Exploring Very High Missing Momenta in Deuteron Electro-Disintegration

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Abstract

We propose to measure the D(e,e$'$p)n cross section at $Q^2 = 3.5$ (GeV/c)^2 and $x_{bj} = 1.30$ for missing momenta ranging from $p_m = 0.5$ GeV/c to $p_m = 1.0$ GeV/c expanding the range of missing momenta explored in the Hall A experiment (E01-020) for the same electron kinematics. At these energy and momentum transfers calculations based on the eikonal approximation have been shown to be valid and recent experiments indicated that final state interactions are relatively small and possibly independent of missing momenta. This experiment will provide new data relevant to the study of short range correlations and high density fluctuations in nuclei. For the proposed experiment we need the standard Hall A equipment and requests a total beam time of 17.1 days

1 Physics Motivation

High energy exclusive electro-disintegration of the deuteron is considered as the most effective process in probing two nucleon dynamics at short space time separations. The latter condition is essential for probing the limits of nucleonic degrees of freedom in strong interaction dynamics. The justification for high Q^2 and $x_{bj} > 1$ deuteron break-up being one of the most effective tools for such investigations was based on the theoretical expectation that at these kinematics two-body soft processes are either suppressed (such as meson exchange currents) or under the control (such as isobar contribution and final state interactions).

A previous Hall A experiment determined the D(e,e′p)n cross section at a relatively low momentum transfer of $Q^2 = 0.67$ (GeV/c)^2 for missing momenta up to $p_m = 0.55$ GeV/c at $x_{bj} \approx 1$ [1]. At this kinematic setting final state interactions dominate the cross section especially for missing momenta above 0.4GeV/c. This has been confirmed by two recently completed experiments[2, 3, 4] at Jefferson Lab representing the first attempts to systematically study the exclusive deuteron break-up reactions in the $Q^2 \geq 1$GeV^2 region. They also confirmed that meson-exchange currents are a small correction to the overall cross section and that isobar currents can be kept under control by choosing $x_{bj} > 1$[4].

An important result of these experiments was that even though the final state interaction in many cases is not small it can be understood quantitatively(fig. 1). Already at $Q^2 \geq 2GeV^2$ the eikonal regime is established which allows one to perform increasingly reliable estimates of these effects.

From the theoretical point of the view the main question which is presently considered most intriguing is how far one can extend the boundaries of the theoretical framework based on the description of the deuteron as a two-nucleon system? This question can be answered only if one starts to probe the deuteron at extreme kinematics corresponding to very large initial momenta of nucleons in the deuteron.

In the CLAS experiment, cross sections for large recoil momenta have been determined, however it was necessary to integrate over a wide range of momentum transfers (1 (GeV/c)^2) and neutron recoil angle ($0° - 180°$). As a consequence the reaction dynamics is not well defined for these experimental cross sections and at recoil momenta above 0.5 GeV/c the cross sections are completely dominated by final state interactions.

As we will argue in this proposal, the experience we gained from the two recent JLab experiments allows us for the first time to push our studies to the significantly unexplored kinematical domain of probing missing momenta

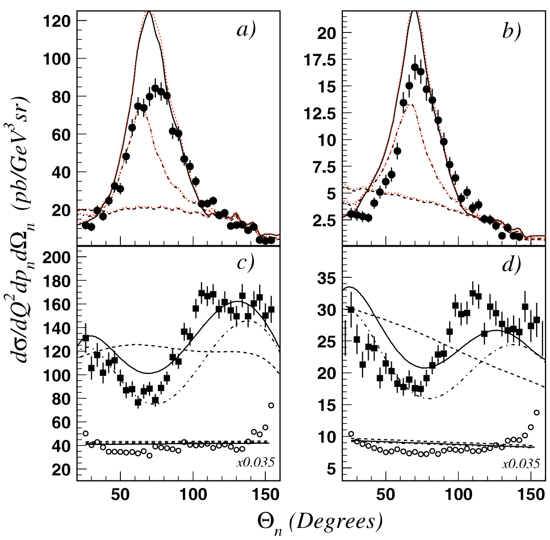

Figure 1: Angular distribution of recoiling neutrons measured in CLAS for (a) $Q^2 = 2 \pm 0.25$ (GeV/c)^2, $400 < p_n < 600$ MeV/c, (b) $Q^2 = 3 \pm 0.5$ (GeV/c)^2, $400 < p_n < 600$ MeV/c, (c) $Q^2 = 2 \pm 0.25$ (GeV/c)^2, $200 < p_n < 300$ MeV/c, (d) $Q^2 = 3 \pm 0.5$ (GeV/c)^2, $200 < p_n < 300$ MeV/c. The data for $p_n < 100$ MeV/c are plotted in the bottom part of (c) and (d), scaled by 0.035. The dashed, dashed-dotted and solid curves are calculations with the Paris potential using PWIA, PWIA+FSI and PWIA+FSI+MEC+IC respectively [4].

