Experiment Proposal for PAC48:

The Two-Photon Exchange Contribution in Elastic *e*-*n* Scattering

On behalf of the nTPE spokespeople;

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Jefferson Lab PAC48

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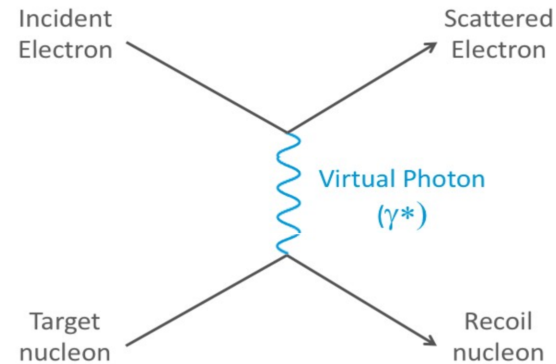
Elastic e-N Scattering, Rosenbluth (1950)

In the One-Photon Exchange (Born) approximation:

$$\left(\frac{d\sigma}{d\Omega}\right)_{eN\rightarrow eN} = \frac{\sigma_{Mott}}{\epsilon(1+\tau)}\left[\underbrace{\tau G_M^2(Q^2)}_{\text{Sachs magnetic FF squared}} + \epsilon \underbrace{G_E^2(Q^2)}_{\text{Sachs Electric FF squared}}\right]$$

with $\tau = Q^2/(4M_N)$



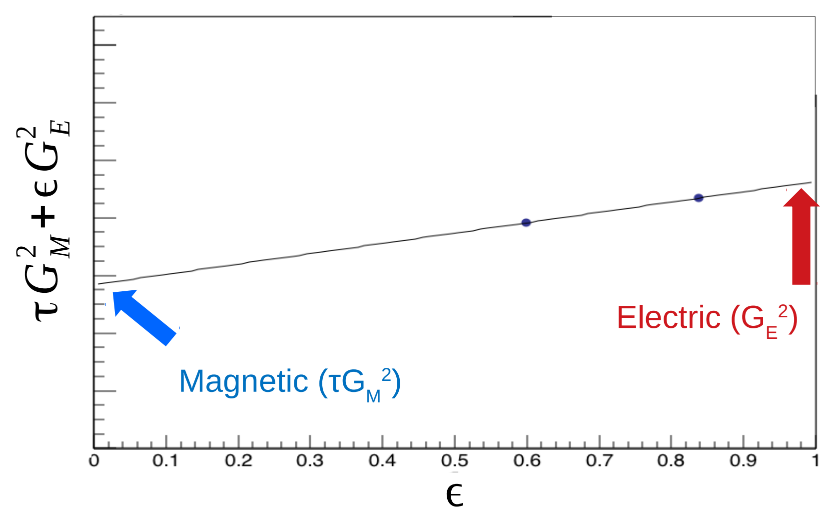
Rosenbluth technique: separate G_M^2 and G_E^2 based

on the linear dependence in $\epsilon = \left[1+2(1+\tau)\tan^2\theta/2\right]^{-1}$

$$\begin{aligned}\sigma_r &= (d\sigma/d\Omega)\cdot\epsilon(1+\tau)/\sigma_{Mott}\\ &= \tau G_M^2(Q^2) + \epsilon G_E^2(Q^2)\\ &= \sigma_T + \epsilon\sigma_L\end{aligned}$$

Two or more measurements, same Q^2,

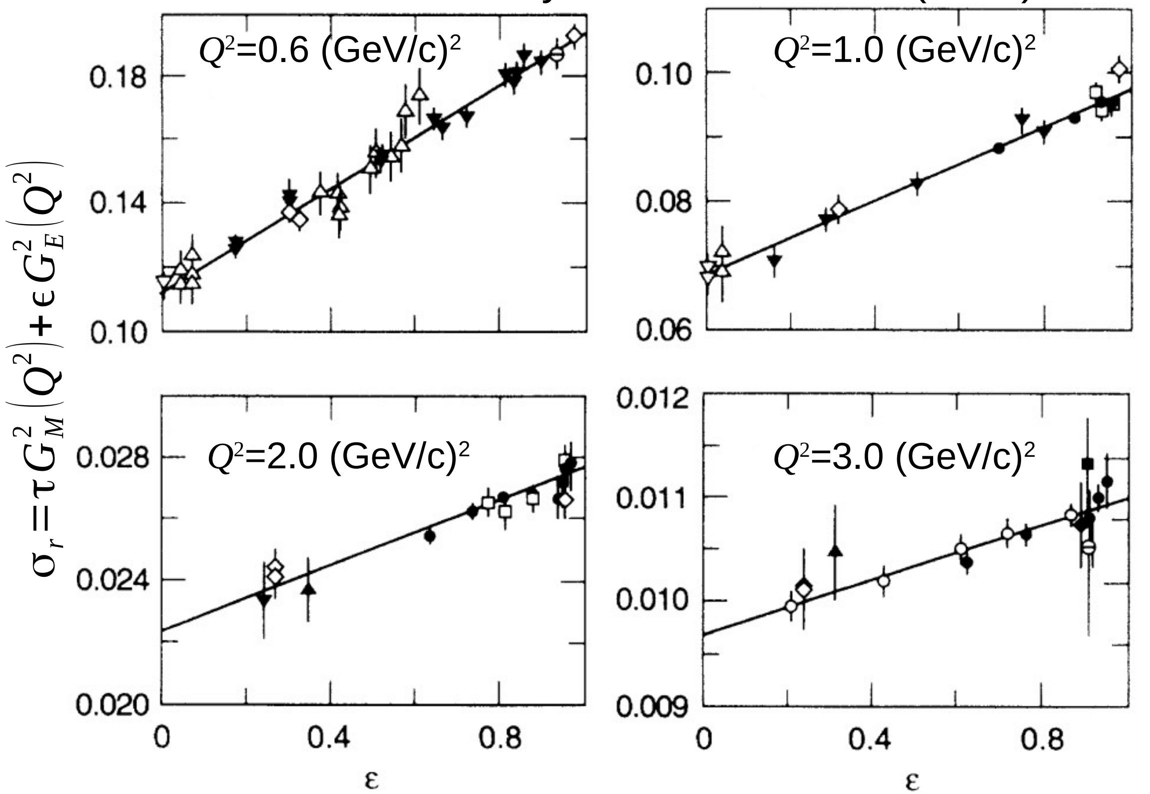
different E and θ (different ϵ)



