric form factor to be equal), while a rise appears, compatible with the presence of a resonant phenomenon. Moreover, contrary to every theoretical expectation, the neutron time-like magnetic FF is about 1.5 times the proton one. The time-like nucleon FFs are evaluated on the basis of the differential cross-sections for the $e^+e^- \to \overline{\mathcal{N}}\mathcal{N}$ reaction through the well known formula

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

where G_E and G_M are, obviously, the electric and magnetic FF, β is the nucleon velocity and C is a Coulomb correction factor, which makes the cross-section at threshold non-zero. s is the square of c.m. energy, and in this case $q^2 = s$, as requested for a time-like reaction. This formula shows clearly that, while at higher q^2 only the the magnetic FF counts, close to threshold the two of them are almost equal, and one would expect an almost isotropic cross section. From this formula it is morever clear that only the modula of these complex quantities may be measured with this method.

The chance of measuring with higher precision these FF will be given by a suitable upgrade of the DAΦNE energy, without special requirements on the reachable luminosity. In the following a description of the capability of the FINUDA apparatus to detect such reactions will be presented: some encouraging hints emerge since the first preliminary studies.

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FINUDA PRESENT LAYOUT AND REQUIRED CHANGES

FINUDA,as an experiment dedicated to hypernuclear physics studies, is conceived so to minimize the amount of material crossed by particles to reduce as much as possible their energy straggling and multiple scatterings. For the detection of a $e^+e^- \to \overline{\mathcal{N}}\mathcal{N}$ reaction such a request is not mandatory; though, some new devices must be inserted to provide the annihilation of the antinucleon and therefore its possible observation, through an annihilation star. A brief sketch of the present FINUDA assembly, arranged in cylindric symmetry from the beam axis outwards (many more details may be found, for instance, in [3]), and helpful to understand the following discussion, can be summarized as:

vertex region

- TOFino: a little barrel composed by 12 scintillators, 0.2 cm thick and 12 cm long, at 5.8 cm from the beam;
- ISIM: 8 modules of Si microstrips, 300 μm thick, ~ 6.3 cm from the beams axis;
- Targets: 8 tiles of solid materials, faced against ISIM modules;

tracking region

- OSIM: 8 modules of Si microstrips, 300 μm thick, ~ 8.3 cm from the beam axis;
- Low mass drift chambers: two series of 8 drift chambers, 6 cm thick each, 43 cm and 75 cm from the beam axis;
- Straw tubes: 6 layers following three orientations, for a total thickness of 16 cm, located at 111 cm from the beam axis;

outer region

- TOFone: 73 scintillator slabs arranged as staves of a cylindric barrel, 10 cm thick, at 127 cm from the beam axis; this detector has an efficiency for the neutron detection of about 15% (this information will be relevant in the following);
- magnet coil: iron, at 138 cm from the beam axis; the magnet provides presently a 1.0 T field;

The whole tracking region is immersed in a Helium atmosphere to minimize the multiple scattering effects.

For the detection of $e^+e^- \to \overline{\mathcal{N}}\mathcal{N}$ this atmosphere is not needed, and the targets may be removed. On the contrary, some suitable converter has to be inserted. A good converter material must have some mandatory requisites as a high cross section for antinucleon annihilation, a low charged pions absorption, a high conversion efficiency for π^0's, and be amagnetic, in case the magnetic field is on. The annihilation cross section on nuclear targets is proportional to $A^{2/3}$ [4]: therefore, a good compromise for the features described so far is, for instance, copper. Exploiting the cylindrical apparatus symmetry, the easiest resort could be to insert a copper tube somewhere beyond the vertex region –taking into account that plenty of space is available between the tracking devices. A possible position could be immediately beyond the OSIM array, 9 cm from the beam: in this way all the annihilation charged products emitted towards the outer part of the apparatus can be traced. Moreover, placing it outside OSIM would allow to use both the microvertex detectors to track the antiproton in the inner region, in the $e^+e^- \to \bar{p}p$ annihilation reaction. Of course the information available for the reconstruction of each track coming from the annihilation star is not redundant, as at most three points per track can be obtained (two from the drift chambers, and one from the straws arrays), and if the magnetic field is on they all must be available for a track to be reconstructed. The thickness of the copper tube must be chosen properly referring to the interaction length for the annihilation process: tentatively, 7 mm of copper correspond to four interaction lengths for 5 MeV/c antineutrons, namely to one interaction length for 25 MeV/c antineutrons, as well as to half a radiation length.