up to $1GeV/c$ at $Q^2 = 3.5GeV^2$ with a kinematic setting that is well defined, minimizes final state interactions, MEC and IC, and suppresses the indirect reaction where the neutron is hit and one observes the recoiling proton. The momentum transfer selected allows us to match the proposed experiment to the previous Hall A experiment (E01-020) for cross calibration and will provide a complete D(e,e$'$p)n cross section data set for missing momenta 0GeV/c $\leq p_m \leq$ 1GeV/c at $x_{bj} = 1.3$ and $Q^2 = 3.5$ (GeV/c)^2.

1.1 Proposed Measurement

In this proposal we plan to perform an exploratory measurement of the:

$$e + d \rightarrow e' + p + n \tag{1}$$

reaction probing missing momenta up to $1GeV/c$ for one setting of Q^2 and x_{bj}. It will be for the first time that high Q^2 deuteron break up is probed in electro-production at such large missing momenta and at a well defined kinematic setting. To interpret this experiment we will use three important

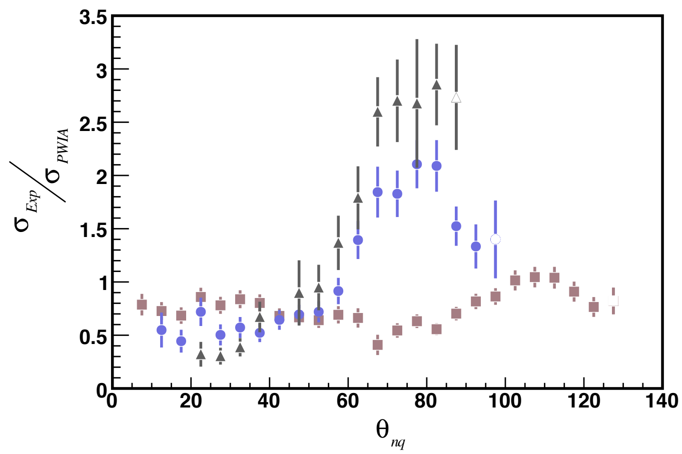

Figure 2: The ratio $R = \sigma_{Exp}/\sigma_{PWIA}$ from the Hall A experiment E01-020 [32].

theoretical observations [5, 6, 7, 8, 9] which the previous two experiments[2, 3] confirmed:

- Generalized eikonal approximation (GEA) is an appropriate theoretical framework for the description of the reaction1 at $Q^2 > 1$ (GeV/c)^2. These experiments confirmed that the FSI is uniquely defined by the missing momenta of the reaction: being dominated by screening effects at $p_m \leq 200$ MeV/c and dominated by pure re-scattering effects at $p_m >$ 300 GeV/c. (See e.g. figure 2).

- At $p_m \geq 400$ MeV/c, the peak of re-scattering is at $\theta_{recoil} = 70^0$ as predicted within GEA[5] and not at 90^0 was was expected within conventional Glauber approximation. (See figure 2)

- The eikonal nature of FSI creates a unique angular dependence of the FSI effects. It is an interplay of screening (interference of PWIA and FSI amplitudes) and re-scattering (square of FSI amplitude) effects which enter with an opposite sign in the cross section of the reaction. The decrease of re-scattering effects at forward and backward recoil angles is associated with the increase of the interference effects. Since both effects are defined by the same re-scattering NN amplitude one arrives at approximate recoil momentum independence of the recoil angles at which these two effects significantly cancel each other (see figure 3).