Rosenbluth for e-p scattering

Technique extensively used to measure Rosenbluth slope for the proton and extract G_E^p

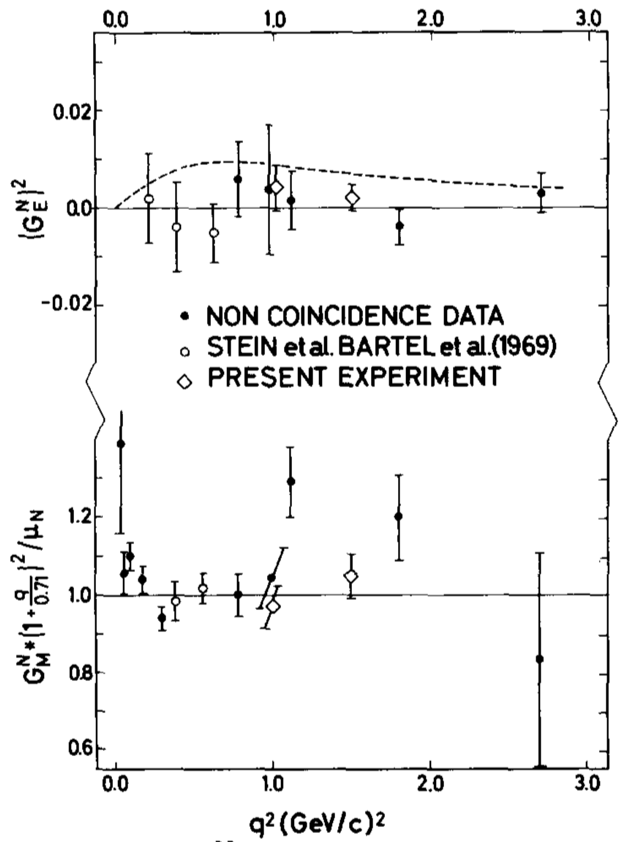
Walker et al. Phys. Rev. D49, 5671 (1994)



Linearity in ϵ well tested up to $Q^2 \leq 3$ (GeV/c)^2

Elastic *e*-*n* measurements at 1-2 (GeV/c)^2 (1960's and 70's)

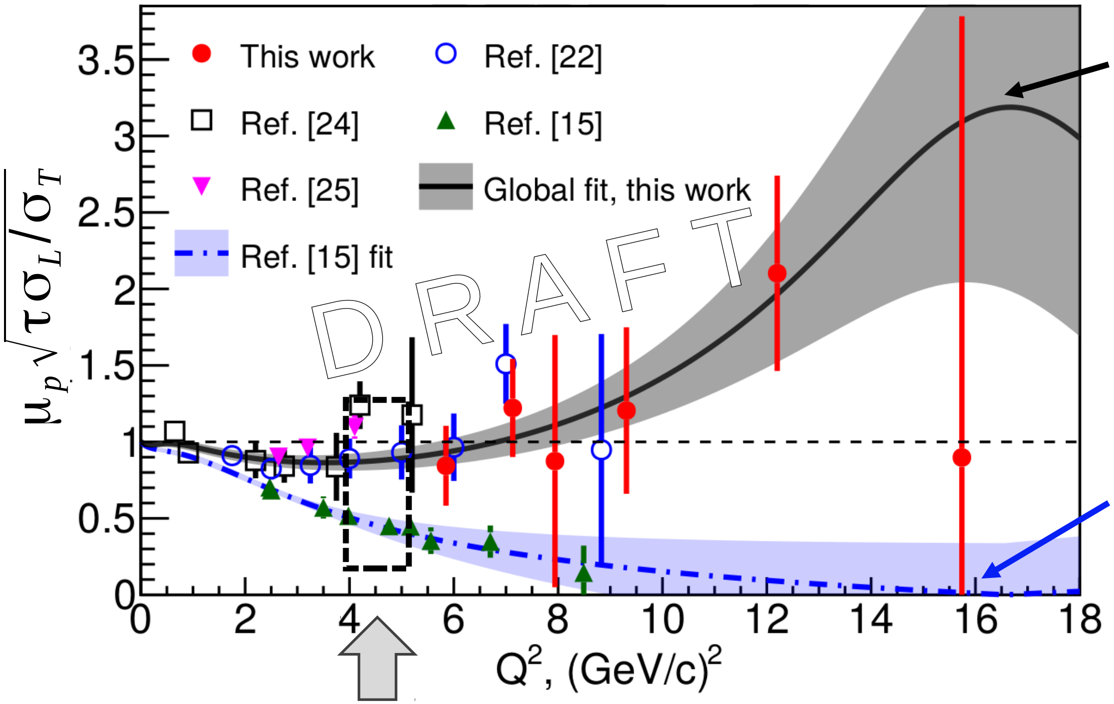
Bartel et al., Phys. Lett. 39B, 407 (1972)



$$\left(G_E^n\right)^2 = S^n \times \tau \left(G_M^n\right)^2$$

Accuracy achieved in *e*-*n* measurements 50 years ago is not sufficient to measure the Rosenbluth slope

Global fit on Rosenbluth slope for elastic e-p



Global fit of the Rosenbluth slope

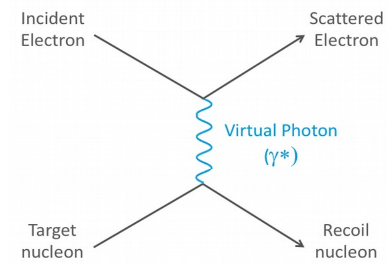
E. Christy et al., “Two-photon exchange in electron-proton elastic scattering at large four-momentum transfer”, (2020), including last Jlab proton data at 12 GeV in preparation for publication in PRL