A second converter tube could be tentatively added, with the same thickness, facing the first layer of drift chambers, in order to increase the detection efficiency for higher momentum antinucleons. A tentative front view of the modified apparatus is shown in Fig. 1.

The use of the magnetic field has some pro's and con's. It would make the rejection of spurious tracks (for instance, cosmic rays) easier, it would help to confine the background events (like Touscheck and even Bhabha ones) within the first converter tube, and would moreover allow the measurement of the momenta of the produced particles –even if this information is not essential to this particular measurement. On the other hand, curved tracks may be reconstructed only if at least three points per each one are measured; in the absence of a magnetic field, two would be enough, and the reconstruction of the annihilation stars would be easier. If the magnetic field is too strong, moreover, a loss of efficiency in the annihilation star detection could be effective due to the difficulty of tracking the e^+e^- Dalitz pairs coming from π^0's immediate conversion, which point to the star vertex and may be used to perfectionate the star topology. On the basis of these observation, a moderate intensity field, say of 0.2 T, seems to be a good compromise solution.

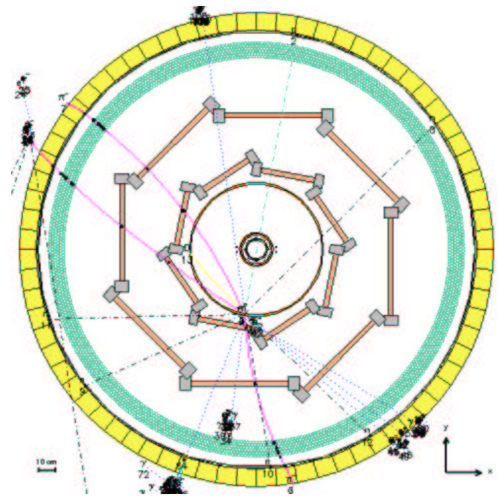

Figure 1: Front view layout of FINUDA apparatus with two copper converter tubes. A typical $e^+e^- \to \bar{n}n$ event is shown, with the antineutron annihilating on the second converter tube.

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

Figs. 2 and 3 show the typical expected topology for a $e^+e^- \to \bar{n}n$ event, as seen in the vertex region and in the full apparatus, respectively. The displayed event has a center-of-mass energy of 1890 MeV, B=0.2 T, and one converter only was inserted for simplicity.

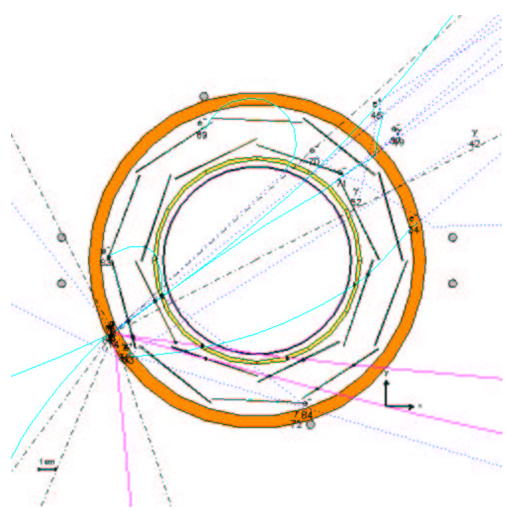

Figure 2: Expanded front view of FINUDA inner region with a typical $e^+e^- \to \bar{n}n$ annihilation event: the antineutron annihilates in the copper converter tube, producing charged pions (magenta tracks), neutral pions (dot-dashed lines) and neutral pions converting immediately into e^+e^- pairs (cyan tracks).

The annihilation star prongs emerge from the converter tube, where the antineutron annihilates, and travel through the apparatus tracking region leaving hits on the drift chambers, on the straw tube arrays and on the outer scintillator hodoscope. The reconstruction of at least two prongs allows to classify the annihilation event. On the other side, the neutron travels through the apparatus leaving a hit on the scintillator hodoscope. Even if the efficiency for its detection is about 15% only, the use of this information would allow a powerful background rejection, since the neutron velocity is fixed, therefore its detection within a definite time gate tags precisely the $e^+e^- \to \bar{n}n$ annihilation reaction.

