A Letter of Intent:

Nucleon-Antinucleon Photoproduction with CLAS

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Abstract

In this LOI we report about studies on $p - \bar{p}$ and $n - \bar{n}$ photoproduction with the CLAS detector. Physics motivations will be presented first, then existing data about $p-\bar{p}$ photoproduction from previous experiments as well as from CLAS will be discussed. Instead, $n - \bar{n}$ photoproduction has never been measured and we suggest that it may be measured for the first time using CLAS. We will report results from preliminary Monte Carlo simulations; further studies will be performed in order to develop a full proposal.

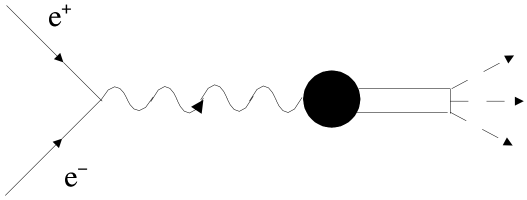

Figure 1: Hadronic production through electron-positron annihilation.

1 Physics Motivations

1.1 Nucleon Form Factors

Electromagnetic production of nucleon pairs has been historically the way to access time-like form factors of proton and neutron, via the reactions $e^+e^- \to p\bar{p}$ and $e^+e^- \to n\bar{n}$. The first of these reactions was measured in several experiments throughout the world[1, 2], while the second has been measured in only one pioneering experiment[3]. The latter obtained a rather surprising result, which we will describe later, on the magnetic time-like form factor of the neutron, $G_M^n(s)$ with $s = q^2 > 0$, where q^2 is the invariant mass squared of the virtual photon produced in s-channel annihilation. Hadronic production via e^+e^- annihilation is shown schematically in figure 1. If we consider the reaction $e^+e^- \to N\bar{N}$, where N is a nucleon, then through one-photon-exchange one obtains that the differential cross section is given by

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

with $q^\mu = k_1^\mu + k_2^\mu$, k_1 and k_2 being the four-momenta of electron and positron; G_E and G_M are the electric and magnetic form factors of the nucleon and since $q^2 > 0$, they are called the time-like form factors of the nucleon. At threshold, only S-wave can be present and therefore

$$G_M = G_E \tag{2}$$

Instead, at $q^2 >> 4M_N^2$, G_M dominates. At present, theoretical expectations on nucleon time-like form factors are well established only for what concerns their asymptotic behaviors. Analyticity implies continuity through infinity between space-like and time-like form factors[4]. Hence, time-like magnetic form factors are expected to behave like space-like magnetic form factors asymptotically, that is $\sim \mu_N/q^4$ and real, positive for the proton, while negative and quite smaller for the neutron. Furthermore, for space-like q^2 the neutron electric form factor is much smaller than the magnetic one, at least up to $q^2 \sim -4$ GeV^2[5], and the same is expected for time-like q^2.

QCD provides similar aymptotic expectations[6]: real magnetic form factors $\sim \mu_N/q^4$ and a neutron magnetic form factor smaller than the proton one[7]. According to QCD sum rules[8], there is a leading quark in the nucleon so that asymptotically it is expected $G_M^n/G_M^p \sim q_d/q_u = -0.5$.

As a typical feature of perturbative QCD predictions, it is not clear beyond which q^2 asymptotia should be reached. However, also nucleon models based on valence quarks will predict neutron form factors smaller than the proton ones. At present G_M^p, the best known form factor, allows checks of analyticity and pQCD predictions, being measured widely for space-like q^2 and for time-like q^2 up to $q^2 \sim 15GeV^2$. Time-like data[9] are consistent with the $1/q^4$ expected asymptotic behavior already for $q^2 \sim 4$ GeV^2, but they exceed the space-like data at the same q^2 by a factor 2. Models based on pQCD with Sudakov effects included[10] and models based on a quark-diquark picture of the nucleon[11] can accomodate this discrepancy, assuming that it will disappear at quite higher q^2. Phenomenological models, based on Vector Meson Dominance[12, 13], provided a very wide range of nucleon time-like form factors expectations, depending on number and position of the various poles. In most models the neutron form factor turns out to be larger or equal to the proton one. Skyrme-inspired models also foresee similar neutron and proton time-like form factors[14] Also dispersion relations have been applied to analyse nucleon form factors from negative to positive q^2[15, 16], obtaining information on phases and to the behaviour relative to asymptotic predictions.

