

# A New Proposal to Jefferson Lab PAC48

## Measurement of the Two-Photon Exchange contribution to the electron-neutron elastic scattering cross section

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## Abstract

We propose to make a high precision measurement of the two-photon exchange contribution (TPE) in elastic electron-neutron scattering at a four-momentum transfer  $Q^2 = 4.5$  ( $\text{GeV}/c$ )<sup>2</sup>. While significant efforts to study the two-photon-exchange have focused around elastic electron-proton scattering, the impact of TPE on neutron form factors was never examined experimentally. The proposed experiment will provide the very first assessment of the two-photon exchange in electron-neutron scattering, which will be important for understanding the nucleon form factor physics.

The proposed experiment will be performed in Hall A using the BigBite (BB) spectrometer to detect the scattered electrons and the Super-BigBite (SBS) to detect the protons and neutrons. The experiment should run concurrently with the E12-09-019  $G_M^n$  and E12-17-004  $G_E^n$ -Recoil experiments, which are expected to run in 2021. The experimental setup of the proposed experiment will be identical to that of E12-09-019 experiment.

The “ratio” method will be used to extract the electric form factor of the neutron  $G_E^n$  by scattering unpolarized electrons from deuterium quasi-elastically at two beam energies 4.4 and 6.6 GeV and electron scattering angles 41.9 and 23.3 degrees respectively. In the proposed approach, systematic errors are greatly reduced compared to those in the traditional single electron arm configuration. Several experiments at Mainz and JLab have used the ratio method to measure the neutron magnetic form factor in the past years. The method can be extended to extract the neutron electric form factor even with less stringent requirements on the knowledge of the absolute neutron detection efficiency and experimental kinematics.

## I. INTRODUCTION

In 1950's, a series of experiments performed by R. Hofstadter [1] revealed that the nucleons have a substructure (would be called later the quarks and gluons). The experiment confirmed M. Rosenbluth's theory [2] based on one-photon exchange approximation. In the Born approximation, where the interaction between the electron and the nucleon occurs *via* an exchange of a one virtual photon (OPE), the unpolarized  $e - N$  elastic cross section can be expressed in terms of a nucleon magnetic,  $G_M$ , and electric,  $G_E$ , form factors. These form factors describe the deviation from a point-like scattering cross section:

$$\left( \frac{d\sigma}{d\Omega} \right)_{eN \rightarrow eN} = \frac{\sigma_{Mott}}{\epsilon(1 + \tau)} [\tau \cdot G_M^2(Q^2) + \epsilon \cdot G_E^2(Q^2)], \quad (1)$$

where  $E$  and  $E'$  are the incident and scattered electron energies, respectively,  $\theta$  is the electron scattering angle,  $\tau \equiv -q^2/4M^2$ , with  $-q^2 \equiv Q^2 = 4EE' \sin(\theta/2)$  being the negative four momentum transfer squared,  $M$  is the nucleon mass, and  $\epsilon = [1 + 2(1 + \tau) \tan^2(\theta/2)]^{-1}$  is the longitudinal polarization of the virtual photon. The reduced cross section is defined by:

$$\sigma_r \equiv \left( \frac{d\sigma}{d\Omega} \right) \cdot \frac{\epsilon(1 + \tau)}{\sigma_{Mott}} = \tau \cdot G_M^2(Q^2) + \epsilon \cdot G_E^2(Q^2) = \sigma_T + \epsilon \cdot \sigma_L, \quad (2)$$

where  $\sigma_L$  and  $\sigma_T$  are the cross sections for longitudinally and transversely polarized virtual photons, respectively.

The linear  $\epsilon$  dependence of the cross section is due to the  $\sigma_L$  term, see Eq. 1. The ratio  $\sigma_L/\sigma_T$  is a Rosenbluth slope related to  $G_E/G_M$  (in OPE), see Fig. 1. The data show that at  $Q^2$  of 4-5 (GeV/c)<sup>2</sup> the Rosenbluth slope is three-four times larger than it suppose to be (in OPE) for the observed values of the  $G_E^p/G_M^p$  ratio.

The nucleon electromagnetic form factors can reveal a lot of information about the nucleon internal structure, as well as the quark distribution. The form factors depend only on one variable, the negative square of the four-momentum transfer carried by the photon,  $Q^2$ . In the limit of large  $Q^2$ , pQCD provides well-motivated predictions for the  $Q^2$ -dependance of



FIG. 1. The square root of Rosenbluth slope, corrected for kinematical factor  $\sqrt{\tau}$  and  $\mu_p$ , observed in elastic electron-proton scattering, adopted from Ref. [3].

the form factors and their ratio. However, it was never predicted at what  $Q^2$  range the pQCD prediction (scaling) will be valid. Studies of GPDs show that pQCD validity will require a very large  $Q^2$  of  $100 \text{ (GeV/c)}^2$ . It was discovered at JLab, using the double polarization methods, that the proton electric and magnetic form factors behave differently starting at  $Q^2 \approx 1 \text{ (GeV/c)}^2$ .

Experimentally, the nucleon form factors can be measured using one of two techniques: polarization transfer technique and Rosenbluth technique. The polarization method examines the polarization transfer from longitudinally polarized electron to the recoiling nucleon and determine the resulting azimuthal asymmetry distribution using a polarimeter. Alternatively, one can use the polarized electron beam and a polarized target. While in the Rosenbluth method, the electric and magnetic form factors can be separated by making two or more measurements with different  $\epsilon$  values (*i.e.* different beam energies and angles), but with same  $Q^2$  value. The Rosenbluth technique requires an accurate measurement of the cross section and suffers from large systematic uncertainties arising from several factors. For instance, an accurate knowledge of the neutron detector efficiency is required.

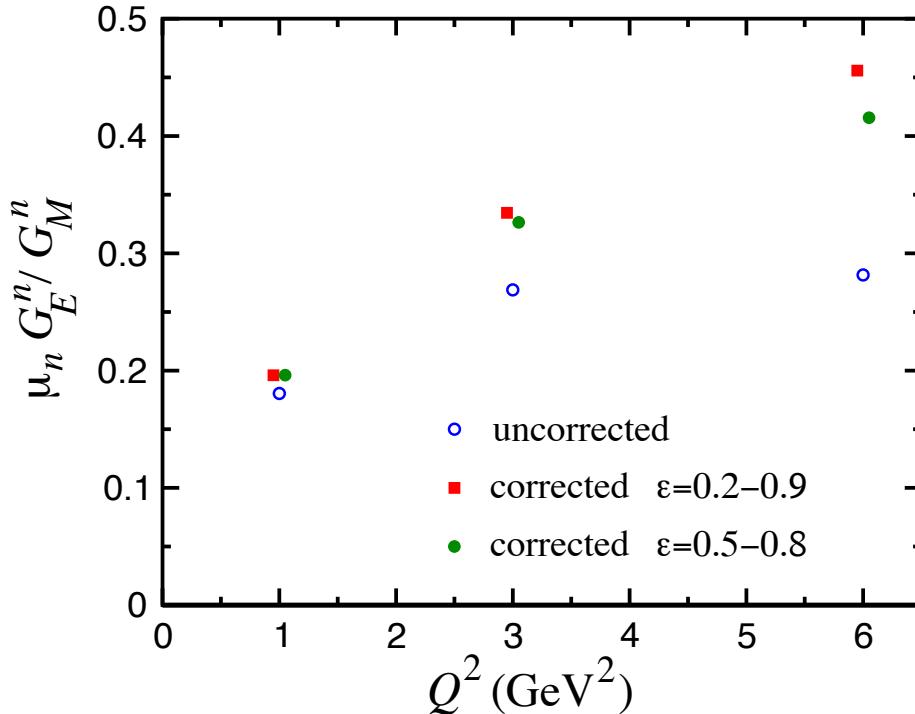


FIG. 2. Projected impact of TPE on  $G_E^n/G_M^n$  using LT separation, according to Ref. [4].

When comparing the values of  $G_E^n/G_M^n$  obtained from both techniques, a significant discrepancy was observed (see Fig. 1). Such discrepancy implies a potential problem in our understanding of the nucleon substructure. Many efforts were made in order to provide legitimate explanation, and it is believed that the inconsistency is due to contribution of two-photon exchange in  $e - N$  elastic scattering process, see Refs. [5, 6]. Predictions made for the neutron case are shown in Fig. 2 , adopted from [4]. The contribution of TPE could reach about 30% of the Rosenbluth slope value at 5 (GeV/c) $^2$ .

In the following we propose to make a precision L/T separation of the elastic electron-neutron cross section and first experimental assessment of the two-photon exchange contribution on the neutron magnetic form factor measurements (see also Ref. [7]). The result of the nTPE experiment will likely add a new component to our understanding of the elastic

<sup>50</sup> electron-nucleon process.

51

## II. PHYSICS MOTIVATION

52      The nucleon plays the same central role in hadronic physics that the hydrogen atom does  
 53    in atomic physics and the deuteron in the physics of nuclei. The structure of the nucleon  
 54    and its specific properties, such as charge, magnetic moment, size, mass; the elastic electron  
 55    scattering form factors, resonances; and structure functions in DIS, are of fundamental sci-  
 56    entific interest. The isospin is a fundamental property of the nucleon, so both the proton and  
 57    neutron investigations are important to do. By using data on the proton and neutron form  
 58    factors the flavour structure could be explored [8]. It is already provided the most direct  
 59    evidence for a diquark correlation in the nucleon [9–11].

