New SBS/Hall A experiment:

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

On behalf of the nTPE spokespeople;
Sheren Alsalmi - King Saud University
Eric Fuchey – University of Connecticut (Speaker)
Bogdan Wojtsekhowski- Jefferson Lab

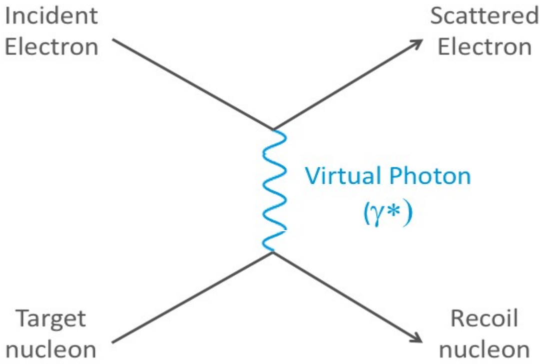
Hall A collaboration meeting,
Jefferson Lab
January 21st, 2021

Elastic *e*-*N* Scattering, Rosenbluth (1950)

In the One-Photon Exchange (Born) approximation:

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

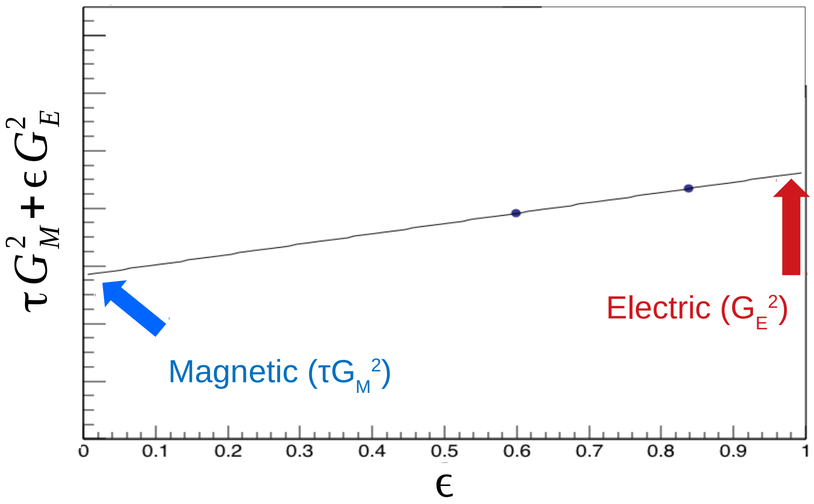
with $\tau=Q^2/(4M_N)$



Rosenbluth technique: separate $G_M{}^2$ and $G_E{}^2$ based on the linear dependence in $\epsilon=\left[1+2(1+\tau)\tan^2\theta/2\right]^{-1}$