1.2 Photoproduction and relationship with time-like form factors

It has been suggested that time-like electromagnetic form factors my also be accessed in an indirect way using photoproduction of the same final states produced in e^+e^- annihilation[17, 18]. This relationship is schematically illustrated in figure 2: the photon can materialize into hadronic intermediate states, which then scatter off the target or "spectator" nucleon. Given the nature of hadronic interactions, we may expect, especially at high photon energies, that the process depicted in the figure be dominated by diffractive elastic scattering of the hadronic components. In the figure, it is assumed that such a scattering would proceed via Pomeron exchange as a common feature of diffractive scattering.

In more quantitative terms, we may write that, for the diffractive photoproduction of a final hadronic state X,

$$\sigma_{diff}\left(\gamma p \to Xp\right) \propto \int \sigma\left(e^+e^- \to X\right) dM_X^2 \qquad (3)$$

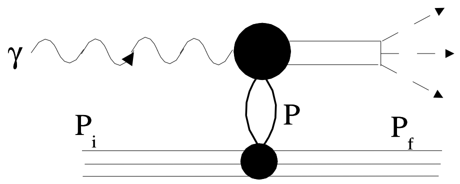

Figure 2: Diffractive hadronic photoproduction.

where $\sigma\left(e^+e^- \rightarrow X\right)$ should depend from the ratio $\frac{\Gamma_{X\rightarrow e^+e^-}}{M_X}$
Actually, it is found in the phenomenology of vector mesons that

$$\frac{\sigma\left(\gamma p \rightarrow \rho p\right)}{\sigma\left(\gamma p \rightarrow \omega p\right)} \sim 11 \tag{4}$$

but also

$$\frac{\Gamma\left(\rho \rightarrow e^+ e-\right)}{\Gamma\left(\omega \rightarrow e^+ e-\right)} \sim 11 \tag{5}$$

having ρ and ω meson about the same mass. This is a phenomenological indication that using in particular diffractive photoproduction one may access the same physical quantities that are measured with the traditional e^+e^- annihilation technique.

We can conceive that a similar diffractive mechanism may be present in the case of the reaction $\gamma p \rightarrow pN\bar{N}$: extracting such a contribution would provide another way to access the time-like form factors of the nucleon and simultaneously study the presence of resonances in the $N\bar{N}$ system at invariant masses close to threshold.

As an example, we depict the possible physical processes contributing to $\gamma p \rightarrow p\bar{p}p$ as follows: picture 3 is reporting the above mentioned diffractive process; figure 4 is illustrating a possible process with proton exchange, that may be identified as a u-channel contribution, while figure 5 shows the same exchange process, but when the antiproton is exchanged.

In principle, one may conceive that whenever a $\gamma N\bar{N}$ vertex appears in a mechanism, a nucleon form factor should enter in the amplitude; therefore, even though the diffractive mechanism is probably cleaner from a theoretical point of view, one may not exclude that,

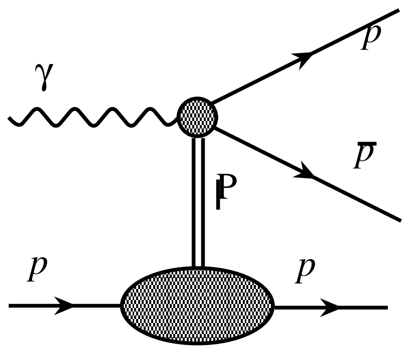

Figure 3: $p\bar{p}$ production through Pomeron exchange.