60      Hadron structure, as seen in elastic electron scattering, in one-photon approximation,  
 61    defined by two functions of four momentum transfer square. They are: the helicity conserving  
 62    Dirac form factor,  $F_1$ , which describes the distribution of the electric charge, and the helicity  
 63    non-conserving Pauli form factor,  $F_2$ , describes the distribution of the magnetic moment.  
 64    These two form factors are the ingredients of the hadronic current. These form factors  
 65    contain information on the transverse charge distribution for an unpolarized and transversely  
 66    polarized nucleon, respectively, in the infinite momentum frame [12, 13].

67      The Sachs form factors,  $G_E$  and  $G_M$ , the ratio of which will be extracted directly from  
 68    the data, are related to  $F_1$  and  $F_2$  by

$$F_1 = \frac{G_E + \tau G_M}{1 + \tau} \text{ and } F_2 = \frac{G_M - G_E}{\kappa(1 + \tau)}, \quad (3)$$

69    where  $\kappa$  is the nucleon anomalous magnetic moment.

70      Already twenty four years ago, important developments in QCD phenomenology has  
 71    been the exploration of the generalized parton distribution (GPD) formalism [14–16], which  
 72    provides relations between inclusive and exclusive observables. The nucleon elastic form  
 73    factors  $F_1$  and  $F_2$  are given by the first moments of the GPDs

$$F_1(t) = \sum_q \int_0^1 H^q(x, \xi, t, \mu) dx \text{ and } F_2(t) = \sum_q \int_0^1 E^q(x, \xi, t, \mu) dx, \quad (4)$$

74    where  $H^q$  and  $E^q$  are two of the generalized parton distributions,  $x$  is the standard Bjorken  
 75     $x$ ,  $\xi$  is the “skewness” of the reaction,  $t$  is the four-momentum transferred by the electron,

<sup>76</sup>  $\mu$  is a scale parameter necessary from the evolution over  $Q^2$ , analogous to DIS parton dis-  
<sup>77</sup> tributions, and the sum is over all quarks and anti-quarks. These may be accessed through  
<sup>78</sup> processes such as deeply virtual Compton scattering, where the interaction is factorized into  
<sup>79</sup> a hard part with the virtual photon/photon interactions with an individual quark and a soft  
<sup>80</sup> part of the residual system where the GPD information is contained.

<sup>81</sup> Fundamental nucleon feature, the spin, is related to GPDs, as shown by X. Ji [15]. The  
<sup>82</sup> moments of GPDs can yield information, according to the Ji's Angular Momentum Sum  
<sup>83</sup> Rule, on the contribution to the nucleon spin from quarks and gluons, including both the  
<sup>84</sup> quark spin and orbital angular momentum.

<sup>85</sup> At present, experimental measurements of GPDs are still scarce. Until high  $Q^2$  DVCS  
<sup>86</sup> data becomes available, work has been done to attempt to parameterize these GPDs, which  
<sup>87</sup> rely heavily on data from electromagnetic form factors and parton distributions from DIS as  
<sup>88</sup> constraints [17]. Data at high  $Q^2$  for  $G_E^n$  would contribute significantly in the development  
<sup>89</sup> of these models.

<sup>90</sup> As we presented above the form factors are important components for GPDs development.  
<sup>91</sup> However, the cross section of elastic  $e-p$  scattering contains a significant contribution to  $\sigma_L$ ,  
<sup>92</sup> which at high  $Q^2$  is much larger than theory calculations expected [18]. Such an alarming  
<sup>93</sup> observation underlines that understanding of TPE effect is essential for hadron physics.

94

### III. TECHNIQUE

95 This proposal is based on instrumentation, simulation, and analysis development made  
 96 by the GMn/SBS collaboration for the GMn, E12-09-019, experiment [19]. The GMn experi-  
 97 ment is one of several form factor experiments approved by JLab PAC. The SBS spectrometer  
 98 was funded by DOE with large contributions provided by the collaborating institutions from  
 99 USA, Italy, UK, and Canada. The apparatus and DAQ installation will start in 2020 and  
 100 the data taking run is expected to be in summer-fall 2021.

101 The neutron form factors are challenging to be determine experimentally especially be-  
 102 cause there is no free neutron target. However, since the deuterium is a loosely coupled  
 103 system, it can be viewed as the sum of a proton target and a neutron target. In fact, quasi-  
 104 elastic scattering from deuterium has been used to extract the neutron magnetic form factor,  
 105  $G_M^n$ , at modestly high  $Q^2$  for decades [20, 21] in the single arm ( $e, e'$ ) experiments. How-  
 106 ever, the proton cross section needs to be subtracted by applying a single-arm quasi-elastic  
 107 electron-proton scattering. This “proton-subtraction” technique suffers from a number sys-  
 108 tematic uncertainties e.g. contributions from inelastic and secondary scattering processes.

109 Many year ago, L. Durand [22] proposed the so-called “ratio-method” based on the mea-  
 110 surement of both  $D(e, e'n)$  and  $D(e, e'p)$  reactions. In this method, many of the systematic  
 111 errors are cancel out. Several experiments [23–25] have applied the ratio-method to deter-  
 112 mine the neutron magnetic form factor.

113 The GMn/SBS experiment [19] will take data for elastic  $e - n$  scattering for several  
 114 kinematics with  $Q^2$  from 3.5 up to 13.5  $(\text{GeV}/c)^2$ . We propose to use this method to  
 115 measure Rosenbluth slope and extract (in OPE approximation) the neutron electric form  
 116 factor,  $G_E^n$ , at one value of momentum transfer. In fact, one of the required data points  
 117 will be taken by the GMn experiment, so an additional measurement is needed only for one  
 118 kinematics.

119 Data will be collected for quasi-elastic electron scattering from deuteron in process  
 120  $D(e, e'n)p$ . A complementary  $D(e, e'p)n$  data will be taken to calibrate the experiment ap-  
 121 paratus. The current knowledge of the  $e - p$  elastic scattering cross section (obtained in the  
 122 single arm  $H(e, e')p$  and  $H(e, p)e'$  experiments) will be also used for precision determination

<sup>123</sup> the experiment kinematics.

<sup>124</sup> Applying the Rosenbluth technique to measure  $G_E^n$  requires accurate measurement of the  
<sup>125</sup> cross section and suffers from large uncertainties. To overcome this issue, we propose to  
<sup>126</sup> extract the value of  $G_E^n$  from the ratio of quasi-elastic yields,  $R_{n/p}$ , in scattering from a  
<sup>127</sup> deuteron target as follows:

$$R_{n/p} \equiv R_{observed} = \frac{N_{e,e'n}}{N_{e,e'p}} \quad (5)$$

<sup>128</sup>  $R_{observed}$  needs to be corrected to extract the ratio of e-n/e-p scattering from nucleons:

$$R_{corrected} = f_{corr} \times R_{observed} , \quad (6)$$

<sup>129</sup> where the correction factor  $f_{correction}$  takes into account the variation in the hadron efficiencies  
<sup>130</sup> due to changes of the  $e - N$  Jacobian, the radiative corrections, and absorption in path from  
<sup>131</sup> the target to the detector, and small re-scattering correction.

<sup>132</sup> In one-photon approximation,  $R_{corrected}$  can be presented as:

$$R_{corrected} = \frac{\sigma_{Mott}^n \cdot (1 + \tau_p)}{\sigma_{Mott}^p \cdot (1 + \tau_n)} \times \frac{\epsilon \sigma_L^n + \sigma_T^n}{\epsilon \sigma_L^p + \sigma_T^p} \quad (7)$$

It is important that the ratio  $R_{Mott} = \frac{\sigma_{Mott}^n \cdot (1 + \tau_p)}{\sigma_{Mott}^p \cdot (1 + \tau_n)}$  could be determine with very high relative accuracy even with modest precision for the beam energy, electron scattering angle, and detector solid angle. Now, let us write the  $R_{corrected}$  at two values of  $\epsilon$  using  $R_c^{n(p)} = \sigma_L^{n(p)} / \sigma_T^{n(p)}$  as:

$$R_{corrected,\epsilon_1} = R_{Mott,\epsilon_1} \times \frac{\epsilon_1 \sigma_L^n + \sigma_T^n}{\epsilon_1 \sigma_L^p + \sigma_T^p} \quad R_{corrected,\epsilon_2} = R_{Mott,\epsilon_2} \times \frac{\epsilon_2 \sigma_L^n + \sigma_T^n}{\epsilon_2 \sigma_L^p + \sigma_T^p}$$

In these two equations there are two unknown variables:  $\sigma_L^n$  and  $\sigma_T^n$ . The dominant contribution to the uncertainty of the slope of the cross section vs.  $\epsilon$ ,  $S_c^n = \sigma_L^n / \sigma_T^n$ , will come from the uncertainty of  $S_c^p$ . At  $Q^2=4.5$  (GeV/c)<sup>2</sup>, according to the global analysis of  $e - p$  cross section [3], the value of  $S_c^p$  is close to  $1/(\tau \mu_p^2) = 0.107$  with uncertainty of 0.01. The resulting equation for  $S_c^n$  is:

$$A = B \times \frac{1 + \epsilon_1 S_c^n}{1 + \epsilon_2 S_c^n} \approx B \times (1 + \Delta \epsilon \cdot S_c^n),$$

where the variable  $A = R_{corrected,\epsilon_1}/R_{corrected,\epsilon_2}$  will be measured with relative precision of 0.1%. Assuming, for this estimate, equal values of  $Q^2$  for two kinematics, the  $\tau$  and  $\sigma_T$  for two kinematics are canceled out, and the variable  $B = R_{M,\epsilon_1}/R_{M,\epsilon_2} \times (1 + \epsilon_2 S_c^p)/(1 + \epsilon_1 S_c^p)$ . For actual small range of  $\epsilon$  and small value of the slope, the  $B \approx (1 - \Delta\epsilon \cdot S_c^p)$ . The value of  $B$  will be determined from global proton  $e - p$  data to a precision of  $0.25 \times 0.01$ .

