

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 $Q^2 = 4.5$ $(\text{GeV}/c)^2$. 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, θ 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 square, 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 σ_L and σ_T are the cross sections for longitudinally and transversely polarized virtual photons, respectively.

The linear ϵ dependence of the cross section is due to σ_L term, see Eq. 1. The ratio σ_L/σ_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 $(\text{GeV}/c)^2$ 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

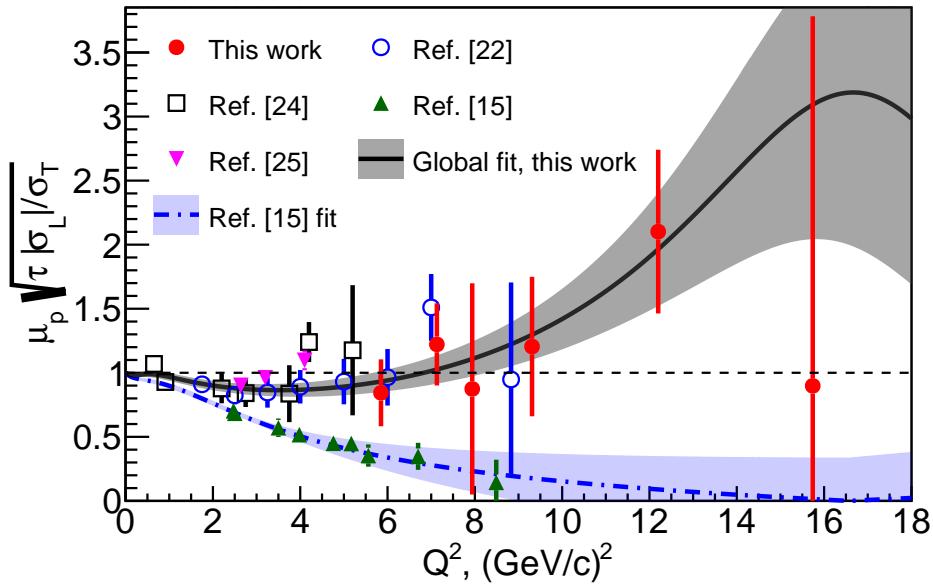


FIG. 1. The square root of Rosenbluth slope, corrected for kinematical factor $\sqrt{\tau}$ and μ_p , observed in elastic electron-proton scattering, adopted from Ref. [3].

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 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 ϵ values (*i.e.* different beam energies and angles), but with same Q^2 value. Rosenbluth technique requires an accurate measurement of the

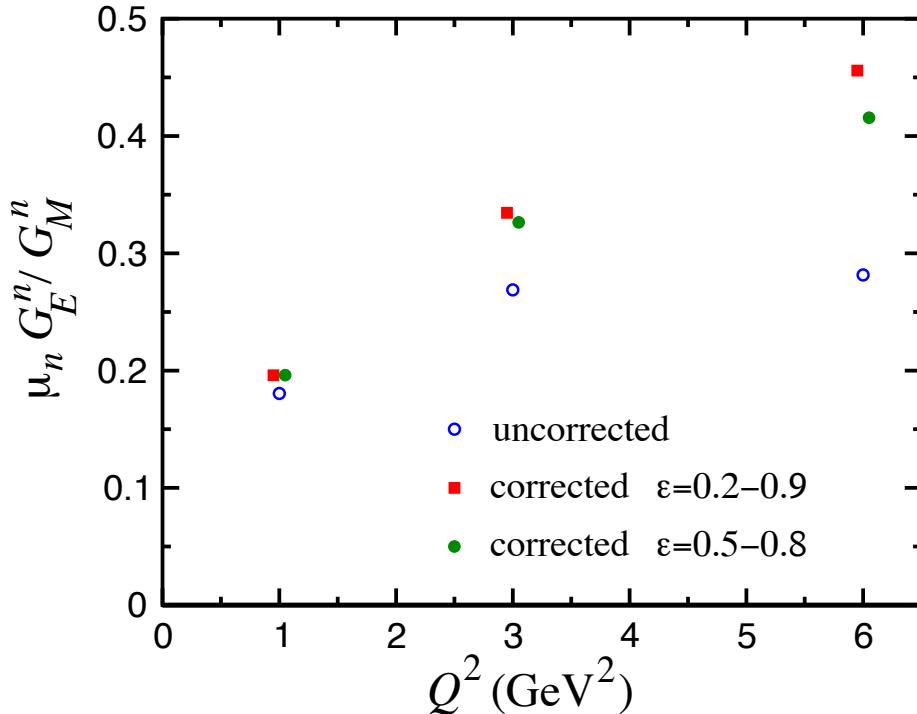


FIG. 2. Projected impact of TPE on G_E^n/G_M^n using LT separation, according to Ref. [4].

cross section and suffers from large systematic uncertainties arising from several factors. For instance, an accurate knowledge of the neutron detector efficiency is required.

When comparing the values of G_E^p/G_M^p 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 Rosenbluth slope value at 5 (GeV/c) 2 .

In the following we propose to make 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

50 the nTPE experiment will likely add a new component to our understanding of the elastic
51 electron-nucleon process.

52

II. PHYSICS MOTIVATION

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

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

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

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

70 where κ is the nucleon anomalous magnetic moment.

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

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

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

⁷⁷ μ is a scale parameter necessary from the evolution over Q^2 , analogous to DIS parton dis-
⁷⁸ tributions, and the sum is over all quarks and anti-quarks. These may be accessed through
⁷⁹ processes such as deeply virtual Compton scattering, where the interaction is factorized into
⁸⁰ a hard part with the virtual photon/photon interactions with an individual quark and a soft
⁸¹ part of the residual system where the GPD information is contained.

⁸² Fundamental nucleon feature, the spin, is related to GPDs, as shown by X. Ji [15]. The
⁸³ moments of GPDs can yield information, according to the Ji's Angular Momentum Sum
⁸⁴ Rule, on the contribution to the nucleon spin from quarks and gluons, including both the
⁸⁵ quark spin and orbital angular momentum.