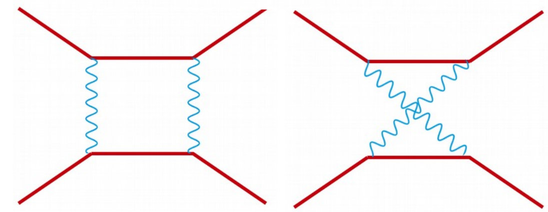
Global fit of polarization transfer data

- At Q^2 = 4.5 (GeV/c)^2, the Rosenbluth slope is $\boxed{S^p = \sigma_L^p/\sigma_T^p \simeq 0.087 \pm 0.01}$
- Rosenbluth and polarization transfer methods have a *large* discrepancy
- Missing contribution, likely to be due to two-photon exchange (TPE)

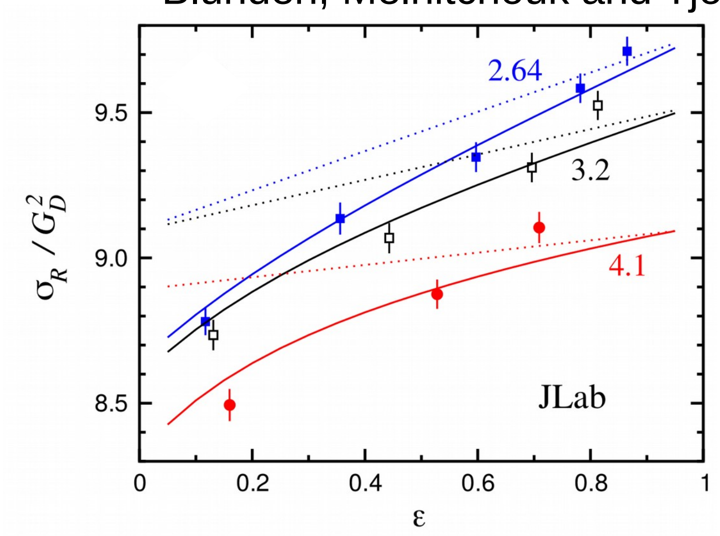
Mechanism of e-N scattering (proton)

- Until GEp-I at Jefferson Lab, Phys. Rev. Lett. 84, 1398 (2000), OPE accepted to be a sufficient approximation
- Investigation of two-photon exchange is mandatory
- Many experiments were dedicated to measure two-photon exchange (TPE), including Rosenbluth and $e^{\pm}$-p scattering
- Linearity at mid ϵ does not exclude TPE





Blunden, Melnitchouk and Tjon, Phys. Rev. C**72**, 034612 (2005)



Fit from polarization transfer $G_E^{\,p}/G_M^{\,p}$ data

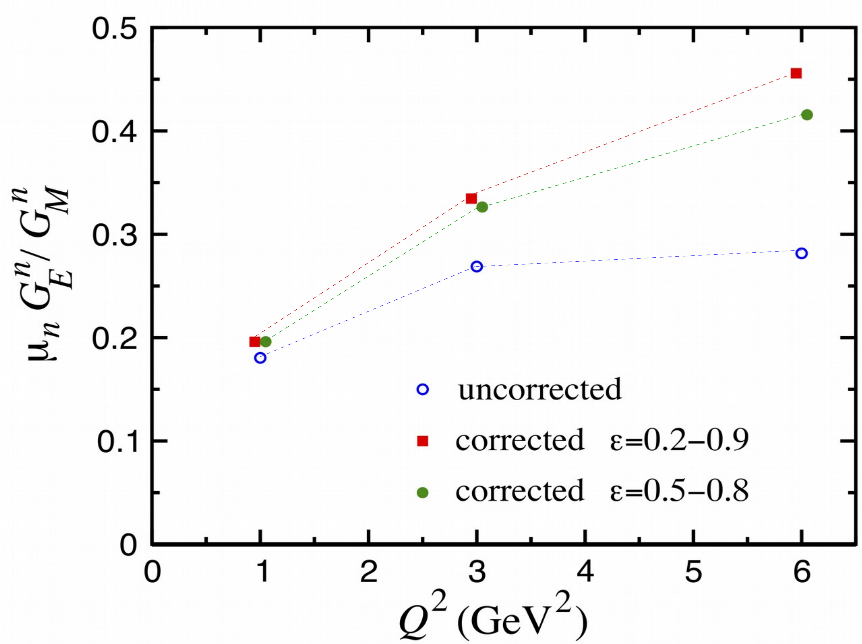
same, corrected with TPE contributions

Data, Phys. Rev. Lett. 94, 142301 (2005)

measurement on neutron will bring new insight to this physics

Two-Photon Exchange contribution (Neutron)

- Two-Photon Exchange (TPE) contribution never measured for the neutron.
- Blunden, Melnitchouk and Tjon, Phys. Rev. C**72**, 034612 (2005) gave a prediction of the impact of the TPE correction on G_E^n/G_M^n using Rosenbluth separation method.



- Uncorrected $\mu_n G_E^n/G_M^n$ from Mergell Meissner Drechsel parameterization in Nucl. Phys. A596, 367 (1996)
- Corrected with TPE contribution between two hypothetical measurements at $\epsilon = 0.2$ and 0.9
- Corrected with TPE contribution between two hypothetical measurements at $\epsilon = 0.5$ and 0.8

Proposed experiment

Goals:

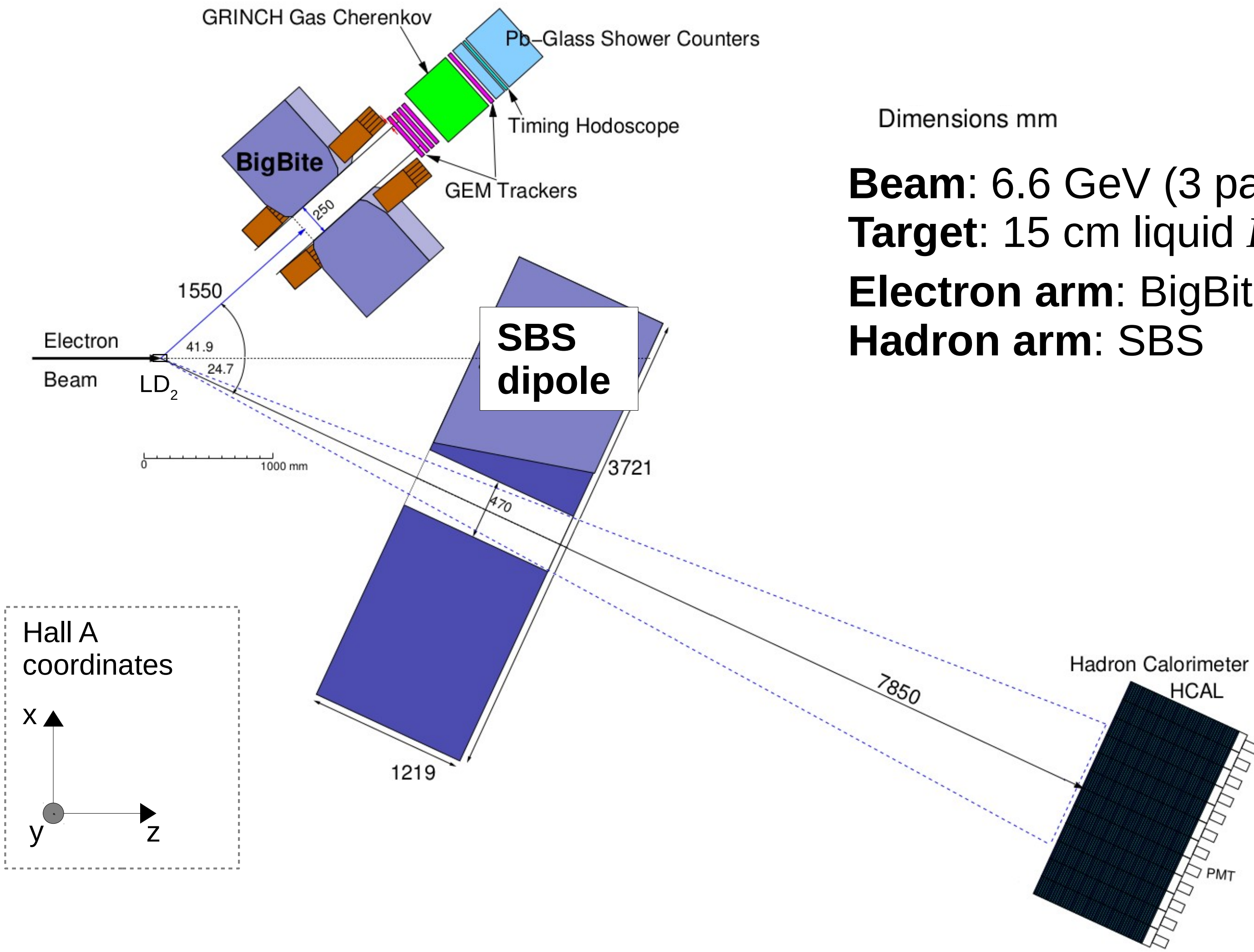
- Measure the Rosenbluth slope for elastic e-n scattering for the first time since 1972, with 10 times improved accuracy
- Extract the two-photon exchange contribution on elastic e-n scattering

Means:

Use equipment and data from approved experiment E12-09-019 (GMn) in Hall A

Kin	Q^2 $(\mathrm{GeV}/c)^2$	E (GeV)	E' (GeV)	θ_{BB} (deg)	θ_{SBS} (deg)	ϵ	
1	4.5	4.4	2.0	41.88	24.67	0.599	← Approved E12-09-019
2	4.5	6.6	4.2	23.23	31.2	0.838	← Requested for nTPE

Plan view of $Q^2 = 4.5$ (GeV/c)^2, $\epsilon = 0.6$ kinematic setting



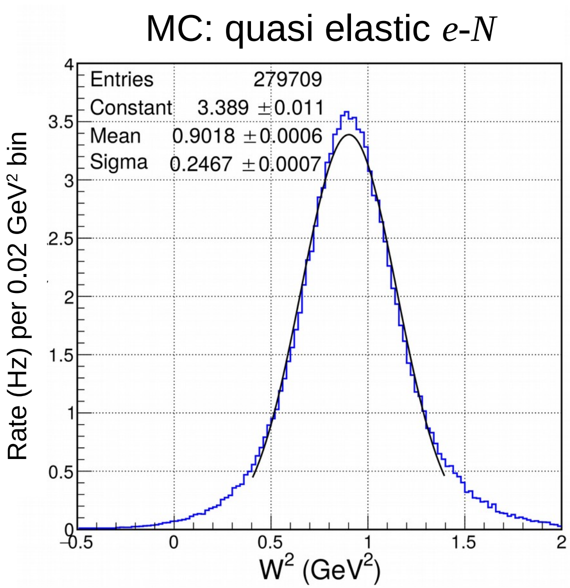
Dimensions mm

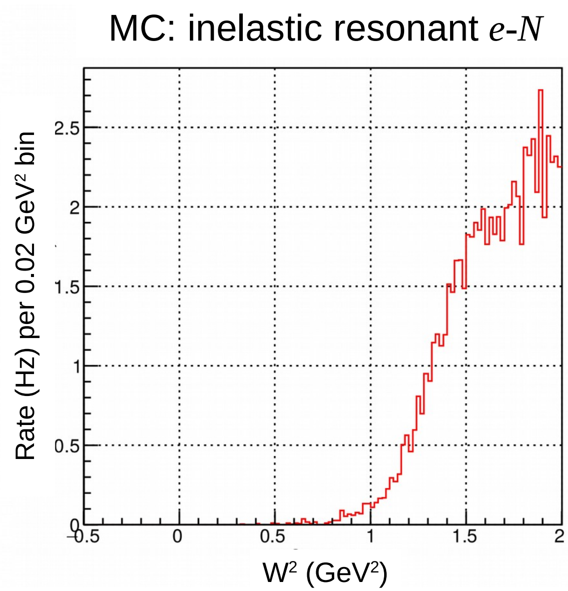
Beam: 6.6 GeV (3 pass), 30 μA
Target: 15 cm liquid D_2
Electron arm: BigBite
Hadron arm: SBS