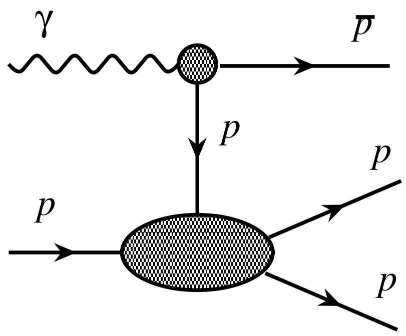

Figure 4: $p\bar{p}$ production through proton exchange.

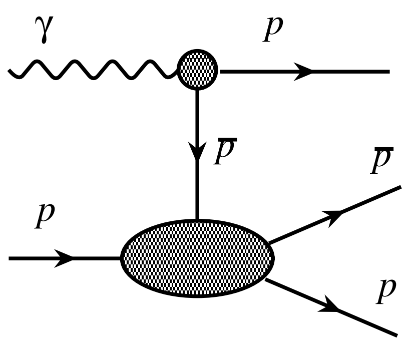

Figure 5: $p\bar{p}$ production through antiproton exchange.

given an appropriate theoretical treatment of such possible mechanism, information on the nucleon time-like form factor may be extracted even in absence of a dominant diffractive mechanism.

1.3 Narrow $N-\bar{N}$ states

The measurement of the nucleon form factors very near threshold deserves a special interest. Years ago models have predicted $N\bar{N}$ bound states[19]. Many narrow resonances below threshold were predicted on the basis of a mostly attractive $N\bar{N}$ potential, as deduced by means of the meson exchange model of the NN potential and of the exchanged G parity. The experimental results in $p\bar{p}$ annihilation[2] are not in agreement with this prediction and an imaginary part to be included in the $p\bar{p}$ potential may account for it[20]. It is relevant that data on the $p\bar{p}$ interaction like annihilation into e^+e^- pairs and total cross sections in the region above threshold are rather sparse and often with quite large errors. In the past and recently narrow candidates have been indicated from quasi-free $n\bar{p}$ annihilation in this mass region [21]. Moreover, a recent paper[22] has discussed a comprehensive evidence for a narrow state with a mass of 2.02 GeV in experiments with π^+p and π^-p collisions performed with the Omega spectrometer at CERN. It has been speculated that narrow resonances decay into $N\bar{N}$ final states may either come from "molecular" baryon-antibaryon states, or from the decay of exotic $qq-\bar{q}\bar{q}$ states, whose decay into ordinary mesonic final states would be suppressed based on considerations about the basic QCD color mechanisms, while decay into nucleon-antinucleon would be favoured. Needless to say, it would be of extreme importance to confirm the existing observations via a different production channel with a different experimental set-up: photoproduction would be an alternative way of studying such a sytem, with the great technical advantage that, due to the Lorentz boost, even for an invariant mass of the $N-\bar{N}$ system very close to threshold, the nucleon and the antinucleon emerge from the reaction with high momenta, making it possible for them to cross the full detector region. We will show explicitly these features in the section dedicated to the analysis of existing $p\bar{p}$ CLAS data. Moreover, there are no observations at all for the $n-\bar{n}$ channel and therefore any evidence in this channel would make the impact much stronger. Confirmation of the existence of such narrow states would be equivalent to the discovery of exotic mesons and would strongly impact our understanding of hadronic physics.

2 Phenomenology of $\gamma p \to pp\bar{p}$

2.1 Previous Data

Data on $p\bar{p}$ photoproduction were obtained in three experiments performed at different facilities[23, 24, 25, 26]. Picture 6 from [26] shows the compilation of data points from the various experiments: the situation is therefore not very clear, considering in particular