⁸⁶ At present, experimental measurements of GPDs are still scarce. Until high Q^2 DVCS
⁸⁷ data becomes available, work has been done to attempt to parameterize these GPDs, which
⁸⁸ rely heavily on data from electromagnetic form factors and parton distributions from DIS as
⁸⁹ constraints [17]. Data at high Q^2 for G_E^n would contribute significantly in the development
⁹⁰ of these models.

⁹¹ As we presented above the form factors are important components for GPDs development.
⁹² However, the cross section of elastic $e-p$ scattering contains a significant contribution to σ_L ,
⁹³ which at high Q^2 is much larger than theory calculations expected [18]. Such an alarming
⁹⁴ observation underlines that understanding of TPE effect is essential for hadron physics.

95

III. TECHNIQUE

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

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

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

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

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

¹²⁴ the experiment kinematics.

¹²⁵ Applying Rosenbluth technique to measure G_E^n requires accurate measurement of the cross
¹²⁶ section and suffers from large uncertainties. To overcome this issue, we propose to extract
¹²⁷ the value of G_E^n from the ratio of quasi-elastic yields, $R_{n/p}$, in scattering from a deuteron
¹²⁸ target as follows:

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

¹²⁹ $R_{observed}$ needs to be corrected to extract the ratio of e-n/e-p scattering from nucleons:

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

¹³⁰ where the correction factor $f_{correction}$ takes into account the variation in the hadron efficiencies
¹³¹ due to changes of $e - N$ Jacobian, the radiative corrections, and absorption in path from the
¹³² target to the detector, and small re-scattering correction.

¹³³ 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 ϵ 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: σ_L^n and σ_T^n . The dominant contribution to the uncertainty of the slope of the cross section vs. ϵ , $S_c^n = \sigma_L^n / \sigma_T^n$, will come from the uncertainty of S_c^p . At $Q^2=4.5$ (GeV/c)², 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 τ and σ_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 ϵ 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 0.25×0.01 .

At $Q^2=4.5$ (GeV/c) 2 the ratio $\mu_n G_E^n/G_M^n$ is of 0.55 ± 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], shown in 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.

145

IV. EXPERIMENTAL SETUP

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

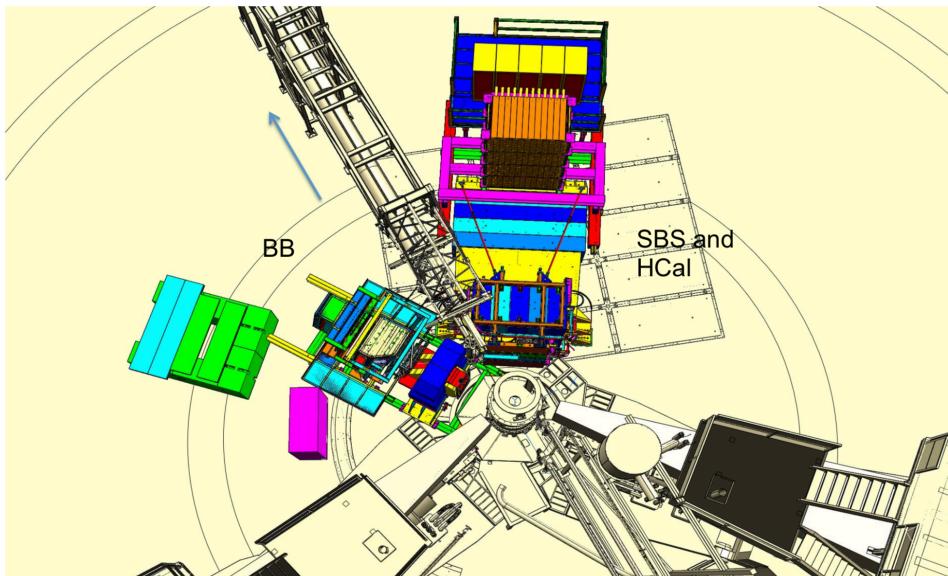


FIG. 3. Layout of the experimental setup in nTPE.

152

1. Parameters of the SBS

153 The 48D48 magnet from Brookhaven was acquired as part of the Super Bigbite project
 154 and will be available for this experiment. It consists of a large dipole magnet which provides
 155 a field integral of about $1.7 \text{ T} \cdot \text{m}$, allowing for quasielastic protons to be sufficiently deflected
 156 to allow clear differentiation from neutrons. The active field volume has an opening of $46 \times$
 157 $25 \text{ vertical} \times \text{horizontal}$), matching the aspect ratio of the neutron arm, and a depth of 48
 158 cm.

159 The placement of this magnet will be 1.6 m away from the target, which would normally
160 interfere with the beamline. To accommodate this, modifications were made to the iron yoke
161 such that the beamline will pass through the magnet yoke area.

162 The field configuration will be such that positively charged particles will be deflected
163 upwards away from the hall floor. For a field integral of 1.7 Tesla-m, protons of momentum
164 2.5 GeV/c will be deflected 250 mrad, which translates to a displacement of xxm. Including
165 expected detector resolution, the $p_{miss,\perp}$ distribution will be similar to what was seen in
166 E02-013, so cuts of < 100 MeV/c will be appropriate. Monte Carlo simulations show a
167 contamination of charged quasielastics to be negligible.

168 The presence of the magnet also works to sweep low energy charged particles from the
169 target away from the neutron arm. Particles of momentum less than 1.3 GeV/c will be
170 entirely swept outside of the neutron arm acceptance. This greatly reduces the amount of
171 charged low energy background.