Key experimental parameters

- Electron-nucleon luminosity: **2.8 x 10^{38} cm^{-2}/s**

- BigBite: **$\Delta\Omega_e$ = 32 msr**; **$\Delta p/p$ = 1.0%**, **$\Delta\theta$ = 1.2 mrad**, **$\Delta\varphi$ = 2.0 mrad**.
  => resolution in $W^2 = M_N^{\ 2}+2M_N(E-E')-Q^2$ of the quasi-elastic peak: 0.25 GeV^2



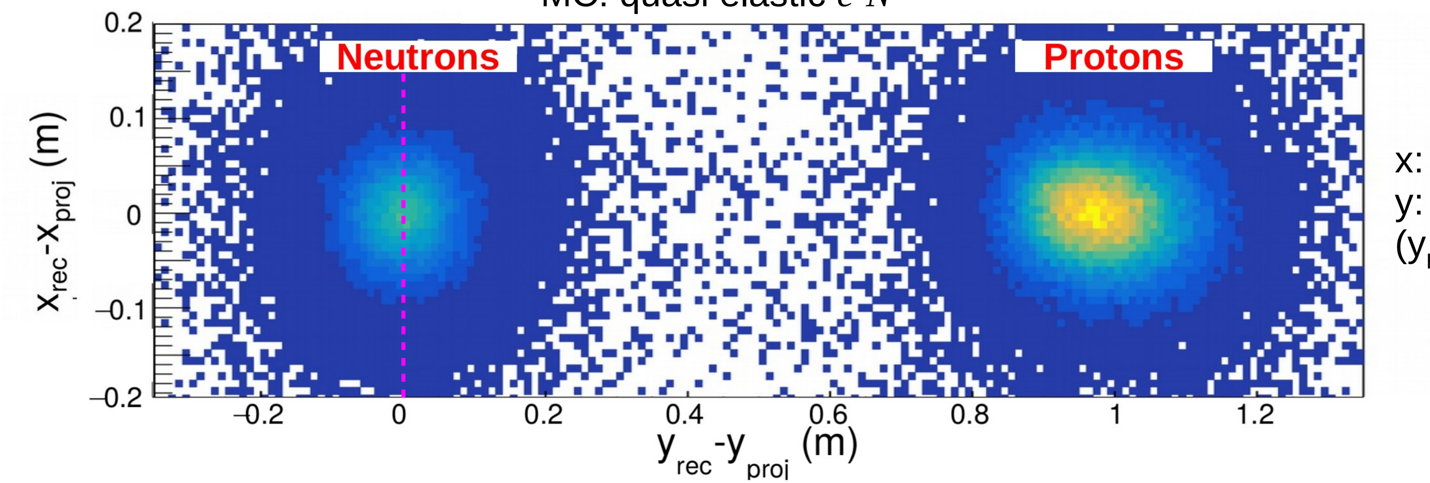


- Calorimeter threshold: **3.0 GeV** for 4.2 GeV mean elastic peak.
  => Projected single rates for BigBite: **8 kHz**

Key experimental parameters

- SBS: $\Delta\Omega_{SBS}$ **= 71 msr**; **$\Delta\theta = \Delta\varphi$ = 5 mrad**, **Δt / t = 0.5 ns / 25 ns**, $\Delta E/E$ = 0.4
  Nucleon identification by reconstructed vs projected position in HCal

MC: quasi elastic e-N



x: non-dispersive
y: *dispersive*
($y_{HCal} \equiv y_{Hall}$)

- Calorimeter threshold: **0.10 GeV** for 90% efficiency of the 3.2 GeV/c nucleons
  which deposit 0.20 GeV in the HCal (scintillator material)
  => Projected single rates for SBS: **3.3 MHz**

- Projected trigger rates (30 ns coincidence window with BigBite): **820 Hz**
  Projected quasi-elastic rates: **180 Hz** (45 Hz *e-n* +135 Hz *e-p*)

Durand technique (1959) to measure neutron Form Factors

Simultaneous elastic e-n/e-p measurement off deuterium : measure σ_{en}/σ_{ep}

- Cancellation of nucleon momentum/binding effects in σ_{en}/σ_{ep} ratio;
- Other effects are partially cancelled and the σ_{en}/σ_{ep} ratio
  - Nucleon charge exchange in final state interactions
  - inelastic e-N contamination

Durand technique extensively used to measure G_M^n
recently at JLab and Mainz

Technique

- Using Durand technique (discussed for G_E^n at JLab at High-t (2002))

$$R_{n/p} \equiv R_{observed} = N_{e,e'n} / N_{e,e'p}$$

- Given f_{corr} (including RC, hadron efficiencies, etc) we have $R_{corrected} = R_{n/p} \times f_{corr}$

which can also be written: $R_{corrected} = \frac{\sigma^n_{Mott}(1+\tau_p)}{\sigma^p_{Mott}(1+\tau_n)} \times \frac{\sigma^n_T + \epsilon \sigma^n_L}{\sigma^p_T + \epsilon \sigma^p_L} = R_{Mott} \frac{\sigma^n_T + \epsilon \sigma^n_L}{\sigma^p_T + \epsilon \sigma^p_L}$

- Measurements for two ϵ points: $R_{corrected,\epsilon_{1,2}} = R_{Mott,\epsilon_{1,2}} (\sigma^n_T + \epsilon_{1,2} \sigma^n_L) / (\sigma^p_T + \epsilon_{1,2} \sigma^p_L)$

- Using $\boldsymbol{A} = R_{corrected,\epsilon_1} / R_{corrected,\epsilon_2}$ the **experimental observable** and

$B = (R_{Mott,\epsilon_1} / R_{Mott,\epsilon_2}) \times (1 + \epsilon_2 S^p) / (1 + \epsilon_1 S^p)$, with $S^p = \sigma^p_L / \sigma^p_T \simeq 0.087 \pm 0.01$ we find

$A = B \times (1 + \epsilon_1 S^n) / (1 + \epsilon_2 S^n) \approx B \times (1 + \Delta\epsilon\, S^n)$ with $\Delta\epsilon = \epsilon_1 - \epsilon_2$ => $\boxed{S^n = \frac{A - B}{B \Delta\epsilon}}$

Systematics

As E12-09-019 we use *e-n*/*e-p* ratio to measure electron-neutron cross section.
Dominant sources of systematic uncertainties are cancelled out.