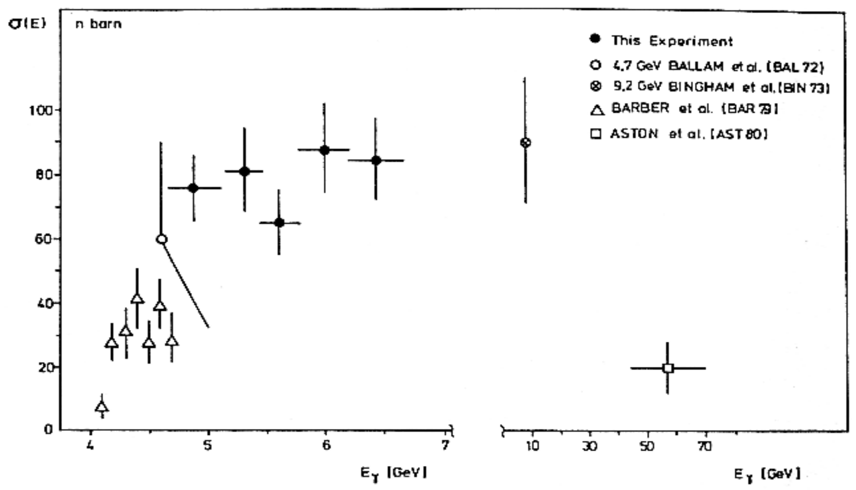

Figure 6: Total cross section for reaction $\gamma p \to p\bar{p}p$ from past experiments.

that all these experiments did not rely on a full particle identification capability, a feature instead typical of CLAS. In [26] there was an attempt to identify the underlying processes, but the limited statistics did not allow to obtain very reliable conclusions. In [26] a possible evidence for narrow states with mass around 2 GeV/c^2 in the $p\bar{p}$ system was reported, although with very limited statistics that makes difficult to draw definite conclusions. These results call for confirmation and it would be of course particularly interesting to observe the formation of such resonant states in photoproduction, therefore with a different production mechanism. No measurements at all exist for $n\bar{n}$ photoproduction. Measuring such process would be very important both to attempt the above mentioned indirect measurement of the neutron time-like form factor as well as for checking the existence of low-mass narrow states.

2.2 Recent data from CLAS

Data from TJNAF experiment E-93-031 have been analysed to extract the $p\bar{p}$ yield[27]: the $p\bar{p}$ production channel was identified requiring detection of two protons and looking for an antiproton peak in the missing mass distribution, which is shown in fig. 7 The total cross section was obtained using reaction $\gamma p \to p\pi^+\pi^-$ as normalisation reference. Angular and mass distributions have been analysed as well. Looking at the $p\bar{p}$ invariant mass (fig 8), data from CLAS actually show a couple of peaks apparently deviating from a smooth background. Two peaks are still visible if only the $p_{slow}\bar{p}$ combination is taken, but statistics is lower and makes it more difficult to draw certain conclusions.

Due to the particular trigger of experiment E-93-031, requiring two charged particles, the available CLAS data do not contain events for the $n-\bar{n}$ reaction. It is also evident that statistics for the $p-\bar{p}$ final state is not sufficient to reliably extract the physics discussed above. On the other hand, the analysis performed indicates the feasibility at least of the