172

A. The BigBite Spectrometer

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

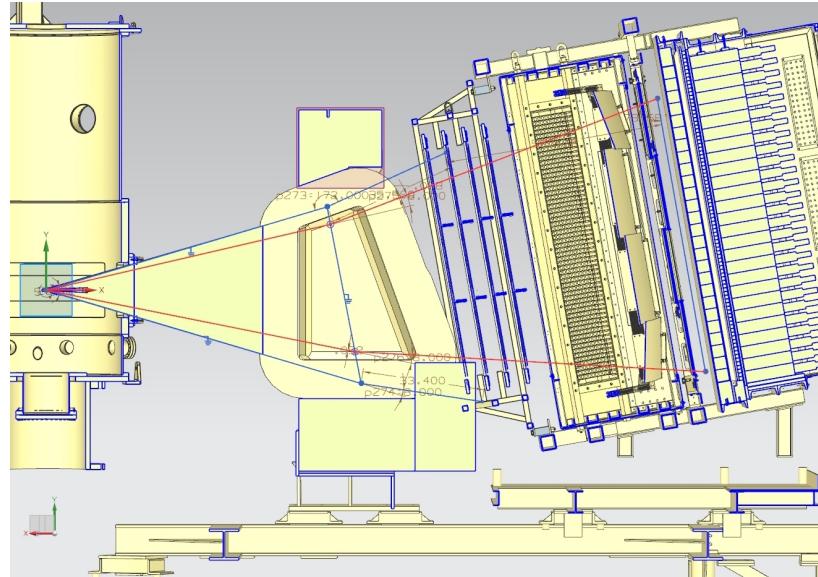


FIG. 4. The BigBite spectrometer with the upgraded detector stack.

176

1. GEM Chambers

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

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

185 three modules each, measuring $40 \times 50 \text{ cm}^2$, such that each layer covers $40 \times 150 \text{ cm}^2$ (the
 186 long dimension being vertical, along the dispersive direction). The readout of these modules
 187 are oriented in the x/y direction *i.e.* parallel and perpendicular to the dispersive direction
 188 (horizontal and vertical). The two other layers are being built by the SBS collaborators from
 189 UVA. They are composed of a single module measuring $40 \times 150 \text{ cm}^2$, the long dimension
 190 again being vertical and along the dispersive direction. The readout of these modules are
 191 oriented in the u/v direction *i.e.* ± 30 degrees with respect to the horizontal direction.

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

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

208

2. Shower/Preshower

209 The electromagnetic calorimeter configuration consists of two planes of lead glass blocks
 210 which we call the preshower and shower. The preshower, located about 80 cm behind
 211 the first GEM chamber, consists of a 2×26 plane of $37 \text{ cm} \times 9 \text{ cm}$ blocks. The shower, about
 212 1 m behind the first GEM chamber, consists of an 7×27 array of $8.5 \text{ cm} \times 8.5 \text{ cm}$ blocks.

213 Sums over these blocks form the physics event trigger for the experiment.

214 The preshower signal can be used to provide an additional method of pion rejection.
215 By selecting low preshower signals, a pion rejection factor of 1:50 can be achieved through
216 optimization. Despite higher particle rates, pion rejection performance is anticipated to
217 be similar to that achieved for Transversity, E06-010. By measuring the pedestal widths
218 and resolution for E06-010 and scaling to this proposal's conditions, overall relative energy
219 resolution for the detector is expected to become worse by a factor of 1.6, to about $\sigma_{\delta E/E} =$
220 25%.

221 3. Timing hodoscope

222 The BigBite timing hodoscope has been built the the SBS collaborators from Glasgow,
223 to replace the BigBite scintillator plane. It will be composed of 90 bars stacked in a plane,
224 each with dimensions 1 in. \times 1 in. \times 60 cm. The paddle stack will be oriented such as
225 the long dimension of the bars is horizontal *i.e.* perpendicular to the dispersive direction.
226 Each of these elements are readout by a PMT on each side, mostly to provide measurement
227 redundancy.

228 This plane will primarily be used to provide a signal for nucleon time of flight reconstruc-
229 tion. A time resolution of 200 ps is anticipated. This fine segmentation is meant to lower the
230 rates in the detector. Background studies made for the G_M^n experimental readiness review
231 demonstrated that the rates experienced by each element was \leq 500 kHz at a luminosity of
232 2.8×10^{38} cm $^{-2}$ s $^{-2}$. The PMTs pulses are processed by NINO front-end cards which, when
233 the PMT pulse crosses the NINO threshold, will produce a digital signal to be readout by
234 CAEN 1190 TDCs which record a leading time and a trailing time.

235 4. GRINCH cherenkov detector

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

²³⁹ array (60 lines of PMTs, with lines of 9 PMTs alternating with lines of 8 PMTs) placed away
²⁴⁰ from the beam. The radiation gas will be C_4F_8 , which is by far the best compromise between
²⁴¹ light yield for electrons and operating cost. With $n - 1 = 1.35 \times 10^{-3}$, the π threshold is only
²⁴² about 2.7 GeV, so the additional pion rejection will be most effective below this threshold.

²⁴³ As for the timing hodoscope The PMTs pulses are processed by NINO front-end cards
²⁴⁴ which, when the PMT pulse crosses the NINO threshold, will produce a digital signal to
²⁴⁵ be readout by VETROC TDCs, which for each PMT hit will record a leading time and a
²⁴⁶ trailing time. The analog signal will not be recorded however, which means that for each
²⁴⁷ PMT hit, the information of the number of not directly available (although it can in theory
²⁴⁸ be deduced from the time over threshold).

²⁴⁹ All of this implies that the electron selection relies on the number of GRINCH PMT
²⁵⁰ firing, instead of relying on the signal amplitude.

251

B. Hadron Calorimeter (HCal)

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

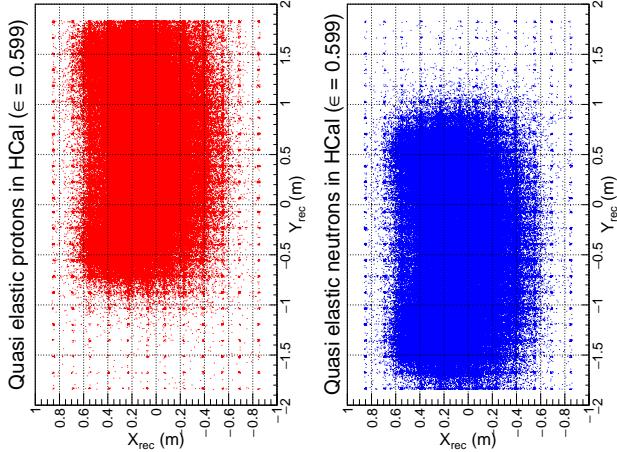


FIG. 5. Reconstructed HCal cluster from quasi-elastic events generated by G4SBS. The left distribution in red is for the proton, the right distribution in blue is for the neutron.