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

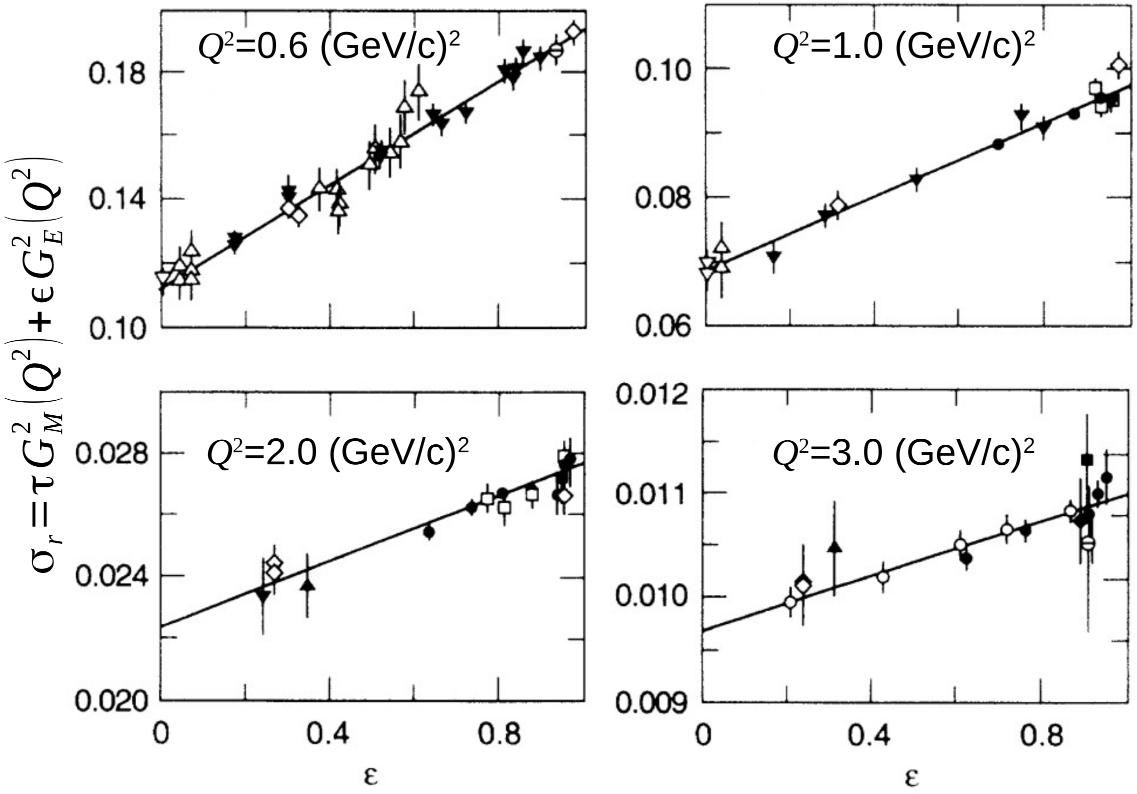
Two or more measurements, same Q^2, different E and θ (different ϵ)



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)