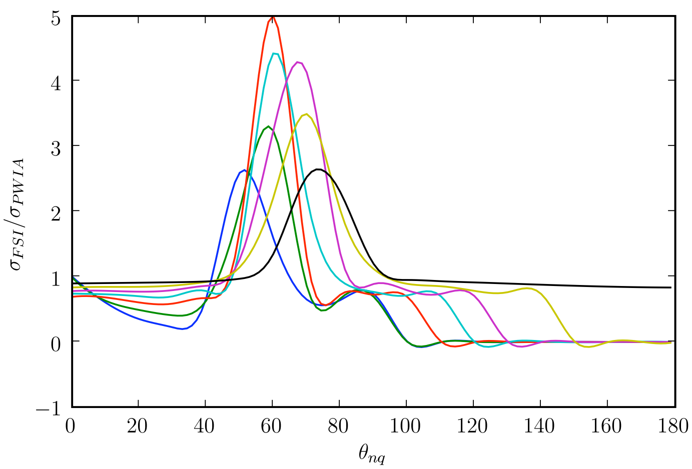

Figure 3: The ratio R ($\sigma_{FSI}/\sigma_{PWIA}$) calculated for missing momenta ranging from 0.4 GeV/c up to 1.0 GeV/c.

The last point of the above observation opens a rather unexpected window to probe the deuteron at very high missing momenta. As it follows from fig. 3 this corresponds to the the recoil angles $\theta_r \approx 70 \pm 30^0$ for which FSI effects are confined within $\approx 30\%$ for missing momenta up to 1 GeV/c.

1.2 What can be learned from these measurements?

Being able to confine FSI effects within 30% and pushing the measurements up to $p_m = 1GeV/c$ will allow us for the first time to probe the sensitivity of the scattering process to the (i) Reaction dynamics (ii) Deuteron wave function and (iii) Non-nucleonic degrees of freedom.

1.2.1 Reaction Dynamics

The description of the electromagnetic interaction with bound (off-shell) nucleons possesses many theoretical uncertainties. The origin of the off-shell effects in the $\gamma^* N_{bound}$ scattering amplitude is somewhat different for low and high energy domains. In the case of low energy transfer the nucleons represent the quasi-particles whose properties are modified due to the in-medium nuclear potential (see e.g. [17]). At high Q^2 the virtual photon interacts with nucleons and the phase volume of the process is sufficiently large. As a result the off-shell effects in the high energy limit are mostly related to the non-nucleonic degrees of freedom. There are several approaches to treat the off-shell effects in the high energy limit. One of the frequently used models is the virtual nucleon approximation (see e.g.[18, 19, 6], in which the scattering is described in the LAB frame of the nucleus and electrons scatter off the virtual nucleon whose virtuality is defined by the kinematic parameters of the spectator nucleon. In this case the form of the wave function is defined through the evaluation of the amplitude at the one-mass shell pole of the spectator nucleon propagator in the Lab frame. This yields an off- energy - shell state of the bound nucleon.

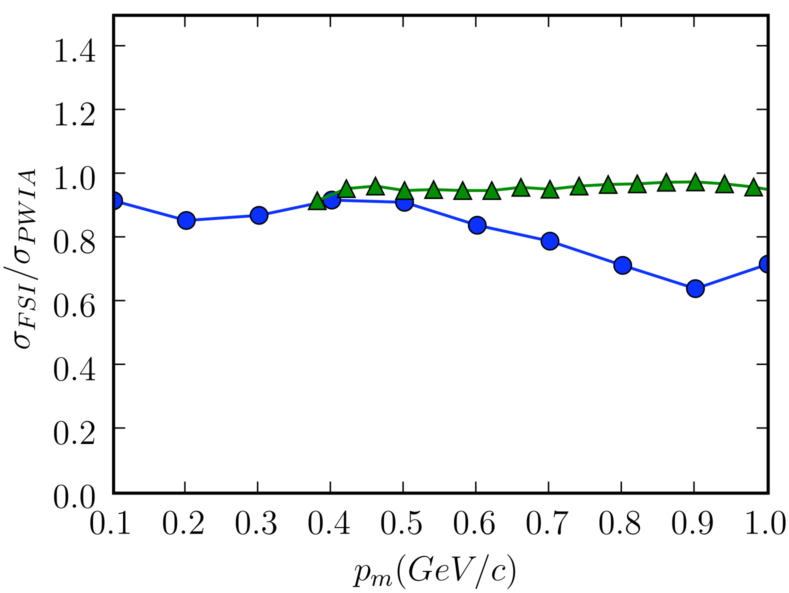

Figure 4: The ratio R for $x_{bj} \approx 1.3$ as calculated my M.Sargsian (blue circles) and J.M.Laget (green triangles).