259

260

261 The HCal (which CAD model is shown on Fig. 6) is composed of 288 modules arranged in
 262 an array of 12×24 . In front of the full assembly is located a $3/4$ in steel plate which purpose
 263 is double:
 264

- 265 • initiate the hadronic shower to optimize the calorimeter response;
 - 266 • shield the modules from a fraction of the low energy secondaries;
- 267 Each of these modules measures $6 \times 6 \text{ in}^2$ section, for 3 ft length. They are composed of
 268 alternating tiles of scintillators and iron around a central light guide which collects the light

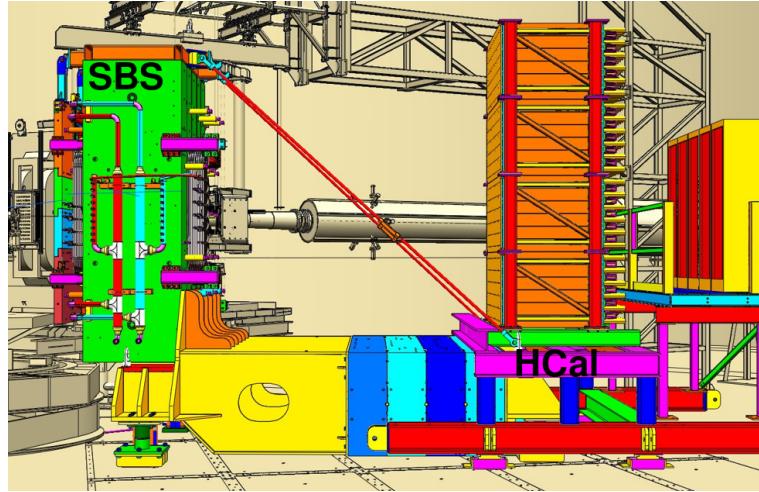


FIG. 6. CAD representation of HCal (right) with the SBS magnet (left)

²⁶⁹ generated in the scintillators by the hadronic shower, and guides it to the PMT at the end of
²⁷⁰ the block. Cosmics tests have determined that the average light yield for the HCal modules
²⁷¹ is around 5 photoelectrons per MeV deposited in the scintillator tiles.

²⁷² The PMTs are readout with FAD250 which sample the PMT signal every 40 ns and allow
²⁷³ to reconstruct the PMT pulse shape, hence its timing. They are also readout by TDCs which
²⁷⁴ provide additional timing information. Thanks to this, the timing resolution can be better
²⁷⁵ than 1 ns, which cosmics tests (in progress) seem to confirm.

²⁷⁶ The energy resolution is intrinsically broad (see Fig. 9 in Section V), due mostly to the
²⁷⁷ small fraction of energy from the hadronic shower actually measured by the scintillator tiles
²⁷⁸ (≤ 0.1 - refer yet again to Fig. 9).

279 **V. SIMULATIONS, ESTIMATIONS OF COUNTING RATES AND**
 280 **ACCIDENTALS**

281 The estimations of counting rates accidentals have been performed using G4SBS, the
 282 GEANT4-based simulation package developed for the SBS experiment [27]. This package
 283 includes a wide range of event generators, which allows to evaluate the rates for both events
 284 of interest (signal) and background. The representation of the experiment apparatus in
 285 G4SBS is shown in the high ϵ configuration on Fig. 7.

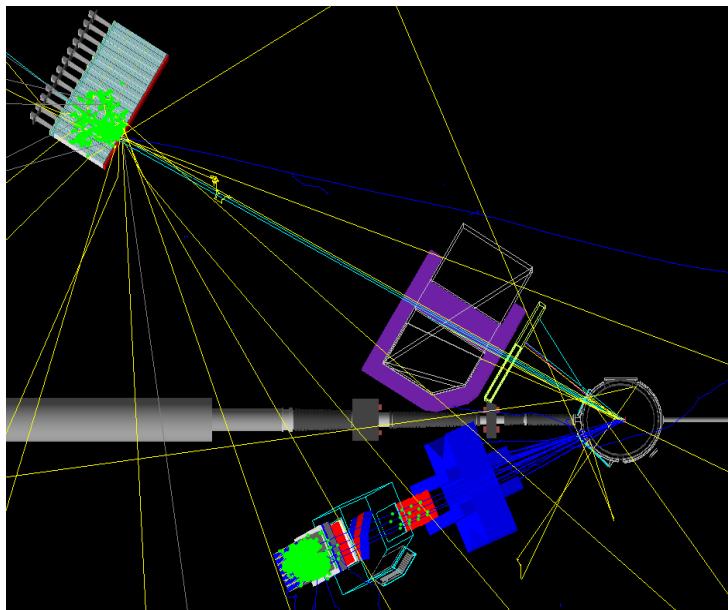


FIG. 7. Top view of the experimental apparatus model in G4SBS, shown in the high ϵ configuration. The beam direction is indicated, as well as the main elements (HCal, SBS magnet, BigBite spectrometer)

286
 287 **A. Background and trigger rates**

288 The main processes expected to contribute the trigger rates for the BigBite spectrometer
 289 are:

291 • the inelastic electron nucleon scattering process;

292 • photons from inclusive π^0 production;

293 • and to a lesser extent, charged pions.

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

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

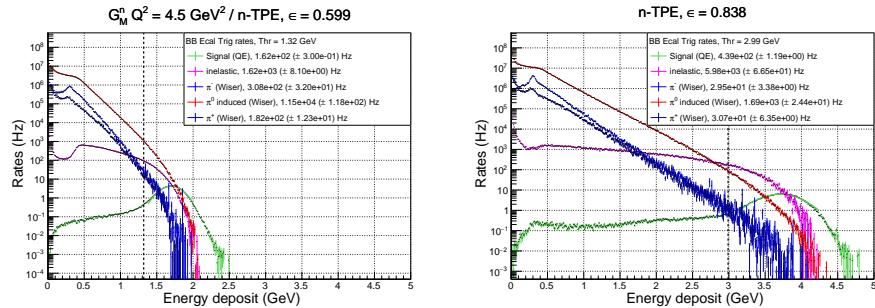


FIG. 8. Rates of the different process contributing to the BigBite electron arm trigger, for the low ϵ (left) and the high ϵ (right). Quasi-elastic is in green, inelastic in magenta, π^0 in red, π^- in blue, and π^+ in dark blue. Note the resolution for the elastic peak in the BigBite shower is ~ 0.3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

304

305

306 Since HCal is a sampling calorimeter (meaning that only a fraction of the shower energy
 307 is measured), it's resolution is significantly wider (~ 0.7 GeV). Due to this, the threshold
 308 is at 90% efficiency (which corresponds to ~ 0.1 GeV for both kinematics. Fig. 9 presents

309 the distributions of rate of energy deposit for the different processes involved in the BigBite
 310 trigger rates.