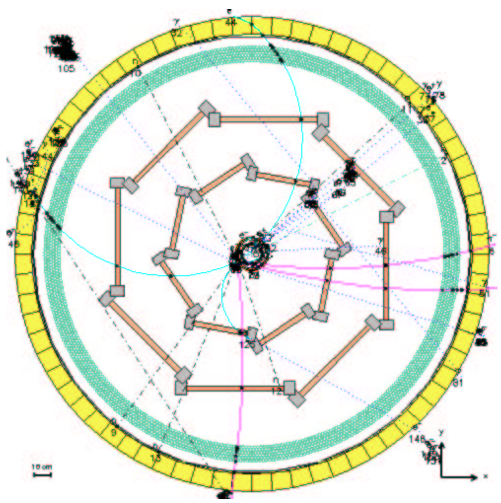

Figure 3: Full front view of FINUDA apparatus with a typical $e^+e^- \to \bar{n}n$ annihilation event: the charged pions (magenta tracks) and the e^+e^- pairs (cyan tracks) coming from the π^0 conversion hit the tracking devices leaving signals for their reconstruction.

Several simulations have been performed in order to evaluate the detection efficiencies for such topologies, in the geometric layouts with one or two converter tubes, asking for at least two tracks with three hits each pointing to the same vertex to define the annihilation star. Assuming as tentative average luminosity $\mathcal{L} = 5 \times 10^{31}$ cm^{-2}s^{-1}, corresponding to an integrate luminosity per day of about 4 pb^{-1}, an $e^+e^- \to \bar{n}n$ annihilation cross section of 1 nb, a chamber transparency of 85% and the already mentioned 15% efficiency for the neutron detection, a rough estimation of the number of collectible event per day may be inferred. They are reported in Tab. 1.

A decreasing trend of the detection efficiency is clear with the increase of center-or-mass energy; in any case, the number of good detectable events per day is about, or exceeding, the total amount of events collected by FENICE in all its data takings. The insertion of a second converter enhances the number of annihilations, therefore of detectable events, from 20 to 60%, depending on the momentum of the produced antinucleons (favouring the conversion of higher energy particles). The most of 5 MeV/c antineutrons (produced at $\sqrt{s} = 1879.15$ MeV) annihilate on the beam pipe, on TOFino, on the microstrip arrays and on the first converter; 29 MeV/c antineutrons ($\sqrt{s} = 1880$ MeV) annihilate on the first converter with a 44% probability, while on the second one the 20% of the times; finally, 197 MeV/c antineutrons ($\sqrt{s} = 1920$ MeV) annihilate the 13% of the times on the first converter, the 8% on the second one, the 22% on the drift chamber structures, the 16% on TOFone, and the 28% on the iron magnet coil. These last events can possibly be detected by a backtracking of the annihilation prongs towards the apparatus' centre.

Table 1: Detection efficiencies of $e^+e^- \to \bar{n}n$ events topologies in FINUDA, and number of detectable events with neutron signal coincidence: the first two columns are referring to the case of a single converter geometry, the second two to the case of two converters.

$\sqrt{s}$ (MeV)	ϵ_{1C}	Events 1C	ϵ_{2C}	Events 2C
1879	0.31	158	0.37	190
1880	0.24	122	0.31	157
1890	0.16	96	0.27	119
1900	0.13	66	0.20	102
1920	0.08	41	0.14	66
1940	0.06	31	0.10	50
2000	0.06	31	0.10	51

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

The range of 300 MeV/c protons in copper is 1.88 g cm^{-2}, corresponding to 2.1 mm. This means practically that all protons (and antiprotons) stop on the first converter, and are therefore insensitive to the presence of the second one. At $\sqrt{s} = 1879.13$ MeV, threshold for $\bar{n}n$ production, the momentum of the outgoing $\bar{p}p$ is 48 MeV/c, therefore they never spiralize before reaching the beam pipe, even in case of a strong magnetic field. At $\sqrt{s} = 1880$ MeV, $p_{\bar{p}} = 57$ MeV/c, all antiproton annihiilations occur of the beam pipe or on TOFino; at higher momenta the most of the annihilations occur on the converter.