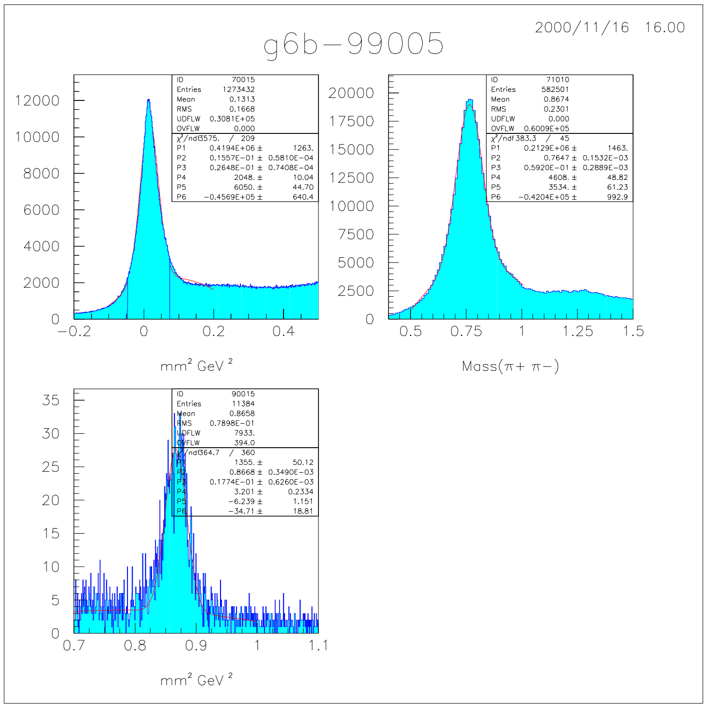

Figure 7: Top left: missing mass distribution for the reaction $\gamma p \to p\pi^+$, the cut around the π^- peak is shown; top right: invariant mass of $\pi^+\pi^-$ pair obtained from events inside the cut of the previous plot; bottom: antiproton production peak in the missing mass for reaction $\gamma p \to pp$. Data from g6b running period.

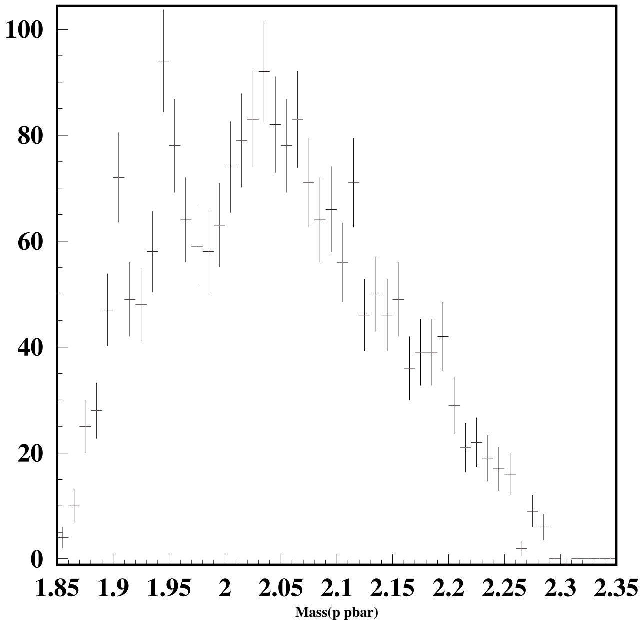

Figure 8: Invariant mass of the system $p - \bar{p}$ from CLAS.

$p-\bar{p}$ measurements: based on that, we began to study how to optimize the performance of CLAS in order to continue and improve the data taking as well as to extend it to the $n-\bar{n}$ reaction.

3 Simulations For a New Experiment with CLAS

To the purpose of understanding acceptances and evaluating the feasibility of a measurement involving detection of $p\bar{p}$ and $n\bar{n}$ states, we performed Monte Carlo simulations with different assumptions about the underlying production mechanisms. We assumed that the nucleon-antinucleon pair could be produced via: 1) generic phase space production, 2) a purely diffractive mechanism and 3) a mixture of (1) and (2) with equal weights. In this first simulation, we wanted to compare our generated distributions with part of the data taken during the g6b run (1999). In this section we will show the most interesting comparison corresponding to the last photon energy bin, between 5 and 5.2 GeV. To take into account the detector features, events were thrown into the GEANT package which describes the CLAS detector in full detail, then reconstructed applying the same analysis chain as for the actual data.

3.1 $p-\bar{p}$

It turns out that at this photon energy the average acceptance for detection of the pp pair is around 6 %. Although the angular cut will be different for protons and neutrons, this Monte Carlo can give an idea of the expected distributions both for $p\bar{p}$ and $n\bar{n}$ photoproduction, of course assuming that the underlying physics be the same.

Figure 9 shows the proton angle distribution in the LAB frame for data and MC. Figure 10 shows the reconstructed antiproton angle distribution in the LAB frame for data and MC.