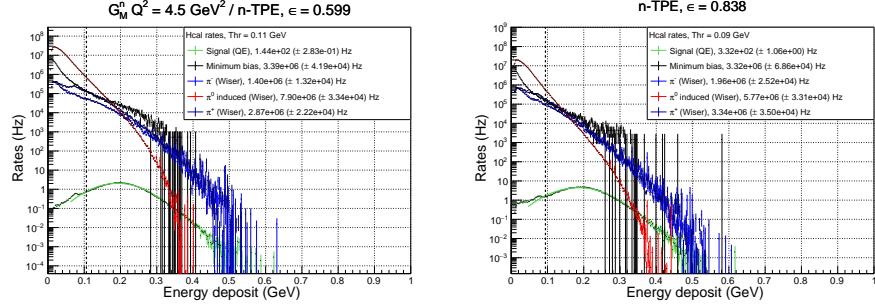


FIG. 9. Rates of the different process contributing to the HCal trigger, for the low ϵ (left) and the high ϵ (right). Quasi-elastic is in green, minimum bias in black, π^0 in red, π^- in blue, and π^+ in dark blue. Note the peak itself is around 0.2 GeV for 3.2 GeV nucleons.

311

312

313 The thresholds and trigger rates for each arm, as well as the coincidence rate (assuming
 314 30ns coincidence window), are summarized in Table. I.

315

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

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

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

TABLE I. 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.

326

B. Contamination from inelastic

327

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

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

330 and the missing transverse momentum of the nucleon

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

331 where M_N is the mass of the nucleon, E and E' the initial and final energy of the electron,
332 and $q_{x,y}$, $p'_{x,y}$ are the projections on x , y of the vectors of the virtual photon and final nucleon.

333 The distributions of these quantities (weighted with cross section and including detector res-
 334 olutions) are displayed for quasi-elastic and inelastic scattering, and for proton and nucleon,
 335 on Fig. 10 for the low ϵ kinematic, and on Fig. 11 for the high ϵ kinematic. Provided that

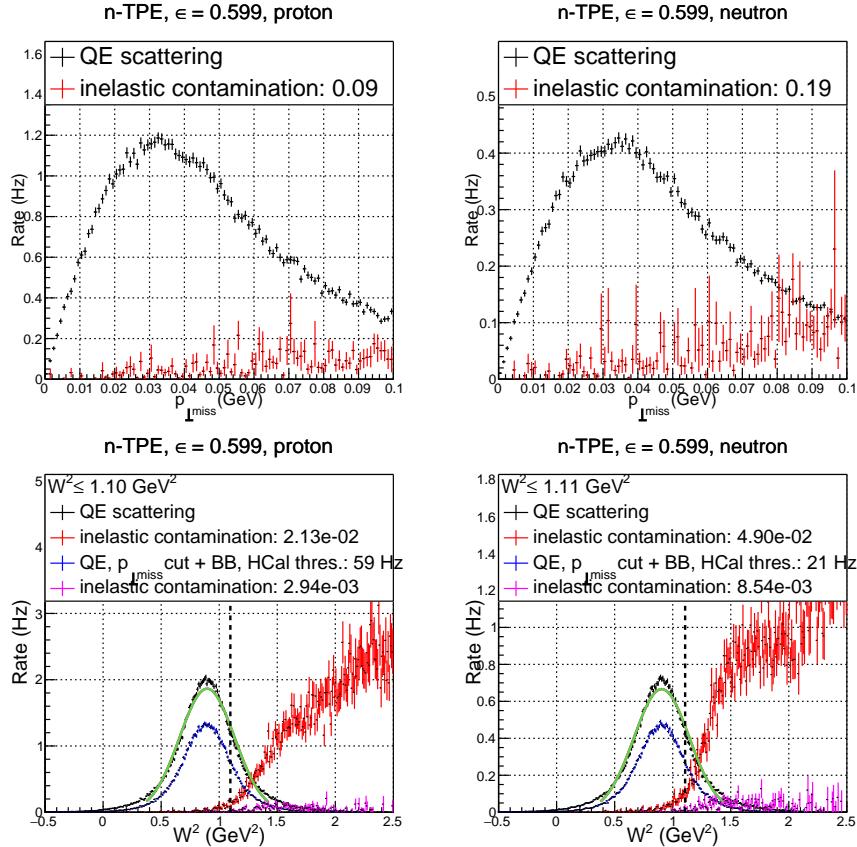


FIG. 10. Compared quasi-elastic and inelastic distributions (including detectors resolutions) for $p_{\perp \text{miss}}$ (top) and W^2 (bottom), for the low ϵ kinematic. Comparison for protons is on the left, and comparison for neutrons is on the right. On the bottom panel, black and red are before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

336

338

339 we are not limited by statistics and the sample purity is capital for our experiment, we set
 340 the selection criteria on W^2 and $p_{\perp \text{miss}}$ to maximize inelastic contamination (ideally below
 341 1 %). Setting $p_{\perp \text{miss}} \leq 0.1 \text{ GeV}$ and $W^2 \leq 1.1 \text{ GeV}^2$, the inelastic contamination of the