A typical topology for a $e^+e^- \to \bar{p}p$ annihilation event is shown in Figs. 4 and 5: in this case the annihilation occurs on the beam pipe.

The topology difference with respect to the antineutron case stands in the fact that, if antiprotons cross TOFino, they leave here a hit back-to-back to the proton one, giving a good signature for the trigger of such an event. If their energy is moreover enough for them to cross TOFino and leave a hit on at least one microstrip module, the trajectory of the antiproton-proton back-to-back tracks can be easily determined, and the efficiency for the reconstruction of the annihilation vertex can be increased since one more track pointing to it is available.

If the annihilation occurs before TOFino, as in the case sketched in the figures, the event topology is similar to the antineutron annihilation one. However, the probability that a few MeV/c antineutron annihilates in this region is less than 10%, so these events can rather safely be ascribed to antiprotons.

A survey of the detection efficiencies for the $e^+e^- \to \bar{p}p$

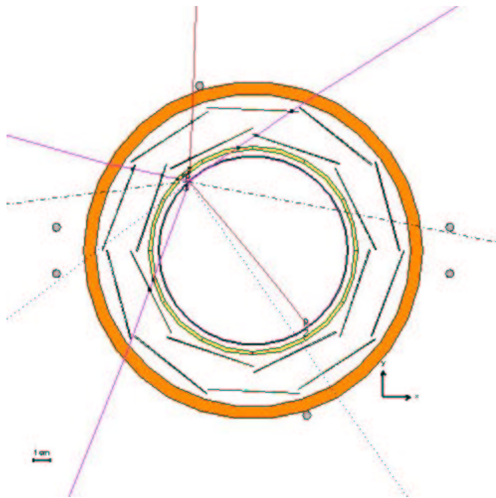

Figure 4: Expanded front view of FINUDA inner region with a typical $e^+e^- \longrightarrow \bar{p}p$ annihilation event: the antiproton annihilates in the beam pipe, producing charged pions (magenta tracks) and a proton (red track). The recoiling proton stops as well in the beam pipe.

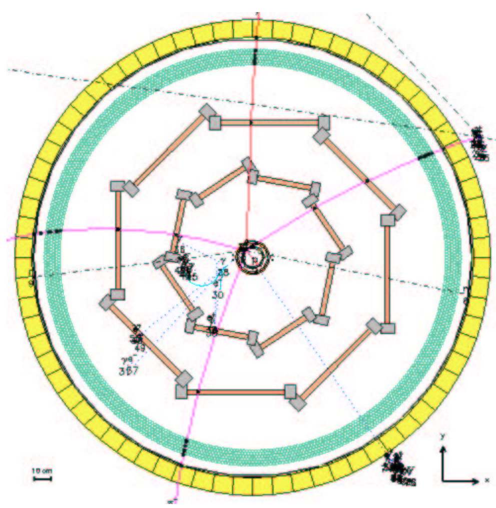

Figure 5: Full front view of FINUDA apparatus with a typical $e^+e^- \longrightarrow \bar{p}p$ annihilation event: the charged pions (magenta tracks) and the proton (red track) coming leave signals on the tracking devices for their reconstruction.

reaction was performed by means of dedicated simulations, and the results are reported in Tab. 2, where the number of detectable events per day is shown, in the hypothesis of an integrated luminosity of 4 pb^{-1}. The detection efficiencies have been evaluated as mean values of the two extremal values obtained in the hypothesis of isotropic annihilation, or following a $(1+\cos^2\theta)$ distribution, which was indicated in Ref. [1] to be effective for annihilation into antiprotons .

Differently from the antineutron case, the detection efficiency is not monotonically decreasing, as a consequence of the different energy loss and straggling effects undergone by antiprotons in matter.

Table 2: Detection efficiencies of $e^+e^- \longrightarrow \bar{p}p$ events topologies in FINUDA, and number of detectable events. Single converter geometry.