At  $Q^2=4.5$  (GeV/c)<sup>2</sup> the ratio  $\mu_n G_E^n/G_M^n$  is  $0.55 \pm 0.05$ , see the review [26]. In a simplest model, the slope  $S_c^n$  is a sum of the slope due to  $G_E^n/G_M^n$  and the TPE contribution. If we use for TPE the prediction [4], Fig. 2, the TPE leads to increase of  $S_c^n$  by a factor of 2, so the result of this experiment for TPE will be  $0.069 \pm 0.012 \pm 0.01$ , where the first uncertainty is due to accuracy of  $G_E^n/G_M^n$  and the second one due to projected precision of this experiment.

It would be a 4-4.5 sigma observation of the neutron TPE.

144

#### IV. PROPOSED MEASUREMENTS

145 We propose to use the same experimental setup of the E12-09-019 experiment. We will  
 146 add a kinematic point at  $Q^2 = 4.5 \text{ (GeV/c)}^2$ , at a higher beam pass (6.6 GeV/3 pass instead  
 147 of 4.4 GeV/2 pass), leading to a higher  $\epsilon$  value. This additional point along with the data  
 148 point of the E12-09-019 experiment will allow us to perform the standard Rosenbluth method  
 149 to obtain (in one-photon approximation) the neutron electric and magnetic form factors. In  
 150 addition, the ratio method (Sec.III), in which the systematic errors are greatly reduced, will  
 151 be implemented to calculate the two photon exchange (TPE) contribution. The study of the  
 152  $\epsilon$  dependance two photon exchange contribution to the neutron form factor ratio  $G_E^n/G_M^n$ .  
 153 Table. I displays the kinematic settings of the proposed experiment.

| Point | $Q^2$<br>(GeV/c) $^2$ | E<br>(GeV) | $E'$<br>(GeV) | $\theta_{BB}$<br>degrees | $\theta_{SBS}$<br>degrees | $\epsilon$ |
|-------|-----------------------|------------|---------------|--------------------------|---------------------------|------------|
| 1     | 4.5                   | 4.4        | 2.0           | 41.88                    | 24.67                     | 0.599      |
| 2     | 4.5                   | 6.6        | 4.2           | 23.23                    | 31.2                      | 0.838      |

TABLE I. Kinematic settings of the proposed experiment. The kinematic point with the lowest  $\epsilon$  value (blue raw) is an existing measurement of the approved E12-09-019 experiment.

154

## V. EXPERIMENTAL SETUP

155 As illustrated in Fig. 3, this experiment will study electron scattering from a 15 cm  
 156 long liquid Deuterium target held in a vacuum. The scattered electron will be detected  
 157 in the BigBite spectrometer with an upgraded electron detector stack. The neutron arm is  
 158 arranged with a dipole magnet 48D48 (SBS) and a segmented hadron calorimeter HCAL. The  
 159 whole detector package was designed and is now under assembling for the GMn, E12-09-019,  
 160 experiment.

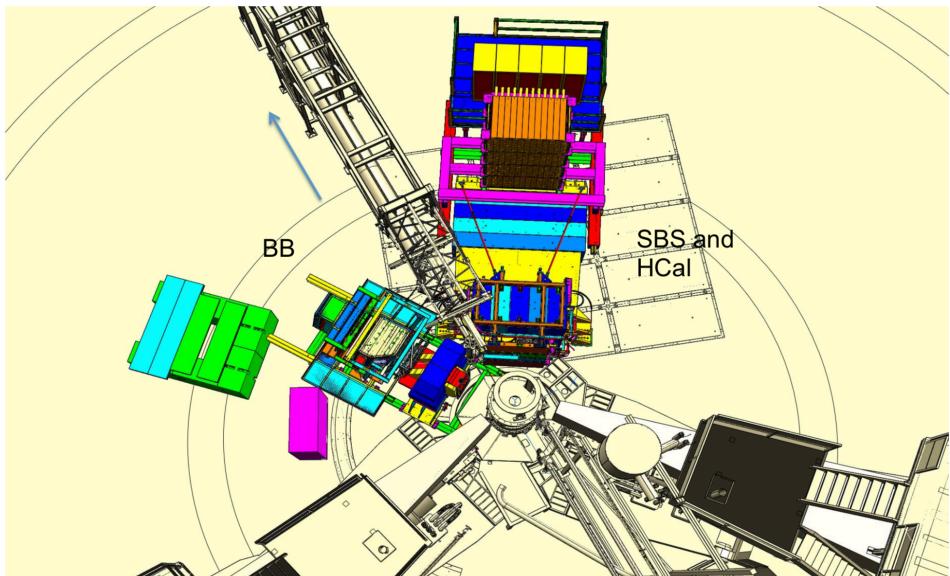


FIG. 3. Layout of the experimental setup in nTPE.

161

### 1. Parameters of the SBS

162 The 48D48 magnet from Brookhaven was acquired as part of the Super Bigbite project  
 163 and will be available for this experiment. It consists of a large dipole magnet which provides  
 164 a field integral of about  $1.7 \text{ T} \cdot \text{m}$ , allowing for quasielastic protons to be sufficiently deflected  
 165 to allow clear differentiation from neutrons. The active field volume has an opening of  $46 \times$   
 166  $25 \text{ vertical} \times \text{horizontal}$ ), matching the aspect ratio of the neutron arm, and a depth of 48  
 167 cm.

<sup>168</sup> The placement of this magnet will be 1.6 m away from the target, which would normally  
<sup>169</sup> interfere with the beamline. To accommodate this, modifications were made to the iron yoke  
<sup>170</sup> such that the beamline will pass through the magnet yoke area.

<sup>171</sup> The field configuration will be such that positively charged particles will be deflected  
<sup>172</sup> upwards away from the hall floor. For a field integral of 1.7 Tesla-m, protons of momentum  
<sup>173</sup> 2.5 GeV/c will be deflected 250 mrad, which translates to a displacement of 1.29 m. Including  
<sup>174</sup> expected detector resolution, the  $p_{miss,\perp}$  distribution will be similar to what was seen in  
<sup>175</sup> E02-013, so cuts of  $< 100$  MeV/c will be appropriate. Monte Carlo simulations show a  
<sup>176</sup> contamination of charged quasielastics to be negligible.

<sup>177</sup> The presence of the magnet also works to sweep low energy charged particles from the  
<sup>178</sup> target away from the neutron arm. Particles of momentum less than 1.3 GeV/c will be  
<sup>179</sup> entirely swept outside of the neutron arm acceptance. This greatly reduces the amount of  
<sup>180</sup> charged low energy background.

181

### A. The BigBite Spectrometer

182 Scattered electrons will be detected in the BigBite spectrometer. The spectrometer con-  
 183 sists of a single dipole magnet (with magnetic field approximately 1.2 T) and a detection  
 184 system, see Fig. 4.

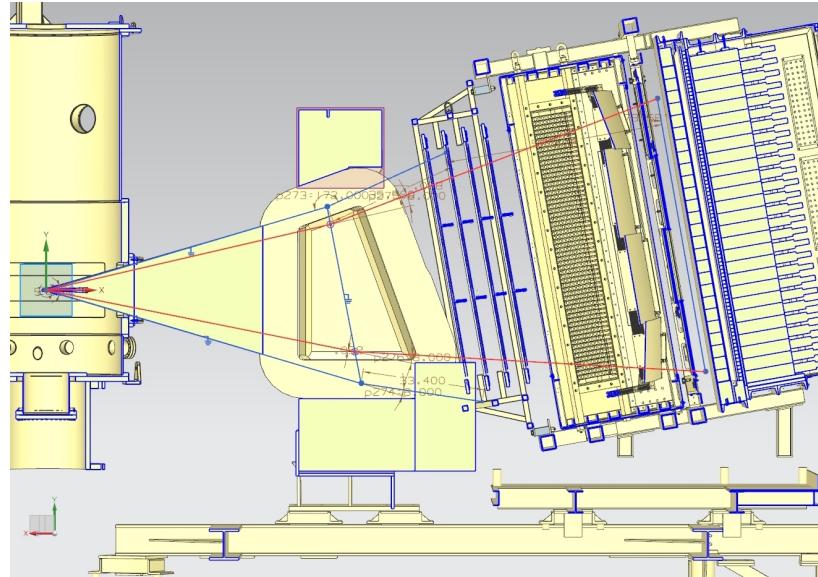


FIG. 4. The BigBite spectrometer with the upgraded detector stack.

185

#### 1. GEM Chambers

186 To perform the tracking of charged particles under the high rates anticipated for this  
 187 experiment, the drift chambers were replaced with gas electron multiplier (GEM) detectors.  
 188 These detectors have proven to be capable of operating under luminosities of  $25 \text{ kHz/mm}^2$   
 189 for the COMPASS experiment at CERN and the spatial resolution of each of these chambers  
 190 is anticipated to be about  $70 \mu\text{m}$ . There will be two sets of GEMs placed on each side of the  
 191 GRINCH Cherenkov detector.

192 The set of GEMs in front of the GRINCH is composed of four layers of GEMs. Two of  
 193 these layers have been built by will the SBS collaborators from INFN. They are composed

<sup>194</sup> three modules each, measuring  $40 \times 50 \text{ cm}^2$ , such that each layer covers  $40 \times 150 \text{ cm}^2$  (the  
<sup>195</sup> long dimension being vertical, along the dispersive direction). The readout of these modules  
<sup>196</sup> are oriented in the  $x/y$  direction *i.e.* parallel and perpendicular to the dispersive direction  
<sup>197</sup> (horizontal and vertical). The two other layers are being built by the SBS collaborators from  
<sup>198</sup> UVA. They are composed of a single module measuring  $40 \times 150 \text{ cm}^2$ , the long dimension  
<sup>199</sup> again being vertical and along the dispersive direction. The readout of these modules are  
<sup>200</sup> oriented in the  $u/v$  direction *i.e.*  $\pm 30$  degrees with respect to the horizontal direction.