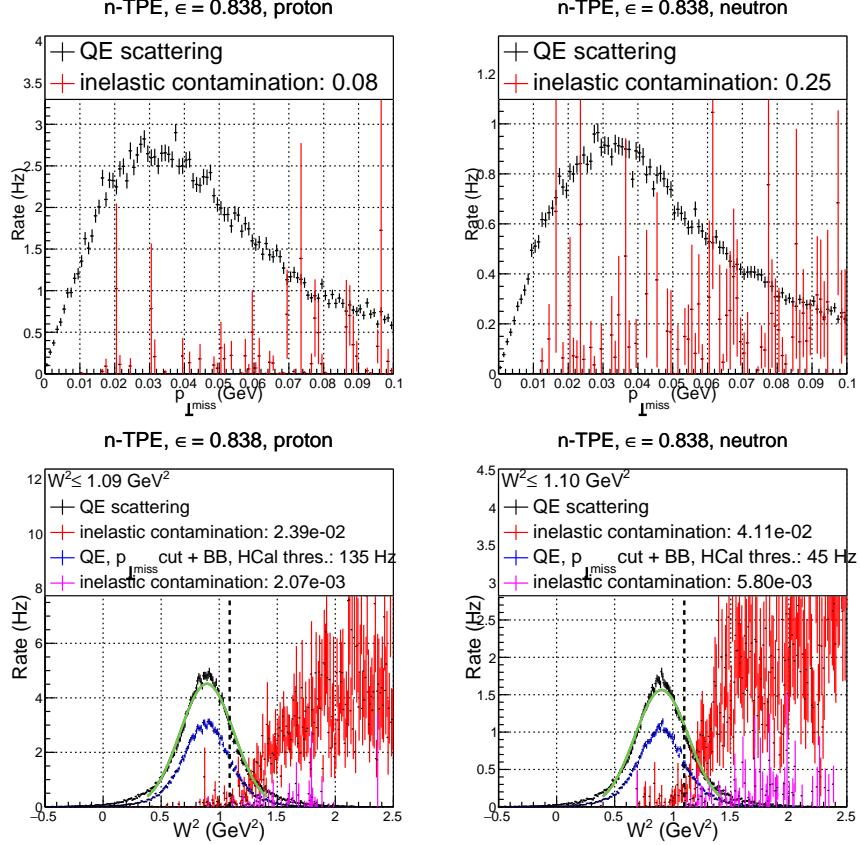


FIG. 11. Compared quasi-elastic and inelastic distributions (including detectors resolutions) for $p_{\perp miss}$ (top) and W^2 (bottom), for the high ϵ kinematic. Comparison for protons is on the left, and comparison for neutrons is on the right. On the bottom panel, black and red are before the $p_{\perp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

342 elastic sample ranges from 0.2 % to 0.9 %, while retaining ≥ 60 % of the quasi-elastic events
 343 properly recorded in the BigBite-SBS pair. Table. II summarizes the quasi-elastic selection
 344 cuts, ad inelastic contamination δ_{inel} .

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

TABLE II. Summary of cuts for quasi-elastic selection and resulting inelastic contamination δ_{inel} .

346

C. Quasi-elastic counting rates

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

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

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

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

357

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

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

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

Point (ϵ)	BB thr. (GeV)	HCal thr. (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 IV. Kinematics electron thresholds, particle detection efficiencies (η_{det}), and efficiency of quasi-elastic selection η_{sel} separated for the proton and the neutron.

363

364 The counting rates are evaluated using among the N_{Gen} events generated the events that
 365 have passed the selection described below, and weighting those events with the cross section
 366 $d\sigma/d\Omega|_i$ calculated by G4SBS, multiplied by the generation solid angle $\Delta\Omega_{Gen}$, using the
 367 formula:

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

368 with \mathcal{L}_{exp} the experimental luminosity and Δt the running time Events are “accepted” if
 369 they meet the following criteria:

- 370 • the electron is in the BigBite acceptance;
- 371 • the electron passes the BigBite threshold defined in Table IV and gives signal in the
 372 GRINCH;
- 373 • the nucleon is in the HCal acceptance and passes the HCal threshold defined in Ta-
 374 ble IV;

- 375 • the event passes the quasi-elastic selection defined in the previous section *i.e.* $W^2 \leq 1.1 \text{ GeV}^2$
 376 and $p_{\perp miss} \leq 0.10 \text{ GeV}$.

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

$$F^2 = \frac{N_{QE}}{\mathcal{L}_{exp} \cdot \Delta t \cdot d\sigma_{Mott}/d\Omega \cdot \Delta\Omega \cdot \eta} \quad (12)$$

378 and its statistical error $\Delta F^2 = F^2 / \sqrt{N_{QE}}$ are compiled for both kinematics in Table. V,
 379 assuming a running time $\Delta t = 12$ hours of running at a beam intensity of $I_{exp} = 30 \mu\text{A}$ on
 380 a liquid deuterium target with length $l_{tgt} = 15 \text{ cm}$ and density $d_{tgt} = 0.169 \text{ g.cm}^{-3}$.

Point (ϵ)	N_{QE} (e-n)	N_{QE} (e-p)	F_n^2 ($\times 10^{-3}$)	ΔF_n^2 ($\times 10^{-6}$)	F_p^2 ($\times 10^{-3}$)	ΔF_p^2 ($\times 10^{-6}$)
1 (0.599)	9.07×10^5	2.55×10^6	0.99	1.04	2.73	1.70
2 (0.838)	1.94×10^6	5.83×10^6	0.72	0.52	1.93	0.80

TABLE V. Quasi-elastic counting rates, and total form factor (defined in Eq. 11). These rates assume $\Delta t = 12$ hours of running at a beam intensity of $I_{exp} = 30 \mu\text{A}$ on a liquid deuterium target with length $l_{tgt} = 15 \text{ cm}$ and density $d_{tgt} = 0.169 \text{ g.cm}^{-3}$

381

382 The expression of the total form factor F^2 is: where Δt the running time, $\Delta\Omega$ is the
 383 convoluted BigBite-HCal solid angle, η is the product of all efficiencies (detection efficiencies
 384 $\eta_{det} \times$ selection efficiency η_{sel}), and \mathcal{L}_{exp} is the experimental luminosity:

$$\mathcal{L}_{exp} = \frac{I_{exp}}{q_e} * L_{tgt} * d_{tgt} \frac{\mathcal{N}_A}{m_D}. \quad (13)$$

385 The calculation of the F_2 term requires the evaluation of the Mott cross section

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

386 The Mott cross section has been calculated with the weighted average of the electron variables
 387 (momentum and polar angle).