Remaining sources of systematic uncertainties come from S^p**,** $\mu_n\left(G_E^n/G_M^n\right)$

Syst. uncertainty \ ϵ	0.599	0.838
Acceptance	0.5%	0.4%
Inelastic contamination	0.9%	0.6%
Nucleon misidentification	0.6%	
Syst. uncertainty on σ_{en}/σ_{ep} (quadratic sum of the above)	1.3%	1.0%

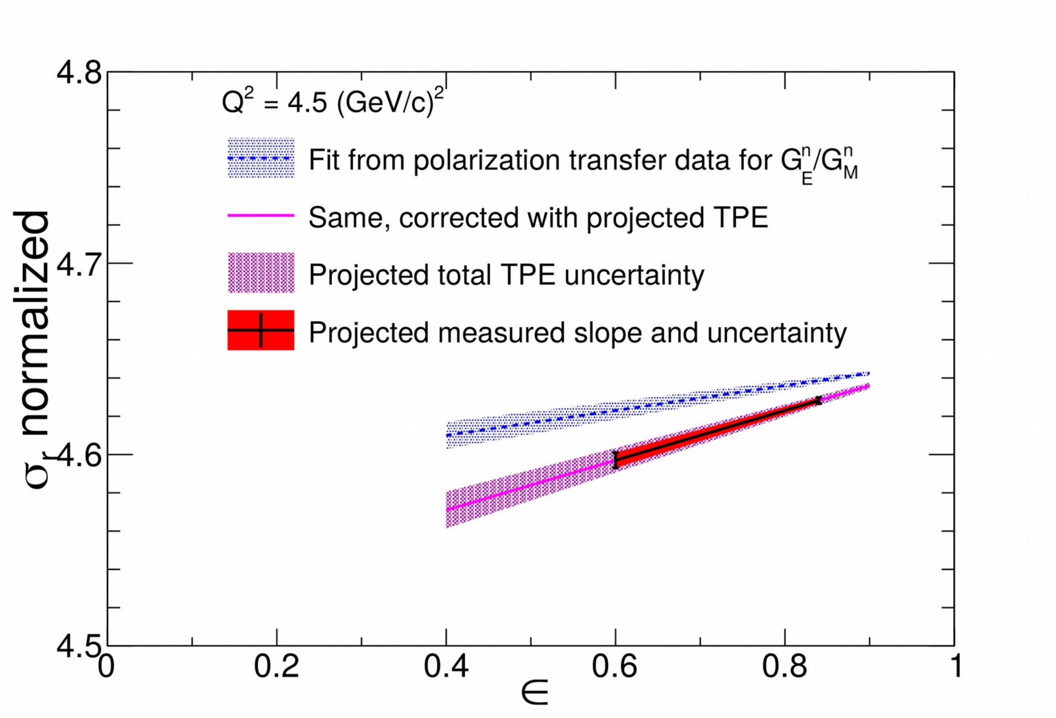
Syst. uncertainty on slope $S^p=\sigma_L^p/\sigma_T^p$	±0.01
Projected systematic uncertainty $S^n=\sigma_L^n/\sigma_T^n$	±0.01
$\mu_n G_E^n/G_M^n=0.55$, Eur. Phys. J. A51, 19 (2015)	±0.05
Combined uncertainty on TPE contribution to S^n	± 0.016

Beam request

Task	Target	I_{exp}	Time requested
Production	15 cm LD_2	30 μA	12 hours
Systematic check	15 cm “dummy”	30 μA	4 hours
Production	15 cm LD_2	15 μA	12 hours
Systematic check	15 cm “dummy”	15 μA	4 hours
Setting changes (BigBite move, beam pass change)			8 hours
Beam tune after pass change			8 hours
Total			**48 hours**

Expected Result

Assuming the same proportions of TPE and G_E^n contributions to S^n as in Blunden, Phys. Rev. C**72**, 034612 (2005), but using G_E^n from the review, Perdrisat et al. Eur. Phys. J. A51, 19 (2015), we expect the nTPE contribution to be: 0.063 ± 0.010 (stat) ± 0.012 (syst)



Measurement insertion in E12-09-19 (GMn) schedule

E12-09-019 (GMn) experiment stage	Task	Q^2 (GeV/c)^2	θ_{BB}/θ_{SBS} degress	E_{Beam} (GeV)	Time (hours)	Tech work time (h)
4b (install GEn-RP) 4b (GEn-RP) 4b (remove GEn-RP)	GEn-RP Production GEn-RP	4.5	41.9 / 24.7	- 4.4	4 104 (calendar) (52 PAC hours) 56	4 24
4e (GMn/nTPE low ϵ)	Production	4.5	41.9 / 24.7	4.4 -	64 (calendar) (32 PAC hours)	
5a (conf. change) 5b (beam tune) 5c (GMn)	BB/SBS/Hcal beam Production	3.5	32.5 / 31.1 32.5 / 31.1 32.5 / 31.1	- 4.4 4.4	32 4 64 (calendar) (32 PAC hours)	16
6a (pass change) 6b (beam tune) 6c	beam/BB beam Production	4.5	23.23 / 31.1 23.23 / 31.1 23.23 / 31.1	6.6 6.6 6.6	8 8 64 (calendar) (32 PAC hours)	4
7a (conf. Change) + (pass change) 7b (beam tune) 7c (GMn)	BB/SBS/Hcal beam beam Production	5.7	58.4 / 17.5 58.4 / 17.5 58.4 / 17.5 58.4 / 17.5	4.4 4.4 4.4	32 during SBS move 4 50 (calendar) (25 PAC hours)	16

Straightforward insertion of the experiment in the approved E12-09-019 schedule

Conclusions

- The knowledge on Two-Photon Exchange (TPE) contribution is essential to shape our understanding of the elastic electron nucleon scattering and hadron structure.
- This experiment will provide the first Rosenbluth measurement of elastic *e*-*n* scattering since 1972, with 10x improved accuracy, at higher Q^2 = 4.5 (GeV/c)^2
- Result will help advancing theoretical understanding of TPE.
- Straightforward insertion of the experiment in the current Hall A E12-09-019 (GMn) schedule, with two PAC days requested.