<sup>201</sup> The set of GEMs behind the GRINCH has been built by the SBS collaborators from  
<sup>202</sup> UVA. It is composed of a single layer composed of four modules measuring  $50 \times 60 \text{ cm}^2$ ,  
<sup>203</sup> such that the layer covers  $60 \times 200 \text{ cm}^2$  (the long dimension again being along the dispersive  
<sup>204</sup> direction). The readout of these modules are all oriented in the  $x/y$  direction.

<sup>205</sup> The level background in the GEMs have been evaluated, thanks to G4SBS ([27] and  
<sup>206</sup> Sec. VI) for the  $G_M^n$  experimental readiness review. For the  $G_M^n$  highest  $Q^2$  point (which is the  
<sup>207</sup> most constraining, since it combines mandatory maximum luminosity and smaller BigBite  
<sup>208</sup> angles, the background level in the front GEMs are of the order of  $120 \text{ kHz/cm}^2$  for the front  
<sup>209</sup> GEM layers, and below  $50 \text{ kHz/cm}^2$  for the back GEM. To perform the GEM tracking within  
<sup>210</sup> such a background environment, we use the cluster reconstructed in the BigBite shower as  
<sup>211</sup> a track seed to clean the large combinatorics that would otherwise be created by the large  
<sup>212</sup> number of hits. After this, the main challenge is the separation by the clustering algorithm  
<sup>213</sup> of the signal and background hits to minimize track smearing. At this level of background, a  
<sup>214</sup> TreeSearch tracking algorithm combined with a fairly simple cluster separation algorithm has  
<sup>215</sup> already proven to achieve 70% efficiency at nominal luminosity. A better cluster separation  
<sup>216</sup> algorithm is currently being developed and should allow to significantly improve this figure.

## <sup>217</sup> 2. Shower/Preshower

<sup>218</sup> The electromagnetic calorimeter configuration consists of two planes of lead glass blocks  
<sup>219</sup> which we call the preshower and shower. The preshower, located about 80 cm behind  
<sup>220</sup> the first GEM chamber, consists of a  $2 \times 26$  plane of  $37 \text{ cm} \times 9 \text{ cm}$  blocks. The shower, about  
<sup>221</sup> 1 m behind the first GEM chamber, consists of an  $7 \times 27$  array of  $8.5 \text{ cm} \times 8.5 \text{ cm}$  blocks.

<sup>222</sup> Sums over these blocks form the physics event trigger for the experiment.

<sup>223</sup> The preshower signal can be used to provide an additional method of pion rejection.

<sup>224</sup> By selecting low preshower signals, a pion rejection factor of 1:50 can be achieved through  
<sup>225</sup> optimization. Despite higher particle rates, pion rejection performance is anticipated to  
<sup>226</sup> be similar to that achieved for Transversity, E06-010. By measuring the pedestal widths  
<sup>227</sup> and resolution for E06-010 and scaling to this proposal's conditions, overall relative energy  
<sup>228</sup> resolution for the detector is expected to become worse by a factor of 1.6, to about  $\sigma_{\delta E/E} =$   
<sup>229</sup> 25%.

### <sup>230</sup> 3. Timing hodoscope

<sup>231</sup> The BigBite timing hodoscope has been built the the SBS collaborators from Glasgow,  
<sup>232</sup> to replace the BigBite scintillator plane. It will be composed of 90 bars stacked in a plane,  
<sup>233</sup> each with dimensions 1 in.  $\times$  1 in.  $\times$  60 cm. The paddle stack will be oriented such as  
<sup>234</sup> the long dimension of the bars is horizontal *i.e.* perpendicular to the dispersive direction.  
<sup>235</sup> Each of these elements are readout by a PMT on each side, mostly to provide measurement  
<sup>236</sup> redundancy.

<sup>237</sup> This plane will primarily be used to provide a signal for nucleon time of flight reconstruc-  
<sup>238</sup> tion. A time resolution of 200 ps is anticipated. This fine segmentation is meant to lower the  
<sup>239</sup> rates in the detector. Background studies made for the  $G_M^n$  experimental readiness review  
<sup>240</sup> demonstrated that the rates experienced by each element was  $\leq$  500 kHz at a luminosity of  
<sup>241</sup>  $2.8 \times 10^{38}$  cm $^{-2}$  s $^{-2}$ . The PMTs pulses are processed by NINO front-end cards which, when  
<sup>242</sup> the PMT pulse crosses the NINO threshold, will produce a digital signal to be readout by  
<sup>243</sup> CAEN 1190 TDCs which record a leading time and a trailing time.

### <sup>244</sup> 4. GRINCH cherenkov detector

<sup>245</sup> The main purpose of the Ring Imaging Cherenkov is to provide additional particle iden-  
<sup>246</sup> tification for offline pion rejection. The GRINCH consists of a tank with a maximum depth  
<sup>247</sup> of 88.9 cm, with 4 cylindrical mirrors focussing the cherenkov light directly onto a 510 PMT

<sup>248</sup> array (60 lines of PMTs, with lines of 9 PMTs alternating with lines of 8 PMTs) placed away  
<sup>249</sup> from the beam. The radiation gas will be  $C_4F_8$ , which is by far the best compromise between  
<sup>250</sup> light yield for electrons and operating cost. With  $n - 1 = 1.35 \times 10^{-3}$ , the  $\pi$  threshold is only  
<sup>251</sup> about 2.7 GeV, so the additional pion rejection will be most effective below this threshold.

<sup>252</sup> As for the timing hodoscope The PMTs pulses are processed by NINO front-end cards  
<sup>253</sup> which, when the PMT pulse crosses the NINO threshold, will produce a digital signal to  
<sup>254</sup> be readout by VETROC TDCs, which for each PMT hit will record a leading time and a  
<sup>255</sup> trailing time. The analog signal will not be recorded however, which means that for each  
<sup>256</sup> PMT hit, the information of the number of not directly available (although it can in theory  
<sup>257</sup> be deduced from the time over threshold).

<sup>258</sup> All of this implies that the electron selection relies on the number of GRINCH PMT  
<sup>259</sup> firing, instead of relying on the signal amplitude.

260

## B. Hadron Calorimeter (HCal)

261 The Hadron Calorimeter (HCal) has been designed specifically to measure the recoil  
 262 nucleon for the SBS experiments. Specifically for this experiment (and for  $G_M^n$ ), HCal  
 263 combined with the SBS (48D48) magnet provides identification of the recoil nucleon, as  
 264 well as additional kinematic constraint and possibly timing information on the measured  
 265 interaction. Nucleon identification is illustrated on Fig. 5. This figure shows the compared  
 266 proton and neutron position distribution in HCal at the same electron kinematics. The  
 267 proton distribution is being shifted upwards by about 1 m compared to the neutron.

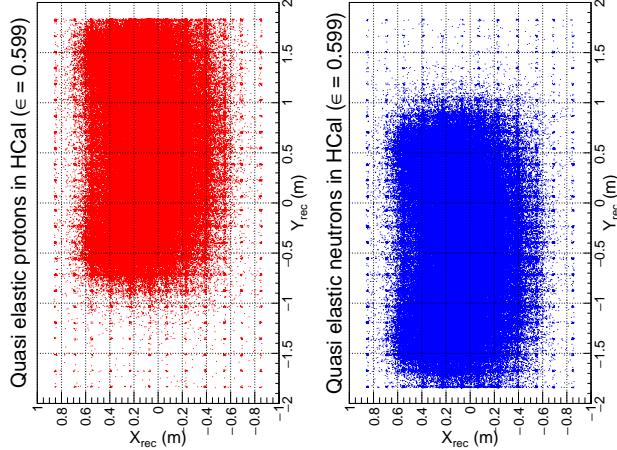


FIG. 5. Reconstructed HCal cluster from quasi-elastic events generated by G4SBS. The left distribution in red is for the proton, the right distribution in blue is for the neutron.

268 The HCal (which CAD model is shown on Fig. 6) is composed of 288 modules arranged  
 269 in an array of  $12 \times 24$

270 In front of the full assembly is located a 3/4 in steel plate which purpose is double:

- 271
- initiate the hadronic shower to optimize the calorimeter response;
  - shield the modules from a fraction of the low energy secondaries;

272 Each of these modules measures  $6 \times 6 \text{ in}^2$  section, for 3 ft length. They are composed of  
 273 alternating tiles of scintillators and iron around a central light guide which collects the light

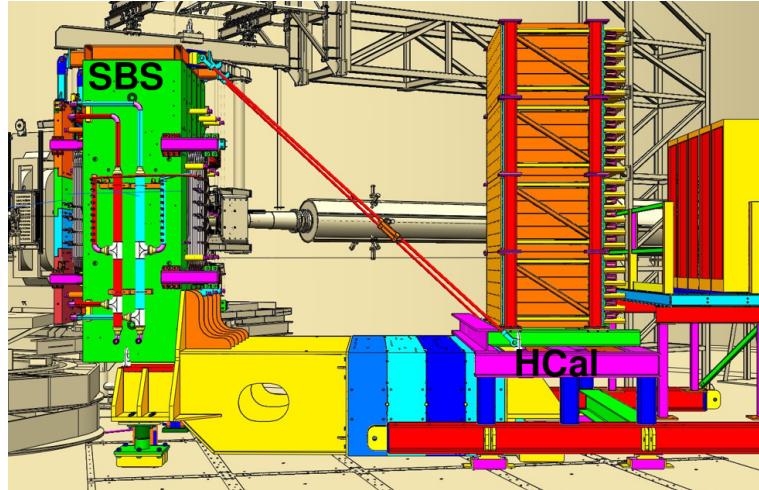


FIG. 6. CAD representation of HCal (right) with the SBS magnet (left)

generated in the scintillators by the hadronic shower, and guides it to the PMT at the end of the block. Cosmics tests have determined that the average light yield for the HCal modules is around 5 photoelectrons per MeV deposited in the scintillator tiles.