1.2.2 Deuteron Wave Function

Our knowledge of the deuteron wave function is restricted up to 400 MeV/c relative momentum. Wave functions based on different NN potentials start to diverge beyond this momentum range. The uncertainty of the deuteron wave function is not only related to the uncertainties of the NN potential. The problem is more conceptual in a sense that the many potentials constructed in configuration space based on the local (static) approximation become less and less relevant with the increase of the relative momenta of the interacting nucleon. Staying within the framework of nucleonic degrees of freedom this issues is related to the accounting for the relativistic effects in two-nucleon systems. These effects are significant in the region influenced by the core of the NN interaction.

The two points discussed above are based on the nucleonic picture of both interaction dynamics and nuclear wave function. These approximations have never before been applied to the large Q^2 kinematics when very large missing momenta are probed.

One expects that at some point these approximations should fail qualitatively similar to what happened in high energy large angle photo-disintegration reactions of the deuteron[20, 21, 22, 23, 24]. The proposed experiment may answer at which kinematics such a breakdown occurs.

1.2.3 Non-nucleonic degrees of freedom

Theoretically one expects that with a recoil energy exceeding the pion-threshold, the contributions due to non-nucleonic degrees of freedom should become increasingly important. To date there are only very few nuclear experiments[20, 21, 22, 23, 24] for which such transition is clearly observed. These experiments played a very significant role in the advance of different theoretical approaches that explicitly take into account quark-degrees of freedom in the nuclear interaction[25, 26, 27].

Deuteron electro-disintegration with 1 GeV/c recoil momentum will be one of such experiments.

We don't expect to resolve all the above issues with one such measurement, however this measurement will be the first one in which the kinematics are taken to the limit where a transition to non-nucleonic degrees of freedom is expected.

1.3 Theoretical support of these studies

The above mentioned experiments[2, 3] generated significant interest in new theoretical studies of high energy electro-disintegration processes. Several theoretical groups now are working on the theory of high energy deuteron electro-disintegration (e.g. [10, 11, 12, 13, 14, 15]). These groups established the benchmarking collaboration to verify the agreement of their calculations at more conventional kinematical situations[16]. Assuming that these groups agree at low missing momentum kinematics, their comparisons with the data at very large missing momenta will allow to set-up the limits on how much the approximations based on nucleonic degrees of freedom can account for the cross section of the reaction.

2 Experimental Program

We plan to measure the D(e,e′p)n cross section at kinematic settings centered on the following missing momenta: $p_m = 0.5$, 0.6, 0.7, 0.8,0.9 and 1.0 GeV/c. For each setting the electron arm will remain unchanged and the electron kinematics will be fixed at $Q^2 = 3.5$ (GeV/c)^2 and at $x_{bj} = 1.3$.

Small recoil momenta of the order of 0.1 GeV/c will be measured as a normalization measurement since at these values contributions of FSI, MEC and IC are small. This has been confirmed by measurements at much lower Q^2 values [29, 30, 31]. In addition we will also measure the ^{1}H(e,e′p) hydrogen elastic cross section in between each kinematic setting.

Fig. 2 shows the ratio between the experimental D(e,e′p)n cross section determined in the E01-020 experiment [32] and the calculated one using PWIA (using MCEEP and the PWIA model of S. Jeschonnek). For $p_m = 0.5$ GeV/c large FSI effects exist for for $\vartheta_{nq} \approx 70°$ ($x_{bj} \approx 1$) as well as for $\vartheta_{nq} \leq 35°$ ($x_{bj} \geq 1.5$). For angles larger than 100° the energy transfer is increasing (x_{bj} is decreasing) and one expects increasing contributions of isobar currents.