Backup

Collaborators

$>$ 70 collaborators!

S. Alsalmi, K. Aniol, D. Armstrong, J. Arrington, T. Averett, C. Ayerbe Gayoso, S. Barcus, V. Bellini, J. Bernauer, H. Bhatt, D. Bhetuwal, D. Biswas, W. Boeglin, A. Camsonne, G. Cates, M. E. Christy, E. Cisbani, E. Cline, J.C. Cornejo, B. Devkota, B. Dongwi, J. Dunne, D. Dutta, L. El-Fassi, I. Fernando, *E. Fuchey,* D. Gaskell, T. Gautam, K. Gnanvo, D. Hamilton, J.-O. Hansen, F. Hauenstein, D. W. Higinbotham, T. Hobbs, M. Jones, A. Karki,A. T. Katramatou, C. Keppel, M. Kohl, T. Kutz, N. Liyanage, D. Mack, P. Markowitz, D. Meekins, F. Meddi, R. Michaels, R. Montgomery, A. Nadeeshani, J. Nazeer, V. Nelyubin, D. Nguyen, T. Patel, G.G. Petratos, C. Petta, A.J.R. Puckett, B. Quinn, P. Reimer, M. Rathnayake, A. Sarty, M. Satnik, B. Sawatzky, A. Schmidt, A. Shahinyan, K. Slifer, G. Smith, C. Sutera, A. Tadepalli, W. Tireman, G. Urciuoli, Z. Wertz, *B. Wojstekhowski,* S. Wood, B. Yale.

Summary

- Motivation: **Form Factors** provide key information about partonic structure
- Issue: Discrepancy between Rosenbluth and polarization transfer methods

  for G_E/G_M in e-p is not fully resolved => TPE likely resolves this discrepancy
- We propose to measure **elastic *e-n* with Rosenbluth separation**
- How to achieve it: high luminosity (2.8 x 10^{38} cm^{-2}/s) with large solid angles

  => **10 times improved accuracy** than in 1972 measurement
- Requested beam time for experiment: **2 PAC days**
- Projected result: S^n = 0.126 ± 0.010 ± 0.010, actual central value is unknown

TAC physics comments

1. Proton and neutron charge exchange will bias the ratios to be measured in this experiment. The significance of this effect could be estimated with an Eikonal-based calculation.

We are collaborating with M.Sargsian. His preliminary estimate of the FSI correction to the *D(e,e'p)* cross section at our experimental kinematics is about 5% or less. Misak also pointed out that the uncertainty in the calculation of this correction is small and the resulting uncertainty is below 0.5% for the cross section. In addition, for the ratio *D(e,e'n)/D(e,e'p)* the correction is even smaller. See the recent paper by M.Sargsian about *D(e,e'p)*: Int. JME E 24, 1530003 (2015). Misak also offered us his guidance in the use of his Eikonal-based code.

Calculations for FSI in nucleon electrodisintegration by Misak Sargsian are presented in Phys. Rev. C82, 014612 (2010). The accuracy of this calculations have been experimentally validated in W. Boeglin et al. Phys. Rev. Lett. 107, 262501 (2011)

TAC physics comments

3. There are no technical issues in this proposal beyond those of the E12-09-019 GMn experiment. The same detectors, spectrometers, target, measurement techniques, data acquisition etc. will be used. The only item of note is that the proposed BigBite spectrometer angle of 23.2^{o} is smaller than the smallest angle planned for the GMn measurements (32.5^{o}), but neither reaching that angle nor the expected data rates in either of the spectrometers at that setting, after trigger threshold adjustment, are of concern. In fact, the coincidence trigger rate for the proposed high-ε data point is expected to be lower than that of the corresponding low-ε point of the GMn program.

The small angle of the BigBite central ray and the magnet location used in our MC simulation are consistent with the Hall A design.

TAC theory comments

A further question is about the calculation of RCs, including TPE, for the quasi-elastic eD scattering and their relation to the RCs for a free neutron. Some of the applicable corrections for the quasi-elastic reaction would involve, for example, one photon exchanged between the electron and proton and one between the electron and neutron, which would not be present in elastic scattering from a free neutron or proton. Are such effects included in the RCs contained in the f_{corr} in Eq. (6)?

Yes, this effect is included in the radiative correction procedure. Such an inclusion is possible for our data due to the kinematical cuts which will be applied to the missing momentum, $p_{\perp miss}$, a difference between the high energy nucleon momentum and electron missing momentum.

The projected accuracy for $p_{\perp \mathrm{miss}}$ (+/- 10 MeV/c) allows us to limit the momentum of a second photon (in the TPE diagram with two nucleons) to below 100 MeV/c.

TAC theory comments

From the calculations in Ref. [4], it's clear from Fig. 12 there that the TPE correction δ decreases with increasing ε, approaching zero as $\varepsilon \to 1$. From the perspective of obtaining a more robust slope of the cross section versus ε, it would be significantly preferable if measurement at a smaller ε value were possible. The range between $\varepsilon = 0.6$ and 0.84 is relatively small, and given the predicted spread in the TPE corrections over this range, the measurement would need to be extremely precise in order to clearly observe the sought-after signal.

We agree that the measurement at lower ε will be a very useful addition to the proposed plan. However, it requires a non-standard beam energy of 3.3 GeV which is difficult to get due to the impact on the other three halls' operation and time consuming reconfiguration of the accelerator.