The PMTs are readout with FADC250 which sample the PMT signal every 4 ns and allow to reconstruct the PMT pulse shape, hence its timing. They are also readout by TDCs which provide additional timing information. Thanks to this, the timing resolution can be better than 1 ns, which cosmics tests (in progress) seem to confirm.

The energy resolution is intrinsically broad (see Fig. 9 in Section VI), due mostly to the small fraction of energy from the hadronic shower actually measured by the scintillator tiles ( $\leq 0.1$  - refer yet again to Fig. 9).

285       **VI. SIMULATIONS, ESTIMATIONS OF COUNTING RATES AND**  
 286       **ACCIDENTALS**

287       The estimations of counting rates accidentals have been performed using G4SBS, the  
 288       GEANT4-based simulation package developed for the SBS experiment [27]. This package  
 289       includes a wide range of event generators, which allows to evaluate the rates for both events  
 290       of interest (signal) and background. The representation of the experiment apparatus in  
 291       G4SBS is shown in the high  $\epsilon$  configuration on Fig. 7.

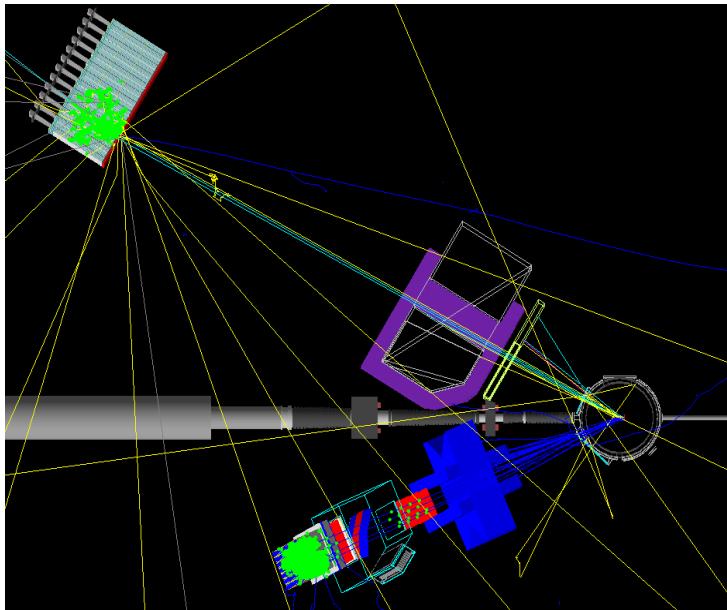


FIG. 7. Top view of the experimental apparatus model in G4SBS, shown in the high  $\epsilon$  configuration. The beam direction is indicated, as well as the main elements (HCal, SBS magnet, BigBite spectrometer)

292       **A. Background and trigger rates**

293       The main processes expected to contribute the trigger rates for the BigBite spectrometer  
 294       are:

- 295       • the inelastic electron nucleon scattering process;

- 296 • photons from inclusive  $\pi^0$  production;

- 297 • and to a lesser extent, charged pions.

298 One the other hand, we expect all sorts of hadronic backgrounds to contribute to the rates in  
 299 HCal, the dominant ones being pions. Both the inelastic scattering and the inclusive neutral  
 300 and charged pion production are implemented in G4SBS, the latter relying on the Wiser  
 301 parametrization [28]. We may also considered the minimum-bias “beam-on-target” gener-  
 302 ator for the HCal background, especially at lower angle (all electromagnetic and hadronic  
 303 processes being built-in in G4SBS).

304 The thresholds to apply to each arm are determined as a function of the elastic peak. For  
 305 the electron arm, the threshold has been set at  $\mu_E - 2.5\sigma_E$ ,  $\mu_E$  and  $\sigma_E$  being respectively  
 306 the position and width of the fitted elastic peak. Fig. 8 presents the distributions of rate of  
 307 energy deposit for the different processes involved in the BigBite trigger rates.

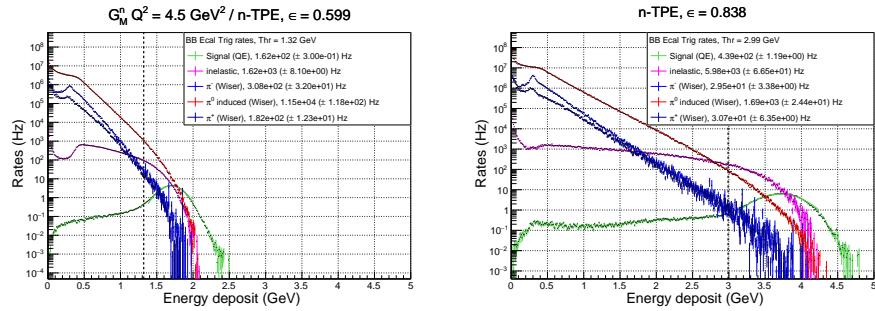


FIG. 8. Rates of the different process contributing to the BigBite electron arm trigger, for the low  $\epsilon$  (left) and the high  $\epsilon$  (right). Quasi-elastic is in green, inelastic in magenta,  $\pi^0$  in red,  $\pi^-$  in blue, and  $\pi^+$  in dark blue. Note the resolution for the elastic peak in the BigBite shower is  $\sim 0.3$  GeV.

308 Since HCal is a sampling calorimeter (meaning that only a fraction of the shower energy  
 309 is measured), it's resolution is significantly wider ( $\sim 0.7$  GeV). Due to this, the threshold  
 310 is at 90% efficiency (which corresponds to  $\sim 0.1$  GeV for both kinematics. Fig. 9 presents  
 311 the distributions of rate of energy deposit for the different processes involved in the BigBite  
 312 trigger rates.

314 The thresholds and trigger rates for each arm, as well as the coincidence rate (assuming

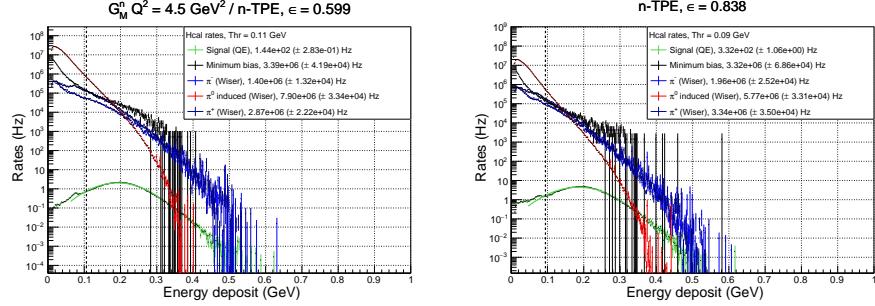


FIG. 9. Rates of the different process contributing to the HCal trigger, for the low  $\epsilon$  (left) and the high  $\epsilon$  (right). Quasi-elastic is in green, minimum bias in black,  $\pi^0$  in red,  $\pi^-$  in blue, and  $\pi^+$  in dark blue. Note the peak itself is around 0.2 GeV for 3.2 GeV nucleons.

316 30ns coincidence window), are summarized in Table. II. Note that for HCal, the “total  
 317 rates” is either the sum of inclusive charged and neutral pions evaluated with the Wiser  
 318 cross sections *or* the “minimum bias” beam on target. We have good reasons to think that  
 319 the Wiser code results actually overestimate the HCal rates, but for the sake of thoroughness,  
 320 we have checked the coincidence rates assuming the sum of the inclusive pions (evaluated  
 321 with the Wiser cross sections) as the HCal rates.

322 In the worst case scenario, the coincidence rates could be as high as 5kHz, which might be  
 323 at the limit of manageability for the DAQ. However, a slight increase on the HCal threshold  
 324 (which would drop the efficiency from  $\sim 90\%$  to  $\sim 85\%$ ) would decrease the total HCal rates by  
 325  $\sim 35\%$  to  $40\%$  in this worst case scenario, which would make the situation more manageable  
 326 (3.3 kHz).

327

## B. Contamination from inelastic

328 The main source of contamination for the quasi-elastic comes from the inelastic electron-  
 329 nucleon scattering. Most of this contamination can be cleaned out thanks to a selection on  
 330 the center of mass energy

$$W^2 = M_N^2 + 2M_N^2(E - E') - Q^2, \quad (8)$$

| Point ( $\epsilon$ )    | 1 (0.599)             |                      | 2 (0.838)             |                        |
|-------------------------|-----------------------|----------------------|-----------------------|------------------------|
|                         | BigBite<br>rates (Hz) | HCal<br>rates (Hz)   | BigBite<br>rates (Hz) | HCal<br>rates (Hz)     |
| threshold (GeV)         | 1.32                  | 0.106                | 2.99                  | 0.090                  |
| Quasi-elastic           | $1.62 \times 10^2$    | $1.44 \times 10^2$   | $4.39 \times 10^2$    | $3.48 \times 10^2$     |
| Inelastic               | $1.62 \times 10^3$    | -                    | $5.98 \times 10^3$    | -                      |
| $\pi^-$ (Wiser)         | $3.08 \times 10^2$    | $1.40 \times 10^6$   | $2.95 \times 10^2$    | $1.96 \times 10^6$     |
| $\pi^0$ (Wiser)         | $1.15 \times 10^4$    | $7.90 \times 10^6$   | $1.69 \times 10^3$    | $5.77 \times 10^6$     |
| $\pi^+$ (Wiser)         | $1.82 \times 10^2$    | $2.87 \times 10^6$   | $3.07 \times 10^2$    | $3.34 \times 10^6$     |
| Minimum bias            | -                     | $3.39 \times 10^6$   | -                     | $3.32 \times 10^6$ (*) |
| <i>Total</i>            | $1.37 \times 10^4$    | $1.22 \times 10^7$   | $8.17 \times 10^3$    | $1.11 \times 10^7$     |
| (min. bias - HCal only) |                       | / $3.39 \times 10^6$ |                       | / $3.32 \times 10^6$   |
| <b>Coincidence rate</b> | $5.01 \times 10^3$    |                      | $2.72 \times 10^3$    |                        |
| (with min. bias HCal)   | $1.39 \times 10^3$    |                      | $8.14 \times 10^2$    |                        |