388

Point (ϵ)	$\langle \theta_e \rangle$ (deg)	$\langle k' \rangle$ (GeV)	$\langle Q^2 \rangle$ (GeV 2)	σ_{Mott} (nb sr $^{-1}$)
1 (0.599)	41.7	2.01	4.47	6.62
2 (0.838)	22.9	4.26	4.40	48.0

TABLE VI. Cross-section weighted average of kinematic variables over the BigBite acceptance.

The Mott cross section has been evaluated at these values.

389

VI. SYSTEMATIC ERRORS

390 In this section we will estimate (or set upper limits on) the contributions to the systematic
 391 uncertainty for this experiment. The sources of systematic uncertainties from the experi-
 392 mental setup (target, acceptance, inelastic contamination) were already estimated for the
 393 SBS G_M^n experiment proposal [19]. Note that some of those systematics (nuclear corrections,
 394 accidentals) cancel in the ratio $R = f_{corr} \times N_{e,e'n}/N_{e,e'p}$. Since the experimental setup has
 395 evolved since then, some of these uncertainties have been reevaluated, namely the acceptance
 396 loss and inelastic contamination.

TABLE VII. Estimated contributions (in percent) to systematic errors on TPE. Quantities marked with * are taken from the SBS G_M^n experiment proposal [19].

Kinematic (ϵ)	(1) 0.599	(2) 0.838
Nuclear correction*	-	
Accidentals*	-	
Target windows*	0.2 %	
Acceptance losses	0.5 %	3.0 %
Inelastic contamination	0.9 %	0.6 %
Nucleon mis-identification*	0.6 %	
Syst. error on $R = f_{corr} \times N_{e,e'n}/N_{e,e'p}$	1.3 %	3.1 %
$S_c^n = \sigma_L^n/\sigma_T^n$	0.107 ± 0.01 (9.3 %)	
$\mu_n G_E^n/G_M^n$	0.55 ± 0.05 (9.1 %)	
Syst. error on TPE	0.069 ± 0.012 (17.4 %)	

397 Table. VII lists the estimated contributions to systematic errors on the two-photon-
 398 exchange contribution (TPE). The systematics for S_c^n and $\mu_n G_E^n/G_M^n$ have already been ex-
 399 plied in Sec. III, and are the leading contributions to the total uncertainty.

400 Inelastic contamination has been reevaluated in Sec. V B. To evaluate the upper limit on

⁴⁰¹ our uncertainty, we added quadratically the inelastic contamination evaluated for the proton
⁴⁰² and the neutron for each kinematics, which is the error we make if we ignore the systematics
⁴⁰³ completely. Even in this case, we expect less than 1% systematic errors.

⁴⁰⁴ The acceptance loss in SBS (*i.e.* the proportion of non-detected nucleons for each detected
⁴⁰⁵ electron) have been evaluated for both kinematics. They are about 10% for the $\epsilon = 0.60$
⁴⁰⁶ kinematic (meaning that for every good electron measured, we will not measure the recoil
⁴⁰⁷ nucleon 10% of the times), but they are over 30 % for the $\epsilon = 0.84$ kinematics, which is due to
⁴⁰⁸ a larger spread of the nucleon imprint. The systematic uncertainty on the acceptance loss for
⁴⁰⁹ the ratio $R = f_{corr} \times N_{e,e'n}/N_{e,e'p}$ is maximized by the proton-neutron solid angle asymmetry
⁴¹⁰ $A_{\Delta\Omega} = \Delta\Omega_n - \Delta\Omega_p/\Delta\Omega_n + \Delta\Omega_p$. This asymmetry is about 0.5% for the $\epsilon = 0.60$ kinematic
⁴¹¹ (consistent with the G_M^n proposal), but goes up to 3% for the $\epsilon = 0.84$ kinematics.

412

VII. PROPOSED MEASUREMENTS

413 We propose to use the same experimental setup of E12-09-019 experiment. We will add
 414 a kinematic point at $Q^2 = 4.5 \text{ (GeV/c)}^2$, but with a higher ϵ value. This additional point
 415 along with the data point of E12-09-019 experiment will allow us to perform LT separation
 416 and obtain (in one-photon approximation) the G_E^n value. Table 1 displays the kinematic
 417 setting of the proposed experiment.

Point	Q^2 $(\text{GeV}/c)^2$	E (GeV)	E' (GeV)	θ_{BB} degrees	θ_{SBS} degrees	ϵ (%)	$\Delta\sigma$ (%)	ΔTPE (%)
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 VIII. Kinematic settings of the proposed experiment. The blue row is a kinematic point of E12-09-019 experiment.

418

419

VIII. BEAM TIME REQUEST

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

425 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
 426 corresponds to a beam intensity of $I_{exp} = 30 \mu\text{A}$ on a liquid deuterium target with length
 427 $l_{tgt} = 15 \text{ cm}$ and density $d_{tgt} = 0.169 \text{ g.cm}^{-3}$. To have a better handle on our backgrounds,
 428 we also plan to take 12 hours of data at half luminosity (basically by lowering the beam
 429 intensity by a factor 2). In each of these configurations, we also need to take data on a
 430 “dummy” target (*i.e.* on a target cell identical to the one used for production, but empty)
 431 to understand the contamination of our data from the target walls.

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

- 434 • SBS magnet and the hadronic calorimeter (HCal) angle change;
- 435 • BigBite spectrometer angle and distance change;
- 436 • Beam energy change;

437 These tasks may be done in parallel, but the SBS configuration is the most-time consuming
 438 task, and determines the time required to perfomr this configuration change.

439 The projected use of this time is summarized in Table. IX.

440

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

Task	Target	I_{exp}	time requested
Data taking (Prod.)	15 cm LD ₂	30 μ A	12 hours
Data taking (Syst.)	15 cm “Dummy”	30 μ A	4 hours
Data taking (Prod.)	15 cm LD ₂	15 μ A	12 hours
Data taking (Syst.)	15 cm “Dummy”	15 μ A	4 hours
Setting changes (SBS, BigBite angles, beam energy)			16 hours
Total			48 hours

TABLE IX. Summary table for the beam time request. Setting changes include SBS and Bigte bite angles change, as well as a beam energy change.

