

Question 3 *Inelastic scattering contribution is discussed, but I’m still a little confused. You state that this background is small. Great, but how uncertain is it?*

The singles rate in HCal is huge and apparently the coincidence rate between BigBite and HCal is also large. How uncertain is the inelastic rate?

You base it on a model, how valid is it for your needs?

How much of the inelastic tail do you measure, e.g. how much of Figs. 10 and 11 will come from data? If this background is twice as big as you expect, do you have recourse?

“Inelastic scattering contribution is discussed, but I’m still a little confused. You state that this background is small. Great, but how uncertain is it?”

The statement made in our proposal is that the inelastic scattering contribution to the quasi-elastic statistics is low. To be specific, in this context, we are discussing the $e - N$ scattering in the resonance region. Our quasi-elastic $e - N$ MC generator uses the Kelly form factor fits¹. Our inelastic resonant $e - N$ MC generator uses the model by P. Bosted and E. Christy². This model is a fit of $e - N$ data in the resonance region from Jefferson Lab Hall C³ which covers $0 \leq Q^2 < 8(\text{GeV}/c)^2$, with beam energies up to 5.5 GeV. According to ², the fit residue to the data between 4 and 6 GeV fluctuates by $\pm 10\%$. We assume a 20% systematic uncertainty on our inelastic cross section.

We have determined that the inelastic scattering contribution to our quasi-elastic sample, within the analysis and selection detailed below, is less than 1%, with 0.2% uncertainty.

As discussed in the proposal, the relevant variables to select the quasi-elastic $e - N$ scattering from the resonant $e - N$ scattering are the missing mass $W^2 = M_N^2 + 2M_N^2(E - E') - Q^2$, evaluated with the BigBite resolution, of the system $N(e, e')X$, and the transverse missing momentum. Figure 1 displays the event distributions in W^2 for both our simulated quasi-elastic and inelastic samples within the following set of fiducial acceptance cuts:

- the electron track is reconstructed in BigBite;
- the total energy deposited in the BigBite calorimeter is above the

¹Phys. Rev. C 70, 068202 (2004)

²Phys. Rev. C81.055213, <https://arxiv.org/abs/0712.3731>

³<http://arxiv.org/abs/nucl-ex/0410027>

3 GeV threshold for an average 4.2 GeV elastic peak (for $\epsilon = 0.84$ kinematic);

- the electron track must fire at least 3 PMTs in the GRINCH detectors;
- the total energy deposited in HCal is above the 0.10 GeV threshold. This corresponds to 90% efficiency of the 3.2 GeV/c nucleons which deposit 0.20 GeV in the HCal (scintillator material).

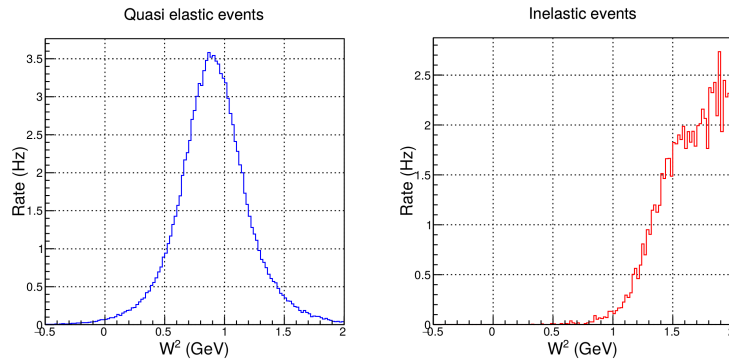


Figure 1: Event distributions in $W^2 = M_N^2 + 2M_N^2(E - E') - Q^2$ for quasi elastic $e - N$ (left) and inelastic resonant $e - N$ (right) within the fiducial analysis cuts.

Before reconstructing the nucleon momentum, it is necessary to apply a selection cut on W^2 to reject a fraction of the inelastic events. To this end, only events for which $W^2 < 1.10 \text{ GeV}^2$ are selected for further discussion. Within this selection, our total number of events counts 97% of quasi-elastic and 3% of inelastic.

Now we will discuss the missing perpendicular momentum. The nucleon momentum and direction is reconstructed using the position of the HCal cluster, on the first step *under the assumption that it is a neutron*. We use the direction of the virtual photon vector \vec{q} (corrected with the vertex position) to project the expected neutron position. The difference between the reconstructed and the projected nucleon position is shown, projected on x (the non-dispersive direction) and y (the dispersive direction), for both quasi-elastic and inelastic events on figure 2. We clearly distinguish in each case two structures, one which can be identified as the neutrons, centered on zero in both x and y , and one which can be identified as the protons, which are deflected upwards and are shifted by about 1 m in y . Figure 3 also shows