$\sqrt{s}$ **(MeV)**	ϵ	**Events**
1879	0.46	1564
1880	0.48	1632
1890	0.51	1734
1900	0.54	1836
1920	0.44	1496
1940	0.40	1360
2000	0.36	1224

FIRST BACKGROUND STUDIES

The most important contribution to background is given by $e^+e^- \rightarrow \gamma\gamma$ annihilation events, whose cross section at these energies is about 3 nb, and whose signature, reported in Fig. 6, can fake $\bar{n}n$ events. In fact, if the photon converts to a e^+e^- pair, the event topology may be similar to a $\bar{n}n$ one if the star is required to be made by two prongs only. The higher cross section for $\gamma\gamma$ events implies a very high yield for such events filtered by the detection criteria. The removal of these background events would be effective by requiring annihilation stars with at least three prongs, and exploiting the information coming from the outer scintillators' hodoscope for the detection of the recoiling neutron within a definite time gate.

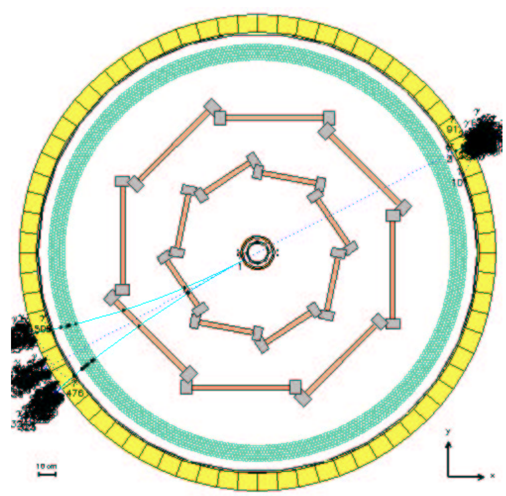

Figure 6: Full front view of FINUDA apparatus with a typical $e^+e^- \longrightarrow \gamma\gamma$ annihilation event: the e^+e^- pair coming from one γ conversion can fake an annihilation star signature if two prongs only are required for the reconstruction of the latter.

The machine background should not be particularly worrying for this kind of measurements. Touscheck events are well confined within the inner region and never trespass the converter layer. Bhabha events have, on the contrary, a totally different signature and may be easily distinguished and separated from the sought signal.

ADVANTAGES AND DRAWBACKS. CONCLUSIONS

From the evaluations discussed so far, a measurement of the time-like FF for both the neutron and the proton seems feasible with FINUDA, after a small number of rather simple changes in the apparatus layout. The detection efficiencies are quite fair, and the situation looks promising.

Unfortunately, one drawback is the total apparatus acceptance, which penalizes particles' emission at forward angles; some more instrumentation, for instance at least in the simple form of a scintillator wall, would be desirable in order to cover the angular region $(-45^\circ \div 45^\circ)$, which could be important in case of a $(1+\cos^2\theta)$-like anisotropic emission.

In spite of the reduced acceptance, FINUDA will offer however a unique possibility, thanks to the relatively large free room available inside the apparatus: the measurement of the nucleons polarization. In principle this could be made placing a suitably thick Carbon converter, beyond which a left/right asymmetry measurement for the emitted nucleon could be performed [5]. This kind of measurement would be of great interest, as it would be a handle to infer something about the relative phases of the magnetic and electric FF, that in the time-like region, as already mentioned, are complex quantities [6].

Another kind of reaction that FINUDA will be able to measure with fair (about 20%) efficiency is the multihadronic annihilation, with the production of, say, four or six pions in the final state. In this case of course the presence of the converter would not be necessary (better would be to remove it completely, in order to minimize the multiple scattering suffered by pions, which however at this energy is not so crucial), and the event signature would be represented by a star of tracks pointing all to the interaction vertex, that could be reconstructed by applying essentially the same algorithm used for $\overline{\mathcal{N}}\mathcal{N}$ events. The interest of such reactions stands in the possible formation of exotic states at a mass close to 1.9 GeV, for which some indications have already been obtained quite recently [7].

In conclusion, some promising hints have been confirmed by extended simulations for the use of FINUDA with an energy-upgraded DAΦNE to measure both the neutron and proton FF with unprecedented precision; some new measurements, like the emitted nucleon polarization, seem to be feasible as well, giving the chance to get some new, never obtained information on the FF relative phases. Concerning this topic, the simulation job is currently underway.

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