From this preliminary analysis, it looks like diffractive scattering is not the only process contributing to $p\bar{p}$ production at this energy; however, also phase space alone does not seem to explain data completely. Work is in progress to introduce other mechanisms in the Monte Carlo, like for instance a u-channel type of process, to compare with data. Having a much higher statistics would help clarifying the physics involved and hopefully indicate a way for extracting the relevant physics.

Both data analysis and simulations indicate that we have a strong fall-off of the acceptance at forward angles and this effect is certainly reducing significantly the amount of information on the nature of the physical mechanisms involved. To increase the acceptance by 20-30 %, one possible technical solution may be to retract the hydrogen target by about 50 cm with respect to the nominal central position in CLAS. This possibility has been extensively studied for the upcoming electron run at 5.75 GeV and showed to be effective. Studies are under way to verify the effectiveness of this experimental set-up.

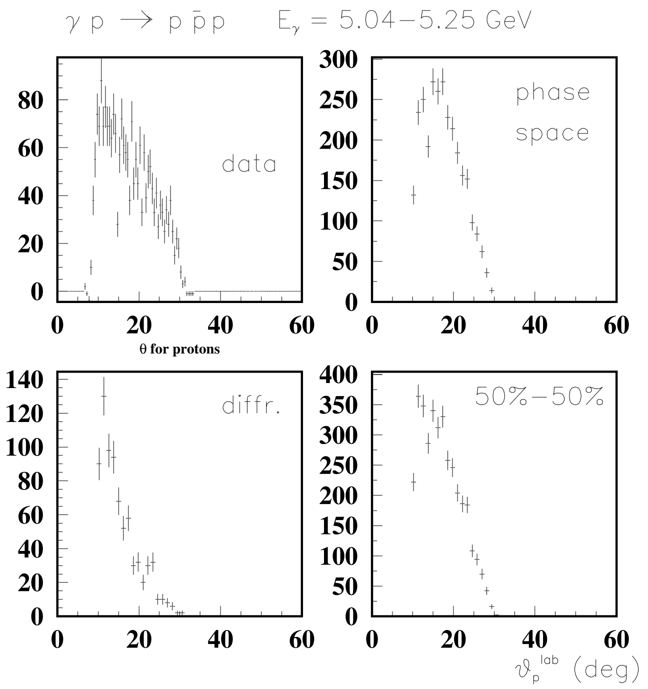

Figure 9: Distribution of θ_p angle in the Lab system; sequence of plots as in previous picture.

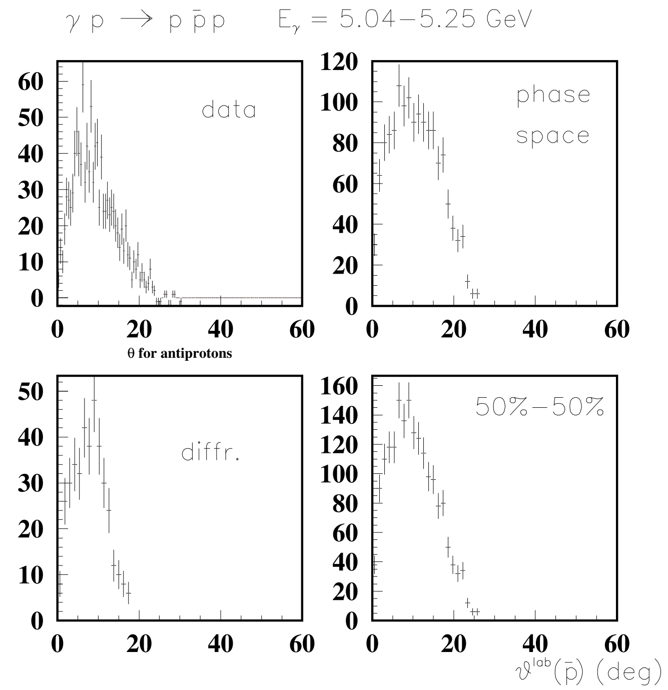

Figure 10: Distribution of $\theta_{\bar{p}}$ angle in the Lab system; sequence of plots as in previous picture.