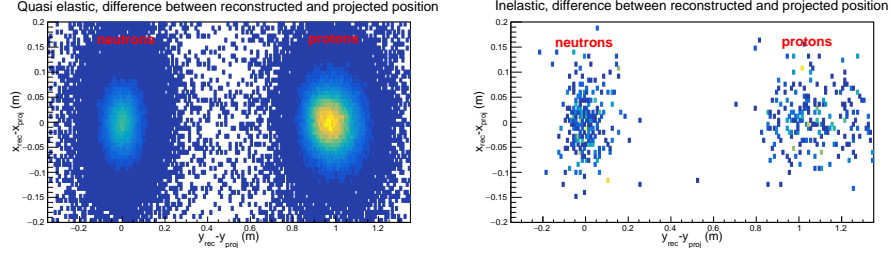


Figure 2: Difference of projected position and reconstructed position for the nucleons in x (non-dispersive direction) and y (dispersive direction), for quasi-elastic events (left) and inelastic events (right). On each plot we clearly notice two structures. The structure on the left, centered at 0, is due to the neutrons. The structure on the right, shifted by about 1 m, is due to the protons, which are deflected upwards by the magnetic field.

the difference between the reconstructed and the projected nucleon position, except projected on y (the dispersive direction), for both the quasi-elastic and inelastic events. Comparing both the expected inelastic and elastic yields in this variable side-by-side evidences further the important role of the $W^2 < 1.10 \text{ GeV}^2$ selection to filter out inelastic events.

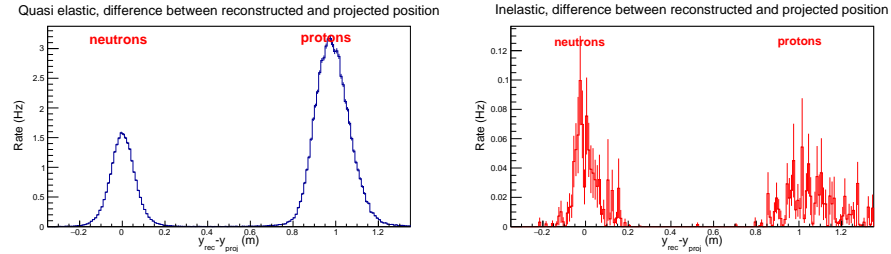


Figure 3: Difference of projected position and reconstructed position for the nucleons projected in y (dispersive direction), compared between quasi-elastic (left) and inelastic (right) events. The selection for these distributions are the fiducial cuts $W^2 < 1.10 \text{ GeV}^2$. We may notice that the selection on $W^2 < 1.10 \text{ GeV}^2$ already reduces drastically the proportion of inelastic with respect to quasi elastic. We may also see that the distribution for the proton is slightly wider.

As a second step, for the nucleons identified as protons (based on the location of the HCal cluster position with respect to its projected position), we need to correct the HCal reconstructed position y_{rec} by the average shift

$\Delta y_{p,avg}$ observed in figure 2 for the nucleons identified as protons.

The nucleon momentum norm $p' = |\vec{p}'|$ is assumed to be equal to the virtual photon norm $|\vec{q}|$. With this information we can calculate the proton shift Δy_p for each proton.

With this information we may build the transverse components of the nucleon momentum (in the SBS coordinates system) $p'_{x,SBS}$ and $p'_{y,SBS}$. For both the protons and neutrons, $p'_{x,SBS}$ can be written as $p'_{x,SBS} = p' \times (x_{rec} - v \sin \theta_{SBS}) / (D_{HCal} - v \cos \theta_{SBS})$ (with v the reconstructed vertex position, D_{HCal} the HCal distance to the target and θ_{SBS} the spectrometer angle. For the neutrons, $p'_{y,SBS}$ is $p'_{y,SBS} = p' \times y_{rec} / (D_{HCal} - v \cos \theta_{SBS})$. For the protons, $p'_{y,SBS}$ must be written as $p'_{y,SBS} = p' \times (y_{rec} - \Delta y_p) / (D_{HCal} - v \cos \theta_{SBS})$.

The nucleon momentum components in the SBS coordinates system $p'_{x,SBS}$ and $p'_{y,SBS}$ can then be transformed (using the corrected HCal distance to the target $D_{HCal} - v \cos \theta_{SBS}$) into the nucleon momentum components in the Hall A coordinate system p'_x , p'_y and p'_z , with the best resolution achievable.

In Hall A coordinate system, using the nucleon momentum combined with the virtual photon vector \vec{q} , we may reconstruct the transverse missing momentum $p_{\perp miss} = \sqrt{(q_x - p'_x)^2 + (q_y - p'_y)^2}$, which is another very powerful variable to reject more inelastic background. Figure 4 displays the event distributions in $p_{\perp miss}$ for our simulated quasi-elastic sample within our fiducial acceptance cuts, and requiring $W^2 < 1.10 \text{ GeV}^2$. After selection on $W^2 < 1.10 \text{ GeV}^2$ and $p_{\perp miss} < 0.1 \text{ GeV}$, the inelastic contamination of our quasi-elastic sample is better than 1%, with 0.2% systematic uncertainties.