TABLE II. Trigger rates for BigBite and HCal, with the different process contributions separated, and the sum. For HCal, the total rates is either the sum of the (Wiser) inclusive pions or the minimum bias. The coincidence rates assume a 30 ns coincidence window.

and the missing transverse momentum of the nucleon

$$p_{\perp miss} = \sqrt{(q_x - p'_x)^2 + (q_y - p'_y)^2}, \quad (9)$$

where  $M_N$  is the mass of the nucleon,  $E$  and  $E'$  the initial and final energy of the electron, and  $q_{x,y}$ ,  $p'_{x,y}$  are the projections on  $x$ ,  $y$  of the vectors of the virtual photon and final nucleon. The distributions of these quantities (weighted with cross section and including detector resolutions) are displayed for quasi-elastic and inelastic scattering, and for proton and nucleon, on Fig. 10 for the low  $\epsilon$  kinematic, and on Fig. 11 for the high  $\epsilon$  kinematic.

Provided that we are not limited by statistics and the sample purity is capital for our experiment, we set the selection criteria on  $W^2$  and  $p_{\perp miss}$  to maximize inelastic contamination (ideally below 1 %). Setting  $p_{\perp miss} \leq 0.1$  GeV and  $W^2 \leq 1.1$  GeV $^2$ , the inelastic

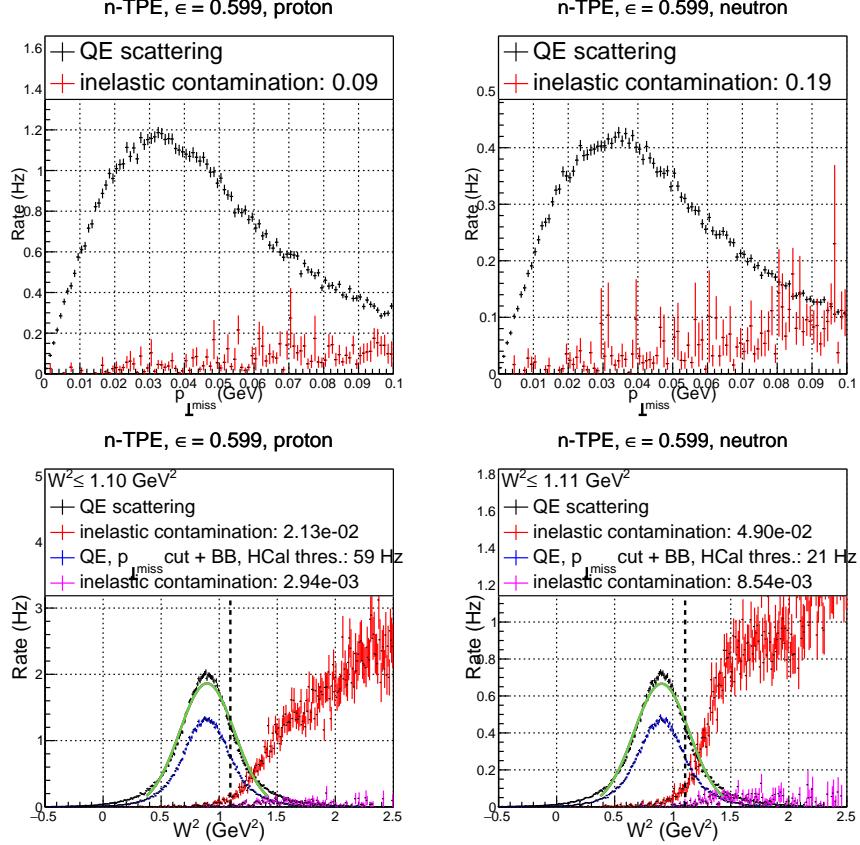


FIG. 10. Compared quasi-elastic and inelastic distributions (including detectors resolutions) for  $p_{\perp miss}$  (top) and  $W^2$  (bottom), for the low  $\epsilon$  kinematic. Comparison for protons is on the left, and comparison for neutrons is on the right. On the bottom panel, black and red are before the  $p_{\perp miss} \leq 0.1 \text{ GeV}$  selection, while blue and magenta are after  $p_{\perp miss} \leq 0.1 \text{ GeV}$  selection and application of BigBite shower and HCAL thresholds.

<sup>340</sup> contamination of the elastic sample ranges from 0.2 % to 0.9 %, while retaining  $\geq 60$  % of  
<sup>341</sup> the quasi-elastic events properly recorded in the BigBite-SBS pair. Table. III summarizes  
<sup>342</sup> the quasi-elastic selection cuts, ad inelastic contamination  $\delta_{inel}$ .

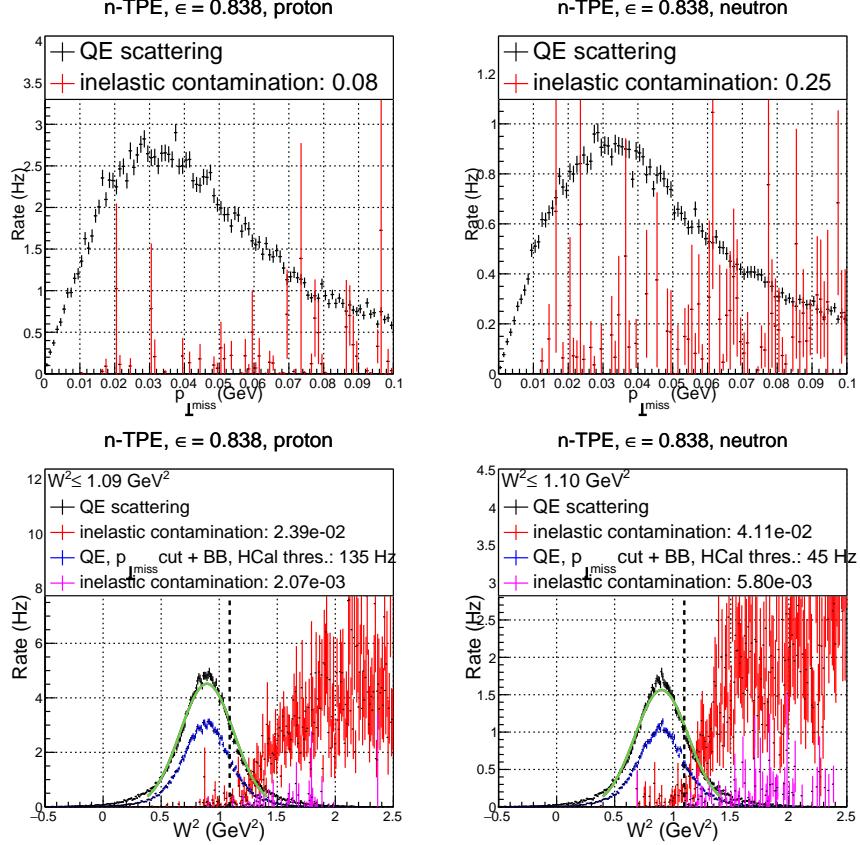


FIG. 11. Compared quasi-elastic and inelastic distributions (including detectors resolutions) for  $p_{\perp miss}$  (top) and  $W^2$  (bottom), for the high  $\epsilon$  kinematic. Comparison for protons is on the left, and comparison for neutrons is on the right. On the bottom panel, black and red are before the  $p_{\perp miss} \leq 0.1$  GeV selection, while blue and magenta are after  $p_{\perp miss} \leq 0.1$  GeV selection and application of BigBite shower and HCal thresholds.

343

### C. Quasi-elastic counting rates

344 The signals for this experiment have been generated using the G4SBS elastic/quasi-elastic  
 345 generator. We generated a reasonably large sample of quasi-elastic events  $N_{Gen}$  for each  
 346 kinematics, on a solid angle  $\Delta\Omega_{Gen}$  that was larger than the detector acceptance. To evaluate  
 347 the detector solid angle, we define simple criteria that each event has to pass, defined as the  
 348 following;

| Point ( $\epsilon$ ) | $N$ | $W^2$ cut | $p_{\perp miss}$ cut | $\delta_{inel}$       |
|----------------------|-----|-----------|----------------------|-----------------------|
| 1 (0.599)            | $n$ | 1.10      | 0.10                 | $2.94 \times 10^{-3}$ |
|                      | $p$ | 1.11      | 0.10                 | $8.54 \times 10^{-3}$ |
| 2 (0.838)            | $n$ | 1.09      | 0.10                 | $2.07 \times 10^{-3}$ |
|                      | $p$ | 1.10      | 0.10                 | $5.80 \times 10^{-3}$ |

TABLE III. Summary of cuts for quasi-elastic selection and resulting inelastic contamination  $\delta_{inel}$ .

- 349     • require a primary track, going through all 5 GEM layers (electron arm);  
 350     • require non-zero energy deposit in both the preshower and shower (electron arm);  
 351     • require non-zero energy deposit in HCal (hadron arm).