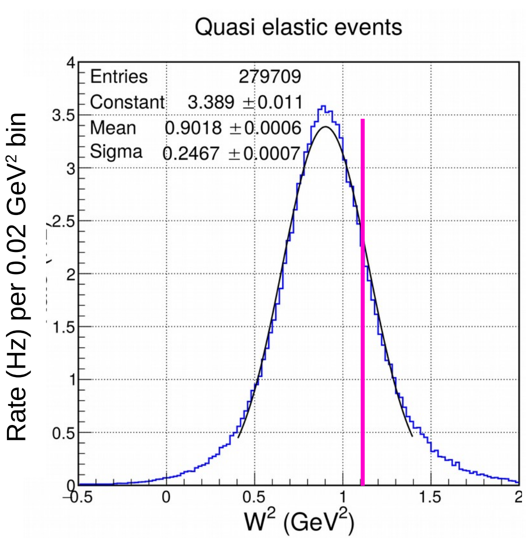
Q^2 (GeV^2)	E (GeV)	E' (GeV)	θ_{BB} (deg)	θ_{SBS} (deg)	ε
4.5	3.3	0.902	75.9	15.9	0.265

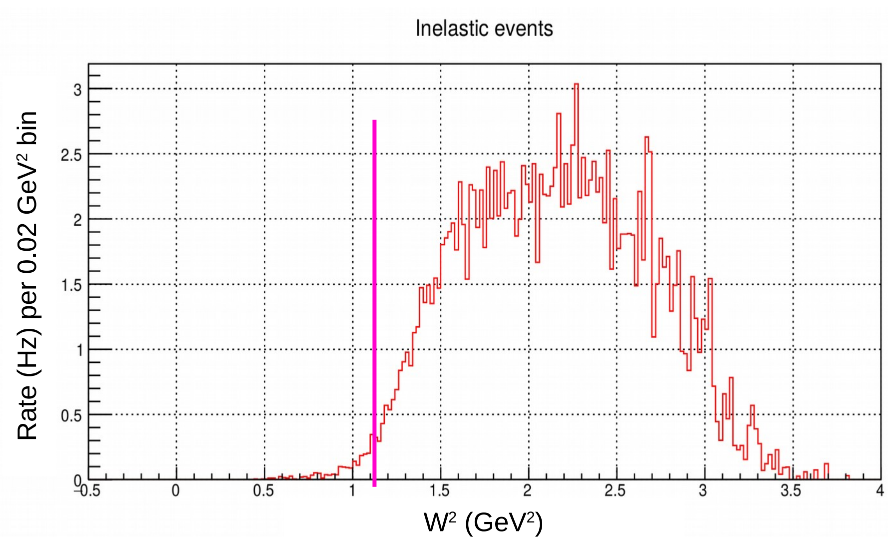
Non standard beam energy at JLab

Analysis (more detailed)

- **Event selection:**
  * Electron track reconstructed in BigBite;
  * Total energy deposited in BigBite calorimeter > 3 GeV threshold (average 4.2 GeV elastic peak, slide 10);
  * Electron track must fire at least 3 PMTs in the GRINCH detector;
  * Total energy deposited in HCal > 0.10 GeV threshold. (90% efficiency of the 3.2 GeV/c nucleons deposit 0.20 GeV in the HCal scintillator material, slide 11).

- ***W^2* reconstruction** (slide 10), **selection cut *W^2* < 1.10 GeV²**
  expected 3% inelastic contamination of quasi elastic sample after *W^2* cut.





Analysis (more detailed)

- **Nucleon projection on HCal assuming:**
  * nucleon is a neutron (unaffected by SBS);
  * $\vec{p}\,'=\vec{q}$ (with *p'* the nucleon momentum and q the virtual photon momentum)
  => Nucleon identification (slide 11)

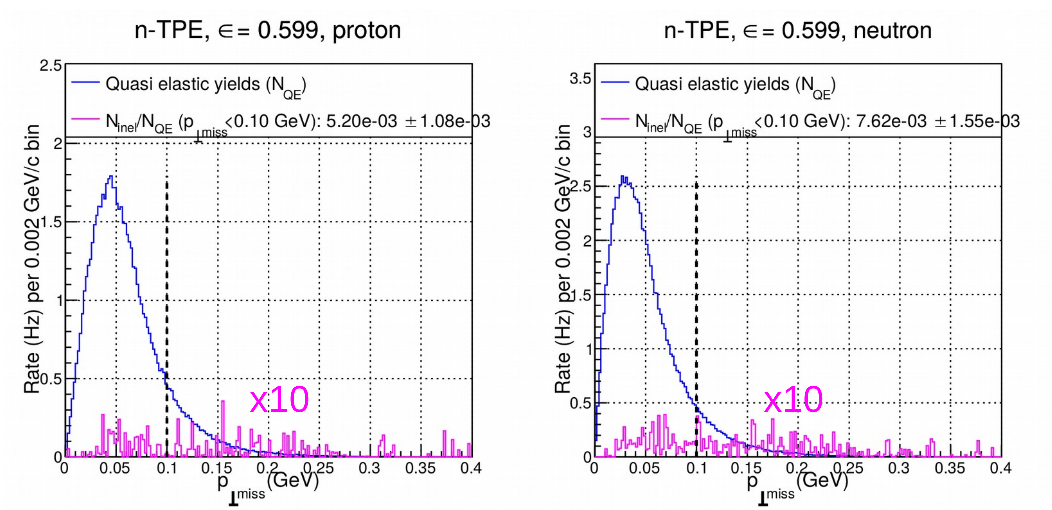
- **Nucleon momentum reconstruction** in SBS coordinates system:

$$p'_{x,SBS}=p'(x_{rec}-v\sin\theta_{SBS})/(D_{HCal}-v\cos\theta_{SBS}) \quad p'_{y,SBS}(n)=p'(y_{rec})/(D_{HCal}-v\cos\theta_{SBS})$$

$$p'_{y,SBS}(p)=p'(y_{rec}+\Delta y_p)/(D_{HCal}-v\cos\theta_{SBS})$$ (Δy_p calculated for each event)

  then translated back to Hall A coordinates system.

- **Transverse missing momentum construction:** $p_{\perp miss}=\sqrt{(q_x-p'_x)^2+(q_y-p'_y)^2}$



Selection cut on $p_{\perp miss}$< 0.1 GeV/c
=> <1% inelastic contamination of quasi elastic

Single rates mitigation

Calorimeter threshold: **0.10 GeV** for 90% efficiency of the 3.2 GeV/c nucleons which deposit 0.20 GeV in the HCal (scintillator material)
=> Projected single rates for SBS: **3.3 MHz**
If rates are significantly higher than expected: HCal threshold raised to 0.15 GeV
=> the elastic nucleon efficiency will drop to 74% (~20% relative drop);
=> singles will drop by a factor 2.5;