The nucleon time-of-flight information can also be used to further suppress background. The HCal time resolution of 0.5 ns allows to resolve time-of-flight for 3.2 GeV/c nucleons with 12% resolution.

In addition, the level of inelastic contamination reported in the document are for the en and ep yields. The observable we are interested in is the ratio N_{en}/N_{ep} , in which the inelastic contribution partly cancels. The cancellation is not complete because the fractional errors in the numerator and denominator will differ. But the partial cancellation results in a fractional error on the ratio which is smaller than the fractional error contributed to the neutron or proton counts. In addition, in the (likely) event that we underestimate our background contamination, we expect to underestimate it by the same amount for $e - p$ and $e - n$, so the point above remains true.

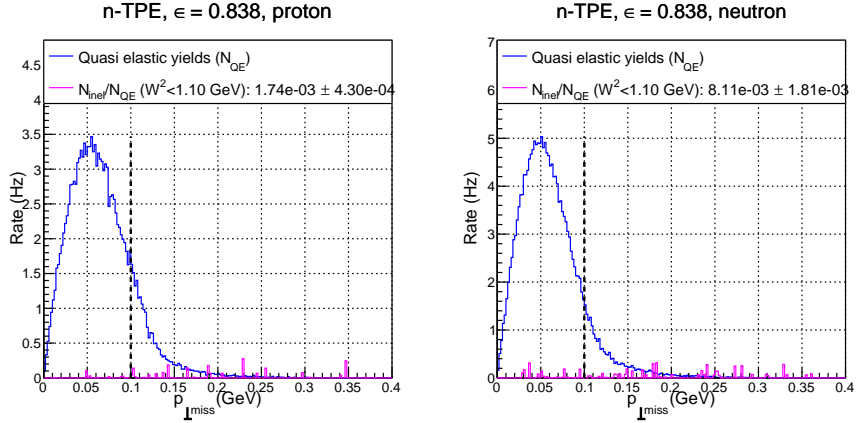


Figure 4: Compared quasi-elastic (blue) and inelastic (magenta) distributions for $p_{\perp miss} = \sqrt{(q_x - p'_x)^2 + (q_y - p'_y)^2}$, within fiducial analysis cuts, after requiring $W^2 < 1.10 \text{ GeV}^2$, for the high ϵ kinematic, separated between protons on the left and neutrons on the right). The inelastic contamination of quasi-elastic events and their error bars are quoted in the legends.

“The singles rate in HCal is huge and apparently the coincidence rate between BigBite and HCal is also large. How uncertain is the inelastic rate?”

The inelastic background has been evaluated by Brian Quinn for the GMn experiment⁴, see also CLAS GMn experiment⁵. Results from our analysis are in agreement with the previous results.

“You base it on a model, how valid is it for your needs?”

As stated earlier, this model is a fit of $e - N$ data in the resonance region from Jefferson Lab Hall C³ which covers $0 \leq Q^2 < 8 \text{ (GeV/c)}^2$, with beam energies up to 5.5 GeV. It may be argued that provided the data set on which this fit is based (for which the beam energy is no higher than 5.5 GeV), we might use it at the limit of its validity for our high ϵ point (for which the beam energy is 6.6 GeV).

“How much of the inelastic tail do you measure, e.g. how much of Figs.

⁴https://www.jlab.org/exp_prog/proposals/09/PR12-09-019.pdf

⁵J. Lachniet *et al.*, Phys. Rev. Lett. 102, 192001 (2009) <https://arxiv.org/abs/0811.1716>, see also Ph.D. thesis from CMU, 2005

10 and 11 will come from data?”

On figure 1, the red spectra are simulated inelastic events detected in the BigBite-SBS coincidence, within our fiducial analysis cuts (defined earlier), in our simulation.

“If this background is twice as big as you expect, do you have recourse?”

If the inelastic background is dramatically larger than what we expect, we should be able to select in our data a clean inelastic sample. We can use this inelastic sample to reevaluate our inelastic contamination prediction and subtract it. We are confident that even if the inelastic background we observe is dramatically higher than our prediction (say, even a factor 10), we have sufficient leverage to understand this contamination and keep the uncertainty on the measured en/ep ratios (and a fortiori on the Rosenbluth slope) under control.

If the single rates in HCal are much higher than expected, we will be aware of the fact early, and we will have the possibility to raise the threshold from 0.1 to 0.15 GeV. The threshold for HCal is set to 0.1 GeV, which selects 90% of the elastic nucleon signal. The energy deposited by an elastic nucleon at 2.4 GeV kinetic energy (corresponding to $Q^2 = 4.5 \text{ GeV}^2$) in the HCal scintillator tiles is 200 MeV with 80 MeV resolution. Raising the threshold to 0.15 GeV would lower the HCal single rates by a factor 3, while only lowering the quasi elastic nucleon efficiency to 74% instead of 90%. Since the accuracy of our measurement is not driven by the statistical uncertainty, we can sacrifice a fraction of our efficiency if the conditions are harsher than we expect.