352     The detector solid angle, for both proton and neutron, are defined in Table. IV. We also  
 353     define there the  $p$ - $n$  acceptance asymmetry  $A_{\Delta\Omega}$  such as:

$$A_{\Delta\Omega} = \frac{(\Delta\Omega_e \otimes \Delta\Omega_n) - (\Delta\Omega_e \otimes \Delta\Omega_p)}{(\Delta\Omega_e \otimes \Delta\Omega_n) + (\Delta\Omega_e \otimes \Delta\Omega_p)} \quad (10)$$

| Point ( $\epsilon$ ) | $\Delta\Omega_e$<br>(msr) | $\Delta\Omega_e \otimes \Delta\Omega_n$<br>(msr) | $\Delta\Omega_e \otimes \Delta\Omega_p$<br>(msr) | $A_{\Delta\Omega}$<br>(%) |
|----------------------|---------------------------|--|--|---------------------------|
| 1 (0.599)            | 52.4                      | 46.7   | 47.2   | 0.5                       |
| 2 (0.838)            | 32.7                      | 20.8   | 22.2   | 3.0                       |

TABLE IV. Kinematics electron solid angle, and convoluted electron/hadron solid angle, and acceptance asymmetry.

354     Then, we evaluate the detection efficiency. For the electron, we require the energy recon-  
 355     structed in the BigBite calorimeter to be above a threshold defined as  $thr = \mu_E - 2.5 * \sigma_E$ ,  
 356     as well as a minimum number of GRINCH PMTs fired due to the primary electron; For  
 357     HCal, we require the threshold to be such as we obtain 90% efficiency. These values are  
 358     summarized in Table. V. Quasi-elastic selection efficiency  $\eta_{sel}$  are also reminded.

359     The counting rates are evaluated using among the  $N_{Gen}$  events generated the events that  
 360     have passed the selection described below, and weighting those events with the cross section

| Point ( $\epsilon$ ) | BB thr.<br>(GeV) | HCal thr.<br>(GeV) | $\eta_{det\ e}$ | $\eta_{det\ n}$ | $\eta_{det\ p}$ | $\eta_{sel\ n}$ | $\eta_{sel\ p}$ |
|----------------------|------------------|--------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1 (0.599)            | 1.32             | 0.11               | 0.902           | 0.904           | 0.892           | 0.589           | 0.605           |
| 2 (0.838)            | 2.99             | 0.09               | 0.808           | 0.889           | 0.882           | 0.617           | 0.647           |

TABLE V. Kinematics electron thresholds, particle detection efficiencies ( $\eta_{det}$ ), and efficiency of quasi-elastic selection  $\eta_{sel}$  separated for the proton and the neutron.

361  $d\sigma/d\Omega|_i$  calculated by G4SBS, multiplied by the generation solid angle  $\Delta\Omega_{Gen}$ , using the  
362 formula:

$$N_{est} = \frac{\mathcal{L}_{exp}\Delta t}{N_{Gen}} \times \sum_{i \in \text{accepted evts}} \left( \frac{d\sigma}{d\Omega} \Big|_i \times \Delta\Omega_{Gen} \right) , \quad (11)$$

363 where  $\Delta t$  the running time and  $\mathcal{L}_{exp}$  the experimental luminosity.  $\mathcal{L}_{exp}$  can be calculated as  
364 follows:

$$\mathcal{L}_{exp} = \frac{I_{exp}}{q_e} \cdot L_{tgt} \cdot d_{tgt} \frac{N_A}{m_D} , \quad (12)$$

365 where  $I_{exp}$  is the beam current,  $q_e$  is the electron charge,  $L_{tgt}$  and  $d_{tgt}$  are the target length  
366 and density respectively,  $N_A$  is Avogadro's number, and  $m_D$  is the deuterium mass number.

367 Events are “accepted” if they meet the following criteria:

- 368 • the electron is in the BigBite acceptance;
- 369 • the electron passes the BigBite threshold defined in Table V and gives signal in the  
370 GRINCH;
- 371 • the nucleon is in the HCal acceptance and passes the HCal threshold defined in Table V;
- 372 • the event passes the quasi-elastic selection defined in the previous section *i.e.*  $W^2 \leq 1.1 \text{ GeV}^2$   
373 and  $p_{\perp miss} \leq 0.10 \text{ GeV}$ .

374 The total quasi-elastic statistics  $N_{QE}$ , as well as the total form factor,  $F^2$ :

$$F^2 = \frac{N_{QE}}{\mathcal{L}_{exp} \cdot \Delta t \cdot d\sigma_{Mott}/d\Omega \cdot \Delta\Omega \cdot \eta} \quad (13)$$

375 and its statistical error  $\Delta F^2 = F^2/\sqrt{N_{QE}}$  are compiled for both kinematics in Table. VI,  
376 assuming a running time  $\Delta t = 12$  hours of running at a beam intensity of  $I_{exp} = 30 \mu\text{A}$  on

<sup>377</sup> a liquid deuterium target with length  $l_{tgt} = 15$  cm and density  $d_{tgt} = 0.169$  g.cm<sup>-3</sup>. In  
<sup>378</sup> Eq.13,  $\Delta\Omega$  is the convoluted BigBite-HCal solid angle, and  $\eta$  is the product of all efficiencies  
<sup>379</sup> (detection efficiencies  $\eta_{det}$   $\times$  selection efficiency  $\eta_{sel}$ ).

| Point ( $\epsilon$ ) | $N_{QE}$<br>(e-n)  | $N_{QE}$<br>(e-p)  | $F_n^2$<br>( $\times 10^{-3}$ ) | $\Delta F_n^2$<br>( $\times 10^{-6}$ ) | $F_p^2$<br>( $\times 10^{-3}$ ) | $\Delta F_p^2$<br>( $\times 10^{-6}$ ) |
|----------------------|--------------------|--------------------|---------------------------------|--|---------------------------------|--|
| 1 (0.599)            | $9.07 \times 10^5$ | $2.55 \times 10^6$ | 0.99                            | 1.04                                   | 2.73                            | 1.70                                   |
| 2 (0.838)            | $1.94 \times 10^6$ | $5.83 \times 10^6$ | 0.72                            | 0.52                                   | 1.93                            | 0.80                                   |

TABLE VI. Quasi-elastic counting rates, and total form factor (defined in Eq. 11).

<sup>380</sup> The calculation of the  $F_2$  term requires the evaluation of the Mott cross section:

$$\sigma_{Mott} \equiv \frac{d\sigma_{Mott}}{d\Omega} = (\hbar c \alpha_{EM})^2 \frac{1}{4E^2} \left( \frac{\cos \theta_e/2}{\sin^2 \theta_e/2} \right)^2 \frac{E'}{E} \quad (14)$$

<sup>381</sup> The Mott cross section has been calculated with the weighted average of the electron variables  
<sup>382</sup> (momentum and polar angle).

| Point ( $\epsilon$ ) | $\langle \theta_e \rangle$<br>(deg) | $\langle k' \rangle$<br>(GeV) | $\langle Q^2 \rangle$<br>(GeV <sup>2</sup> ) | $\sigma_{Mott}$<br>(nb sr <sup>-1</sup> ) |
|----------------------|-------------------------------------|-------------------------------|--|---|
| 1 (0.599)            | 41.88                               | 2.0                           | 4.5  | 6.62                                      |
| 2 (0.838)            | 23.23                               | 4.2                           | 4.5  | 44.2                                      |

TABLE VII. The Mott cross section weighted average of kinematic variables over the BigBite acceptance.

383

## VII. SYSTEMATIC ERRORS

384 In this section we will estimate (or set upper limits on) the contributions to the sys-  
 385 tematic uncertainty for this experiment. The sources of systematic uncertainties from the  
 386 experimental setup (target, acceptance, inelastic contamination) were already estimated for  
 387 the SBS  $G_M^n$  experiment proposal [19]. Note that a majority of the potential sources of sys-  
 388 tematic uncertainties (nuclear corrections, accidentals, radiative corrections, target density,  
 389 etc) cancel in the ratio  $R = f_{corr} \times N_{e,e'n}/N_{e,e'p}$ , which is one of the strengths of this experi-  
 390 mental method. The sources of uncertainties as well as their estimation for each kinematic is  
 391 provided in Table. VIII. Since the experimental setup has evolved since then, some of these  
 392 uncertainties have been reevaluated, namely the acceptance loss and inelastic contamination.  
 393 Table. IX lists the estimated contributions to systematic errors on the two-photon-exchange

TABLE VIII. Estimated contributions (in percent) to the systematic error on  $R = f_{corr} \times N_{e,e'n}/N_{e,e'p}$ . Quantities marked with \* are taken from the SBS  $G_M^n$  experiment proposal [19].

The total systematic errors on  $R$  is the quadratic sum of all other errors.

|   |           |           |
|---|-----------|-----------|
| Kinematic ( $\epsilon$ )  | (1) 0.599 | (2) 0.838 |
| Acceptance losses   | 0.5 %     | 3.0 %     |
| Inelastic contamination   | 0.9 %     | 0.6 %     |
| Nucleon mis-identification*   | 0.6 %     |           |
| Syst. error on $R = f_{corr} \times N_{e,e'n}/N_{e,e'p}$<br>(Quadratic sum of the errors above) | 1.3 %     | 3.1 %     |

394

395

396 contribution (TPE). The systematics for  $S_c^n$  and  $\mu_n G_E^n/G_M^n$  have already been explicated in  
 397 Sec. III, and are the leading contributions to the total uncertainty.