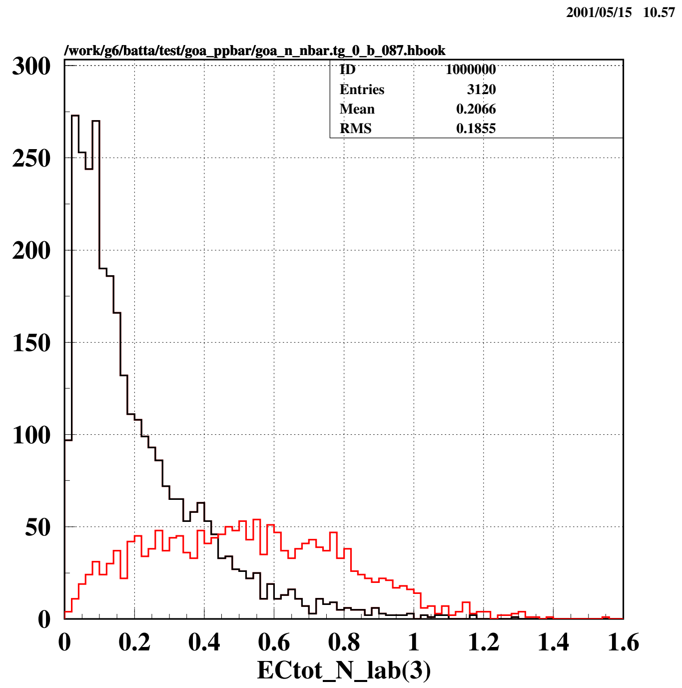

Figure 11: Spectra of total deposited energy in the CLAS forward calorimeters for neutrons (black) and antineutrons (red).

3.2 $n\bar{n}$ production

This measurement would be of extreme interest as it could provide both an alternative method for measuring the neutron time-like form factor and it could provide a confirmation of the existence of narrow states decaying into nucleon-antinucleon pairs: this could be achieved by simply studying the missing mass with respect to the proton only, once the final state is identified. As preliminary investigation, we studied the response of the CLAS forward calorimeters to neutrons and antineutrons using the above mentioned GEANT package. The reaction was simulated again as a mixture of phase space and diffractive production, then we looked at the corresponding spectrum of total energy deposition in the forward CLAS calorimeters: the result is reported in figure 11 This result indicates that a partial identification of antineutrons may be achieved just looking at the total energy deposition, but other distributions need to be investigated, namely the inner versus outer energy deposition provided by the vertical subdivision of the calorimeters into two separate submodules; another important information may be given by the X,Y moments of the energy deposition that are calculated from the transverse energy distribution in the calorimeter cells.

4 Summary

Nucleon-antinucleon photoproduction is connected to basic nucleon form factors, traditionally investigated at electron-positron or proton-antiproton colliders. Thanks to the Lorentz boost, high energy photoproduction can give access to the threshold region in the energy of the nucleon-antinucleon system, allowing to additionally investigate the existence of narrow resonances, indicated by the literature and suggested by recent CLAS measurements. Analysis of available data have shown that CLAS has the capability to detect and identify antiprotons in the final state; preliminary cross sections have been calculated and angular and mass distributions studied. Simulations have shown that CLAS is actually accessing a significant portion of the available phase space; studies are in progress about the possibility of improving the acceptance by retracting the hydrogen target. Neutron-antineutron detection has been simulated and promising results have been obtained, exploiting the large amount of information provided by the CLAS forward calorimeters: $n\bar{n}$ photoproduction has never been measured and it may provide access to the neutron time-like form factor, only studied in one pioneering experiment in Frascati: such measurements produced a puzzle with respect to quark model expectations; moreover, one would expect that if narrow states decaying into $p-\bar{p}$ exist, they should show up in $n-\bar{n}$ as well. We are continuing these studies with the purpose of elaborating a dedicated physics proposal for CLAS.

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