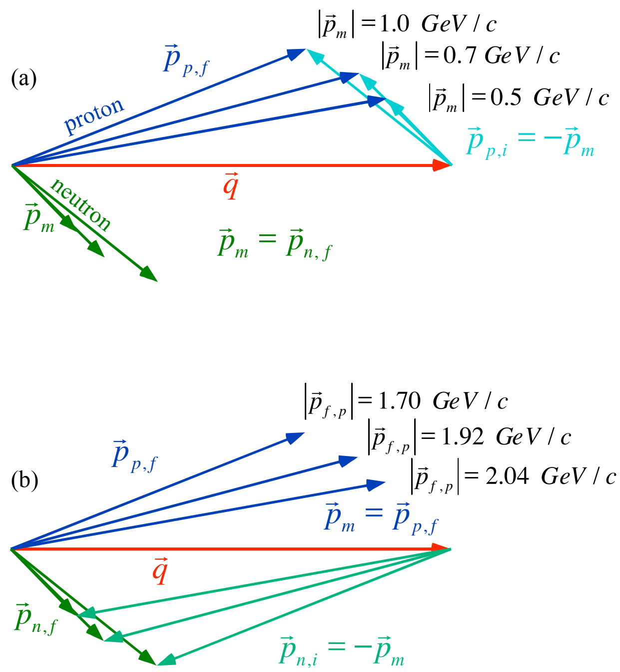

Figure 5: The momentum vectors for the direct proton knockout (a) and for the indirect reaction (b) where the proton is the spectator and the neutron absorbs the virtual photon.

In figure 2 one can see that at a neutron recoil angle of about 40 - 45°, corresponding to a value of x-Bjorken of $x_{bj} \approx 1.3$, the effects of FSI are reduced to 20 - 30% and seem to depend only weakly on the recoil momentum. This phenomenon is reproduced by the calculations of J.M. Laget and M. Sargsian (figure 3). The estimated FSI effect as a function of missing momentum for a fixed neutron recoil angle of 40° is illustrated in figure 4 by the ratio $R = \sigma_{FSI}/\sigma_{PWIA}$. The calculations are from M.Sargsian J.M. Laget. It is due to this observation that we selected the electron kinematics. The following criteria determined the selection of the momentum transfer:

- The momentum transfer has to be large enough for GEA to be applicable
- The final proton momentum has to be significantly larger than the neutron recoil momentum in order to suppress the indirect reaction where struck particle is the neutron and the observed proton is the recoiling spectator. As shown previously the interference of these two processes leads to a reduction of the cross section.
- The proton final momentum has to fit into the momentum acceptance of the right HRS.

The relation between the momentum vectors for the direct and the indirect reaction are illustrated in figure 5 for a range of missing momenta between $p_m = 0.5$ GeV/c and $p_m = 1.0$ GeV/c. The top figure shows the direct reaction where the proton with an initial momentum of for example $p_m = 0.7$ GeV/c absorbs the virtual photon and is ejected with a final momentum of $p_f = 1.99$ GeV/c. For the indirect reaction, a neutron with in initial momentum of 1.99 GeV/c absorbs the photon and the recoiling proton is observed. We expect that the probability to find a nucleon with an initial momentum of 1.9 GeV/c is considerably smaller compared to the one of finding a nucleon with an initial momentum of 0.7 GeV/c. Overall the ratio between the final nucleon momentum and the recoil momentum is always larger than 1.6 in all kinematic setting and consequently we do not expect an effect of the indirect reaction of more than 15%. The detailed kinematics can be found in Tab. 1 below. The acceptance in missing momentum for each kinematic setting is shown in figure 6.

p_m	E_f	ϑ_e	$\lvert\vec{q}\rvert$	p_f	ϑ_p	ϑ_{pq}	ϑ_{nq}
0.5	3.815	24.13	2.358	2.041	51.53	10.11	45.78
0.6	3.815	24.13	2.358	1.985	53.89	12.48	45.63
0.7	3.815	24.13	2.358	1.922	56.20	14.79	44.48
0.8	3.815	24.13	2.358	1.852	58.48	17.07	42.80
0.9	3.815	24.13	2.358	1.777	60.75	19.34	40.82
1.0	3.815	24.13	2.358	1.696	63.03	21.61	38.66

Table 1: Central kinematic settings for the proposed experiment. The incident energy assumed is $E_i = 5.25$GeV. The electron kinematics is help fixed at $x_{bj} = 1.30$ and $Q^2 = 3.5(\mathrm{GeV/c})^2$.