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

447 The set of instrumentation and required beam current for proposed measurement is iden-
 448 tical to one in the GMn experiment. The beam energy of 6.6 GeV will be used. One of two
 449 data points required for the cross section LT separation is already in the data taking plan of
 450 GMn.

451 There are no other measurements of TPE in the $e - n$ elastic scattering and knowledge
 452 of the TPE is essential for the understanding of the elastic electron scattering from neutron
 453 (and proton) and hadron structure. Furthermore, it is a necessary input in the analysis and
 454 interpretation of a wide range of electron scattering processes.

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

458 We propose to measure the Rosenbluth slope and extract (in one-photon approximation)
 459 $\delta G_E^n/G_M^n$ to an accuracy of 0.15, which would bring its precision to a level comparable with
 460 that of the double polarization experiments GEN-RP and GEN-He3 at such value of Q^2 .
 461 Such precision should be sufficient to detect the TPE contribution to the $e - n$ Rosenbluth
 462 slope on the three sigma level.

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- 463 [1] R. Hofstadter, *Rev. Mod. Phys.* **28**, 214 (1956).
- 464 [2] M. N. Rosenbluth, *Phys. Rev.* **79**, 615 (1950).
- 465 [3] E. Christy *et al.*, “Two-photon exchange in electron-proton elastic scattering at large four-
466 momentum transfer,” (2020), in preparation for publication in PRL.
- 467 [4] P. G. Blunden, W. Melnitchouk, and J. A. Tjon, *Phys. Rev.* **C72**, 034612 (2005), arXiv:nucl-
468 th/0506039 [nucl-th].
- 469 [5] J. Arrington, P. G. Blunden, and W. Melnitchouk, *Prog. Part. Nucl. Phys.* **66**, 782 (2011),
470 arXiv:1105.0951 [nucl-th].
- 471 [6] A. Afanasev, P. Blunden, D. Hasell, and B. Raue, *Prog. Part. Nucl. Phys.* **95**, 245 (2017),
472 arXiv:1703.03874 [nucl-ex].
- 473 [7] B. Wojtsekhowski, in *Exclusive processes at high momentum transfer. Proceedings, Newport
474 News, USA, May 15-18, 2002* (2002) arXiv:1706.02747 [physics.ins-det].
- 475 [8] G. D. Cates, C. W. de Jager, S. Riordan, and B. Wojtsekhowski, *Phys. Rev. Lett.* **106**, 252003
476 (2011), arXiv:1103.1808 [nucl-ex].
- 477 [9] C. D. Roberts, M. S. Bhagwat, A. Holl, and S. V. Wright, *Eur. Phys. J. ST* **140**, 53 (2007),
478 arXiv:0802.0217 [nucl-th].
- 479 [10] J. Segovia, I. C. Cloet, C. D. Roberts, and S. M. Schmidt, *Few Body Syst.* **55**, 1185 (2014),
480 arXiv:1408.2919 [nucl-th].
- 481 [11] B. Wojtsekhowski (2020) arXiv:2001.02190 [nucl-ex].
- 482 [12] G. A. Miller, *Phys. Rev. Lett.* **99**, 112001 (2007), arXiv:0705.2409 [nucl-th].
- 483 [13] C. E. Carlson and M. Vanderhaeghen, *Phys. Rev. Lett.* **100**, 032004 (2008), arXiv:0710.0835
484 [hep-ph].
- 485 [14] D. Muller, D. Robaschik, B. Geyer, F. M. Dittes, and J. Horejsi, *Fortsch. Phys.* **42**, 101
486 (1994), arXiv:hep-ph/9812448 [hep-ph].
- 487 [15] X.-D. Ji, *Phys. Rev. Lett.* **78**, 610 (1997), arXiv:hep-ph/9603249 [hep-ph].
- 488 [16] A. V. Radyushkin, *Phys. Lett.* **B380**, 417 (1996), arXiv:hep-ph/9604317 [hep-ph].

- [489] [17] M. Diehl and P. Kroll, *Eur. Phys. J.* **C73**, 2397 (2013), arXiv:1302.4604 [hep-ph].
- [490] [18] N. Kivel, “private communications,” (2020).
- [491] [19] J. Annand, R. Gilman, B. Quinn, B. Wojtsekhowski, *et al.*, unpublished. See https://www.jlab.org/exp_prog/proposals/09/PR12-09-019.pdf, https://www.jlab.org/exp_prog/proposals/proposal_updates/PR12-09-019_pac35.pdf (2008).
- [494] [20] E. B. Hughes, T. A. Griffy, M. R. Yearian, and R. Hofstadter, *Phys. Rev.* **139**, B458 (1965).
- [495] [21] R. G. Arnold *et al.*, *Phys. Rev. Lett.* **61**, 806 (1988).
- [496] [22] L. Durand, *Phys. Rev.* **115**, 1020 (1959).
- [497] [23] E. E. W. Bruins *et al.*, *Phys. Rev. Lett.* **75**, 21 (1995).
- [498] [24] G. Kubon *et al.*, *Phys. Lett.* **B524**, 26 (2002), arXiv:nucl-ex/0107016 [nucl-ex].
- [499] [25] J. Lachniet *et al.* (CLAS), *Phys. Rev. Lett.* **102**, 192001 (2009), arXiv:0811.1716 [nucl-ex].
- [500] [26] V. Punjabi, C. F. Perdrisat, M. K. Jones, E. J. Brash, and C. E. Carlson, *Eur. Phys. J.* **A51**, 79 (2015), arXiv:1503.01452 [nucl-ex].
- [502] [27] A. Puckett, unpublished. See https://hallaweb.jlab.org/wiki/index.php/Documentation_of_g4sbs (2016).
- [504] [28] D. E. Wiser, “Photoproduction of protons, kaons and pions at slac energies,” Ph.D. thesis, University of Wisconsin (1977).