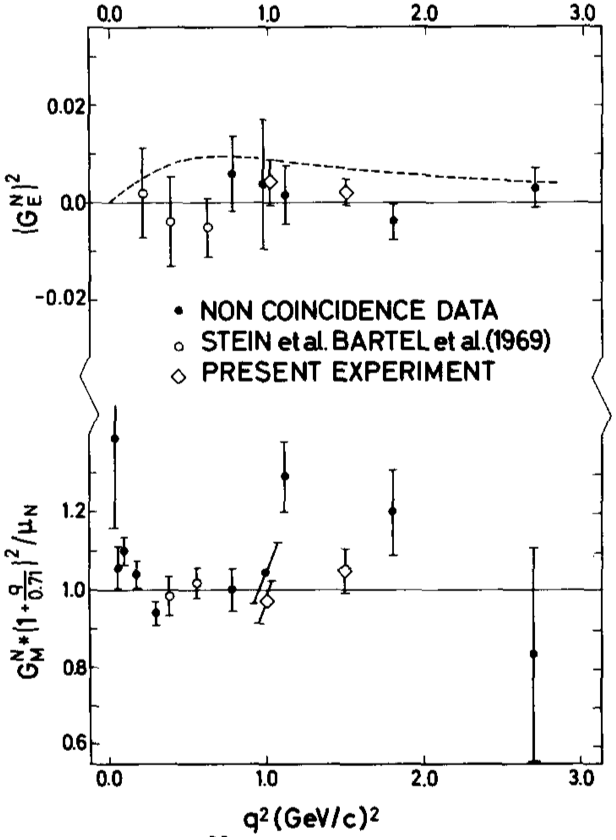


Linearity in ϵ well tested up to $Q^2 \leq 3$ (GeV/c)^2

Rosenbluth for *e*-*n* scattering

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

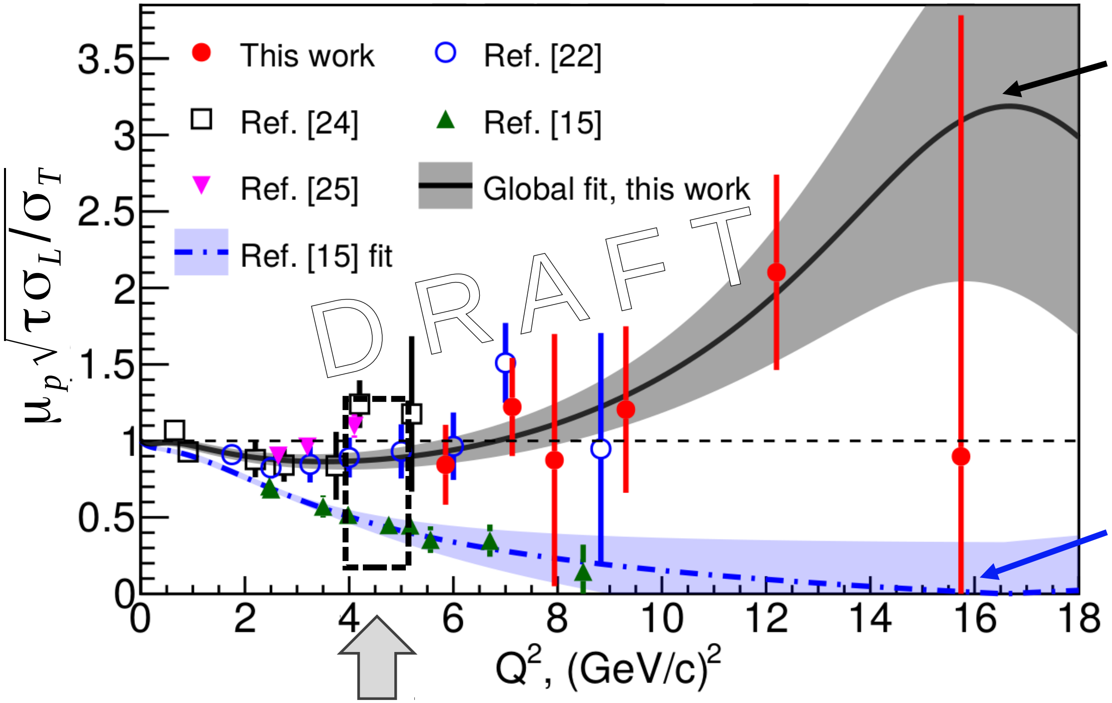
Bartel et al., Phys. Lett. 39B, 407 (1972)



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

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

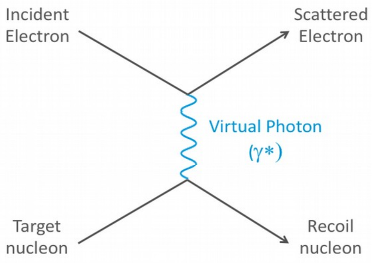
E. Christy et al., “Two-photon exchange in electron-proton elastic scattering at large four-momentum transfer”, (2020), including last Jlab proton data at 12 GeV in preparation for publication in PRL
(See also E. Christy’s talk yesterday)

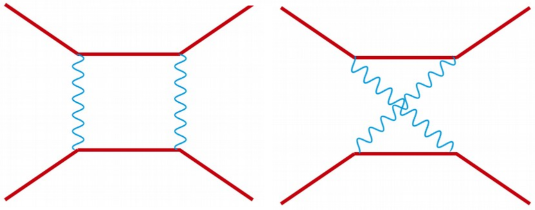
Global fit of polarization transfer data

- 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)

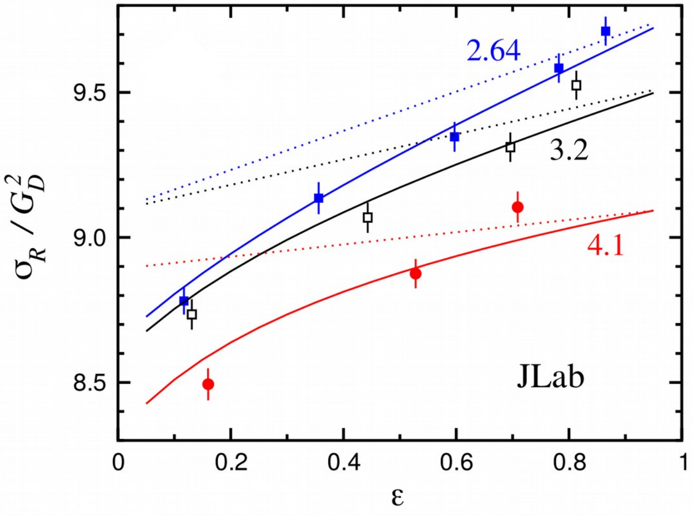
Mechanism of e-N scattering (proton)