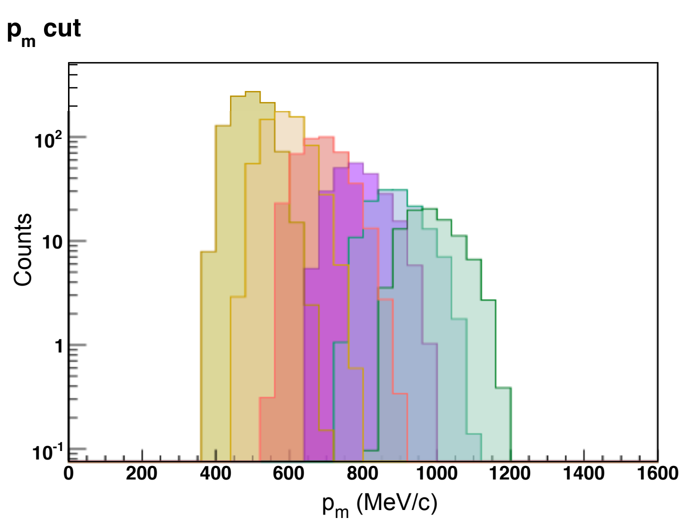

Figure 6: Acceptance in missing momentum for the proposed kinematic settings. The cuts described in the section on count rates have been applied.

Clearly the different setting have considerable overlap. We plan to use this overlap to obtain a continuous data set of cross sections between a missing momentum of 0.5 and 1.0 GeV/c. The estimated statistical errors of the data are indicated in figure 8. We expect that this experiment is dominated by the statistical error since one typically obtains a systematic error of the order of 5 - 7%. The expected statistical errors range from 7% for the lower missing momenta to 25% for 1.0 GeV/c. Given that this kinematic region can be considered as an unexplored new territory we believe that a 25% measurement is still very valuable.

3 Count-Rates

The coincidence count-rates have been estimated using the Hall-A monte-carlo program MCEEP [33].The following additional cuts have been applied:

acceptance : We have used a combined acceptance cut using the r-function with the same value that has been used in the analysis of the E01-020 data namely $r \geq 0.01$.

recoil angle ϑ_{nq} **:** $\vartheta_{nq} = 40° \pm 5°$

missing momentum : missing momentum bin width = ± 0.02 GeV/c

missing energy : $-2. \leq \epsilon_m \leq 15.$ MeV

momentum transfer : $Q^2 = 3.5 \pm 0.25$ (GeV/c)^2

A 15 cm liquid deuterium target and a current of 100μA have been assumed, which results in a luminosity of $L = 4.7 \cdot 10^{38}$ cm$^2 \cdot$ sec^{-1}. The results of these estimates are shown in figure 7 showing the counts per hour as a function of missing momentum and in figure 8 the corresponding, estimated statistical errors. The proposed electron kinematics is basically the same as the one

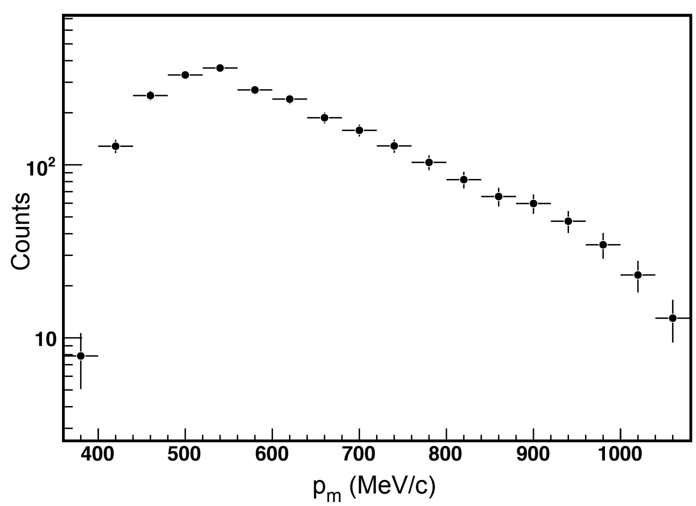

Figure 7: Total counts expected per missing energy bin. Included are all the cuts described in this section and overlapping kinematic settings have been added.

of the previous D(e,e′p)n experiment (E01-020). The singles rates measured previously in E01-020 were 1 Khz for electrons and about 400 Hz for protons for the $p_m = 0.5$ GeV/c setting and we expect similar rates for the proposed kinematics.