398 Inelastic contamination has been reevaluated in Sec. VI B. To evaluate the upper limit on  
 399 our uncertainty, we added quadratically the inelastic contamination evaluated for the proton  
 400 and the neutron for each kinematics, which is the error we make if we ignore the systematics

TABLE IX. Estimated contributions to systematic error on the Rosenbluth slope.

|  |       |
|--|-------|
| Syst. error on $p$ cross section ( $S_c^p = \sigma_L^p / \sigma_T^p$ ) | 0.01  |
| Syst. error on $n$ form factor ( $\mu_n G_E^n / G_M^n$ )               | 0.05  |
| Syst. error on Rosenbluth slope (TPE)                                  | 0.012 |

402 completely. Even in this case, we expect less than 1% systematic errors.

403 The acceptance loss in SBS (*i.e.* the proportion of non-detected nucleons for each detected  
 404 electron) have been evaluated for both kinematics. They are about 10% for the  $\epsilon = 0.60$   
 405 kinematic (meaning that for every good electron measured, we will not measure the recoil  
 406 nucleon 10% of the times), but they are over 30 % for the  $\epsilon = 0.84$  kinematics, which is due to  
 407 a larger spread of the nucleon imprint. The systematic uncertainty on the acceptance loss for  
 408 the ratio  $R = f_{corr} \times N_{e,e'n} / N_{e,e'p}$  is maximized by the proton-neutron solid angle asymmetry  
 409  $A_{\Delta\Omega} = \Delta\Omega_n - \Delta\Omega_p / \Delta\Omega_n + \Delta\Omega_p$ . This asymmetry is about 0.5% for the  $\epsilon = 0.60$  kinematic  
 410 (consistent with the  $G_M^n$  proposal), but goes up to 3% for the  $\epsilon = 0.84$  kinematics.

411

### VIII. BEAM TIME REQUEST

412     We request 48 hours total time (32 PAC hours of beam-on target) to measure  
 413     the two-photon effect (and  $G_E^n$  in one-photon approximation) at  $Q^2 = 4.5$  ( $\text{GeV}/c$ )<sup>2</sup> through  
 414     a measurement of the cross sections of the reaction D(e,e'N) at a large value of the virtual  
 415     photon polarization  $\epsilon=0.84$ . *The measurement at  $Q^2 = 4.5$  ( $\text{GeV}/c$ )<sup>2</sup>,  $\epsilon=0.60$  is already*  
 416     *scheduled as part of the SBS  $G_M^n$  experiment E12-09-019 [19].*

417     We plan to take 12 hours of data at a full luminosity of  $2.86 \times 10^{38} \text{ cm}^{-2}\text{s}^{-1}$ , which  
 418     corresponds to a beam intensity of  $I_{exp} = 30 \mu\text{A}$  on a liquid deuterium target with length  
 419      $l_{tgt} = 15 \text{ cm}$  and density  $d_{tgt} = 0.169 \text{ g.cm}^{-3}$ . To have a better handle on our backgrounds,  
 420     we also plan to take 12 hours of data at half luminosity (basically by lowering the beam  
 421     intensity by a factor 2). In each of these configurations, we also need to take data on a  
 422     “dummy” target (*i.e.* on a target cell identical to the one used for production, but empty)  
 423     to understand the contamination of our data from the target walls.

424     In addition to this beam time, we also require 16 hours (two shifts) to change the exper-  
 425     imental configuration. This configuration change means:

- 426       • BigBite spectrometer angle and distance change;
  - 427       • Beam pass change (from 4.4 GeV/2 pass to 6.6 GeV/3 pass);
- 428     If this experiment is approved, we plan to insert this experiment in the GMn E12-09-019  
 429     run plan in such a way that we can avoid a change in configuration for the SBS magnet  
 430     and the HCal, which is very time consuming. Table. X displays an excerpt of the GMn run  
 431     plan, and points out where the nTPE measurement inserts. The beam pass change and the  
 432     BigBite move may be done in parallel, and should take one shift (eight hours). We require  
 433     an additional shift (eight hours) for beam tuning after beam pass change. The projected use  
 434     of this time is summarized in Table. XI.

437     This experiment will take place in Hall A, along the already scheduled SBS  $G_M^n$  experiment  
 438     E12-09-019, utilizing the BigBite spectrometer to detect electrons scattered off the liquid  
 439     deuterium target, and HCal calorimeter to detect the recoiling neutron and proton.

TABLE X. Excerpt of GMn E12-09-019 run plan table, showing where the  $\epsilon = 0.84$  measurement would be inserted in our run plan. The  $\epsilon = 0.60$  measurement is also emphasized in blue.

| Step #   | task        | $Q^2$<br>(GeV/c) $^2$ | $\theta_{BB} / \theta_{SBS}$<br>degrees | Beam<br>GeV | Time<br>hours                           | Tech work<br>time (h) |
|--|-------------|-----------------------|---|-------------|---|-----------------------|
| 4b (install GEn-RP)                            | GEn-RP      |                       | 41.9 / 24.7                             | -           | 4                                       | 4                     |
| 4c (GEn-RP)                                    | Production  | 4.5                   | 41.9 / 24.7                             | 4.4         | 104 (calendar)<br>(52 PAC hours)        |                       |
| 4d (remove GEn-RP)                             | GEn-RP      |                       | 41.9 / 24.7                             | -           | 56                                      | 24                    |
| <b>4e (GMn/nTPE low <math>\epsilon</math>)</b> | Production  | <b>4.5</b>            | <b>41.9 / 24.7</b>                      | <b>4.4</b>  | <b>64 (calendar)<br/>(32 PAC hours)</b> |                       |
| 5a (conf. change)                              | BB/SBS/HCal |                       | 32.5 / 31.1                             | -           | 32                                      | 16                    |
| 5b (beam tune)                                 | beam        |                       | 32.5 / 31.1                             | 4.4         | 4                                       |                       |
| 5c (GMn)                                       | Production  | 3.5                   | 32.5 / 31.1                             | 4.4         | 64 (calender)<br>(32 PAC hours)         |                       |
| <b>6a (pass change)</b>                        | beam/BB     |                       | <b>23.2 / 31.1</b>                      | <b>6.6</b>  | <b>8</b>                                | <b>4</b>              |
| <b>6b (beam tune)</b>                          | beam        |                       | <b>23.2 / 31.1</b>                      | <b>6.6</b>  | <b>8</b>                                |                       |
| <b>6c see Table. X</b>                         | Production  | <b>4.5</b>            | <b>23.2 / 31.1</b>                      | <b>6.6</b>  | <b>64 (calendar)<br/>(32 PAC hours)</b> |                       |
| 7a (conf. change)                              | BB/SBS/HCal |                       | 58.4 / 17.5                             |             | 32                                      | 16                    |
| + (pass change)                                | beam        |                       | <b>58.4 / 17.5</b>                      | <b>4.4</b>  | during SBS move                         |                       |
| 7b (beam tune)                                 | beam        | -                     | 58.4 / 17.5                             | 4.4         | 4                                       |                       |
| 7c   | Production  | 5.7                   | 58.4 / 17.5                             | 4.4         | 50 (calendar)<br>(25 PAC hours)         |                       |

<sup>440</sup> Data taking (if approved by PAC48) will take place in summer 2021 during the approved  
<sup>441</sup> and scheduled run of the GMn, E12-09-019, experiment, which is going to measure the  $e - n$   
<sup>442</sup> elastic scattering cross section at  $Q^2 = 4.5$  (GeV/c) $^2$  at  $\epsilon=0.60$ .

<sup>443</sup> The set of instrumentation and required beam current for proposed measurement is iden-

TABLE XI. Summary table for the beam time request. Setting changes include SBS and BigBite angles change, as well as a beam pass change from 4.4 GeV (2 pass) to 6.6 GeV (3 pass). This beam pass change can mostly be done in parallel to the SBS

| Task   | Target                | $I_{exp}$  | time requested  |
|--|-----------------------|------------|-----------------|
| Data taking (Prod.)                              | 15 cm LD <sub>2</sub> | 30 $\mu$ A | 12 hours        |
| Data taking (Syst.)                              | 15 cm “Dummy”         | 30 $\mu$ A | 4 hours         |
| Data taking (Prod.)                              | 15 cm LD <sub>2</sub> | 15 $\mu$ A | 12 hours        |
| Data taking (Syst.)                              | 15 cm “Dummy”         | 15 $\mu$ A | 4 hours         |
| Setting changes (BigBite move, beam pass change) |                       |            | 8 hours         |
| Beam tune after beam pass change                 |                       |            | 8 hours         |
| <b>Total</b>                                     |                       |            | <b>48 hours</b> |

<sup>444</sup> tical to one in the GMn experiment. The beam energy of 6.6 GeV will be used. One of two  
<sup>445</sup> data points required for the cross section LT separation is already in the data taking plan of  
<sup>446</sup> GMn.

<sup>447</sup> There are no other measurements of TPE in the  $e - n$  elastic scattering and knowledge  
<sup>448</sup> of the TPE is essential for the understanding of the elastic electron scattering from neutron  
<sup>449</sup> (and proton) and hadron structure. Furthermore, it is a necessary input in the analysis and  
<sup>450</sup> interpretation of a wide range of electron scattering processes.

<sup>451</sup> The kinematics of our measurements emphasize the same  $Q^2$  range where TPE in  $e - p$   
<sup>452</sup> elastic scattering was observed to dominate in Rosenbluth slope. Measuring at this high  
<sup>453</sup> momentum transfers will provide unique input for testing TPE calculations [4].

<sup>454</sup> We propose to measure the Rosenbluth slope and extract (in one-photon approximation)  
<sup>455</sup>  $\delta G_E^n/G_M^n$  to an accuracy of 0.15, which would bring its precision to a level comparable with  
<sup>456</sup> that of the double polarization experiments GEN-RP and GEN-He3 at such value of  $Q^2$ .  
<sup>457</sup> Such precision should be sufficient to detect the TPE contribution to the  $e - n$  Rosenbluth  
<sup>458</sup> slope on the three sigma level.

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