- 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

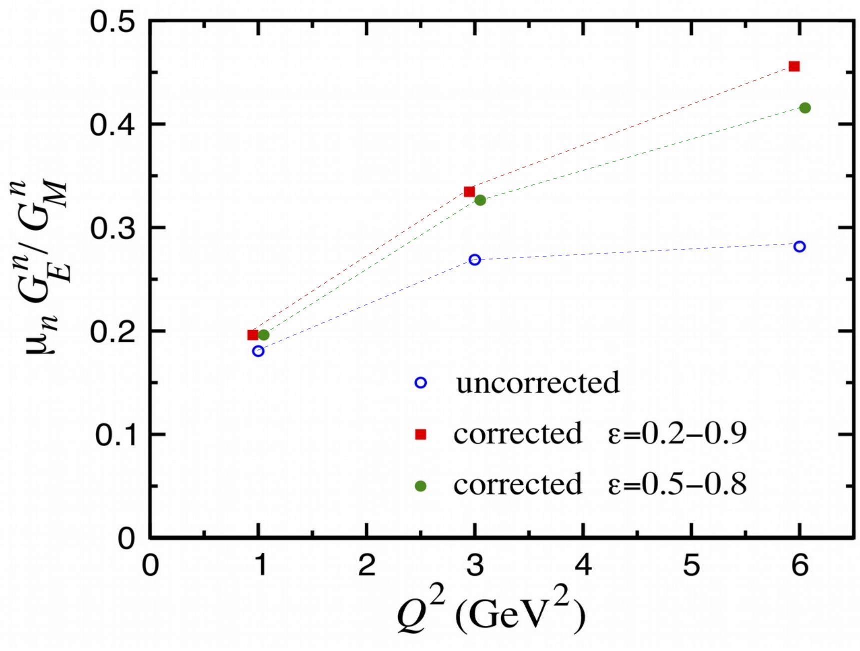
same, corrected with TPE contributions

■ □ ● 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 ϵ = 0.2 and 0.9

● Corrected with TPE contribution between two hypothetical measurements at ϵ = 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 (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
2	4.5	6.6	4.2	23.23	31.2	0.838