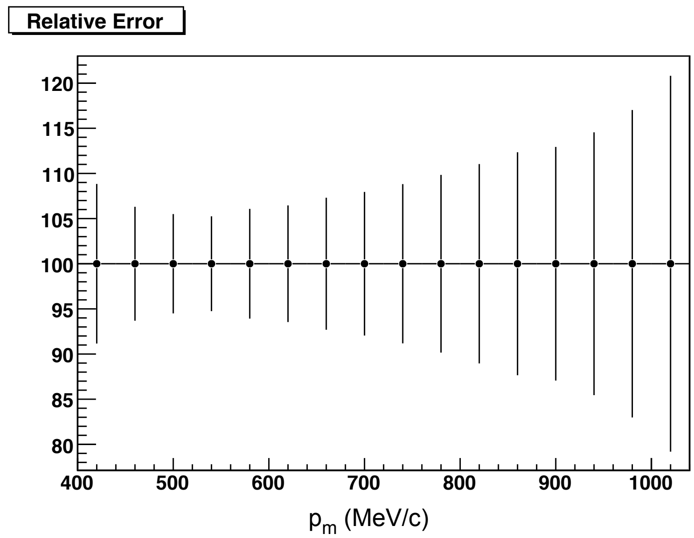

Figure 8: The expected statistical error as a function of missing momentum.

No corrections for accidental coincidences were necessary in the analysis of the $Q^2 = 3.5$ (GeV/c)^2 kinematics of E01-020 data, due to the small single rates (figure 9).

Using the code EPC to estimate the variation of the proton singles rate at the spectrometer settings for the higher missing momenta measurements, we found that it is expected to increase by a factor of 1.6 for the highest missing momentum setting. At this setting the overall signal to noise ratio, using the full acceptance of the spectrometers, a timing window of 5 ns, and without a cut in missing energy was estimated to be 1:1 and we expect this ratio to be much higher once all cuts have been applied.

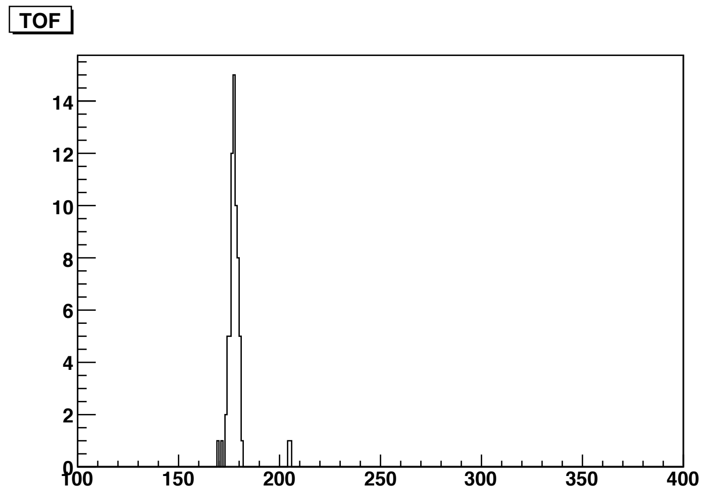

Figure 9: Time of flight spectrum between the two spectrometers as obtained in the E01-020 experiment for $Q^2 = 3.5$ (GeV/c)^2, $p_m = 0.5$ GeV/c and $x_{bj} \approx 1.45$.

Proton and electron singles rates are well within the capabilities of the spectrometer detector systems. The resulting signal to noise ratio is generally large and we do not anticipate any background problems.

In E01-020 we found the Pion rates to be generally well below the singles rates for electron and protons. In the electron arm, pions will be rejected with the Cherenkov detector. For the majority of kinematic settings pions in the hadron arm can be rejected using time-of-flight measurements since the momenta involved are below 3.5 GeV/c and the corresponding time-of-flight difference between pions and protons is $\geq$ 2.9 ns. In addition pion events produce a continuous missing energy spectrum and no significant pion background has been found in the previous experiment.

4 Beam Time Request

We plan to measure a total of 8 different kinematical settings (including the hydrogen elastic calibrations). Table 2 shows the summary of the requested beam time. The beam time on target required to achieve the necessary statistics includes the following items:

- Time to check the spectrometer pointing
- Time for target changes
- Measurements on the dummy target cell
- Time for field changes
- 4 elastic scattering measurements on hydrogen in between new p_m settings.
- A factor of 1.25 has been applied to account for radiative losses.

Also no efficiency factor for Hall A has been taken into account.

p_m GeV/c	Data Taking	Overhead	Sub-total
0.1	1.25	1.58	2.83
0.5	49.26	1.58	50.84
0.6	55.30	1.58	56.88
0.7	54.40	1.58	55.98
0.8	49.00	1.58	50.58
0.9	51.79	1.58	53.37
1.0	81.98	1.58	83.56
Optics Commissioning			16
Target Commissioning			16
^{1}H(e,e′p) calibrations	4.0	20.67	24.67
TOTAL			410.72

Table 2: Beam Time Overview

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