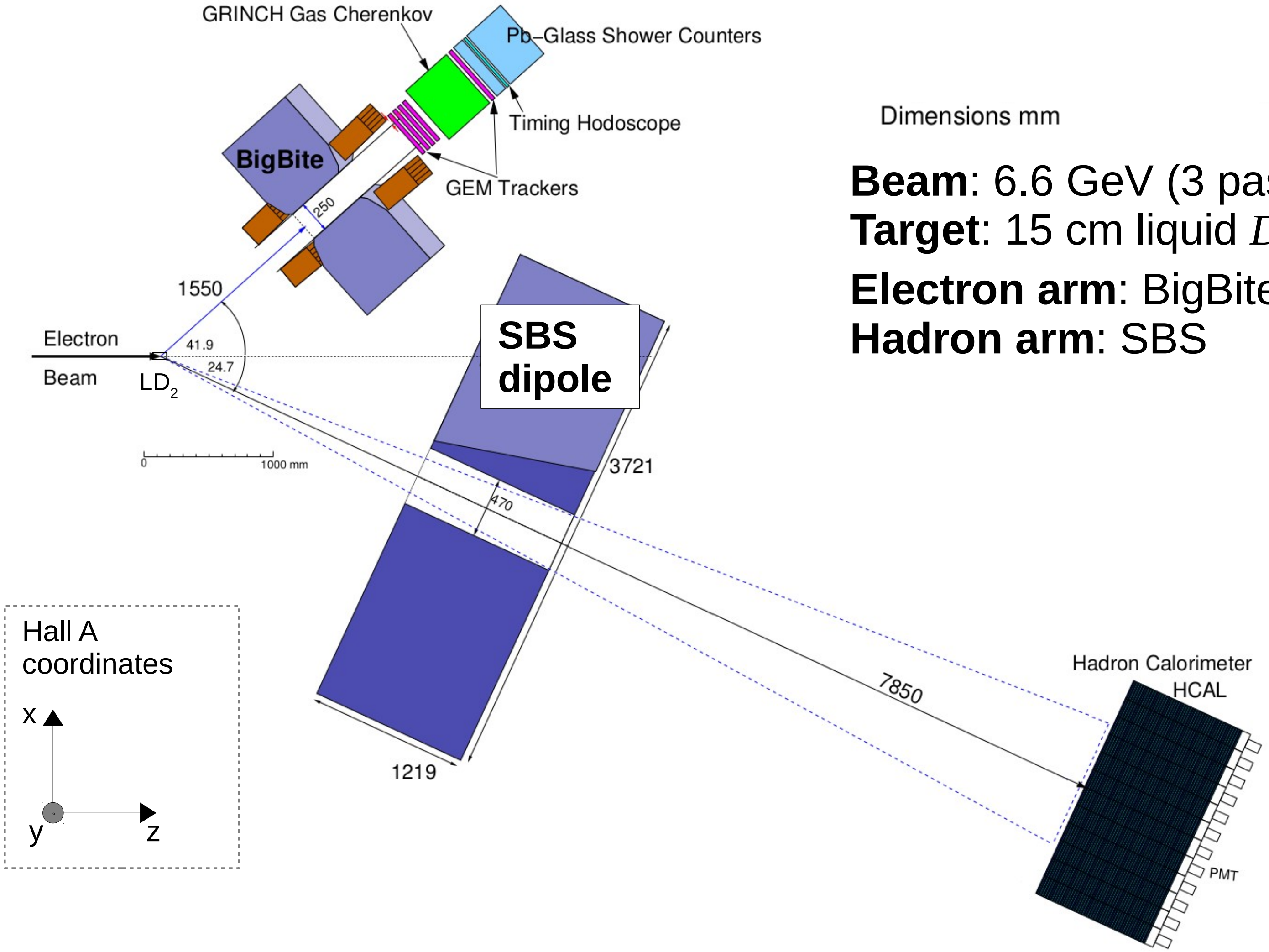
Approved E12-09-019

Requested for nTPE

Note: these settings are being adjusted to the new schedule/beam energy constraints

Experimental Setup in Hall A

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



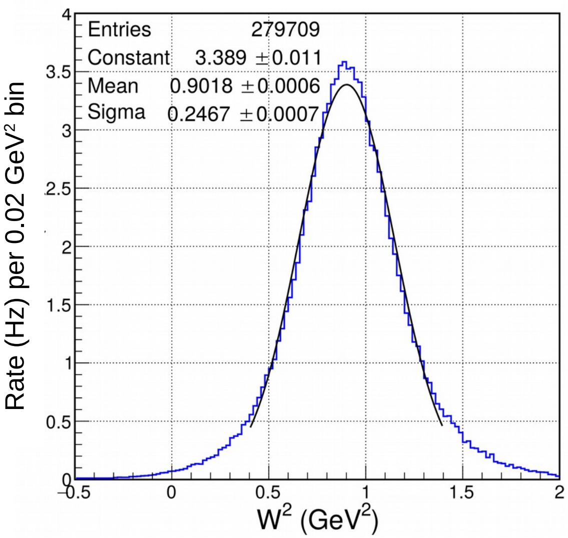
Beam: 6.6 GeV (3 pass), 30 μA
Target: 15 cm liquid D_2
Electron arm: BigBite
Hadron arm: SBS

Key experimental parameters

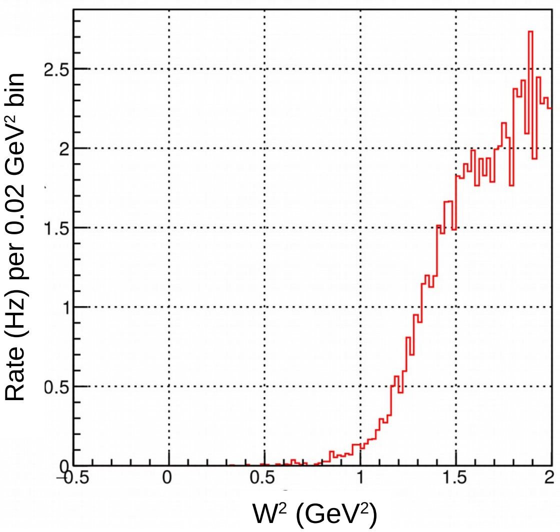
- Electron-nucleon luminosity: **2.8×10^{38} cm^{-2}/s**

- 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

MC: quasi elastic e-N



MC: inelastic resonant e-N



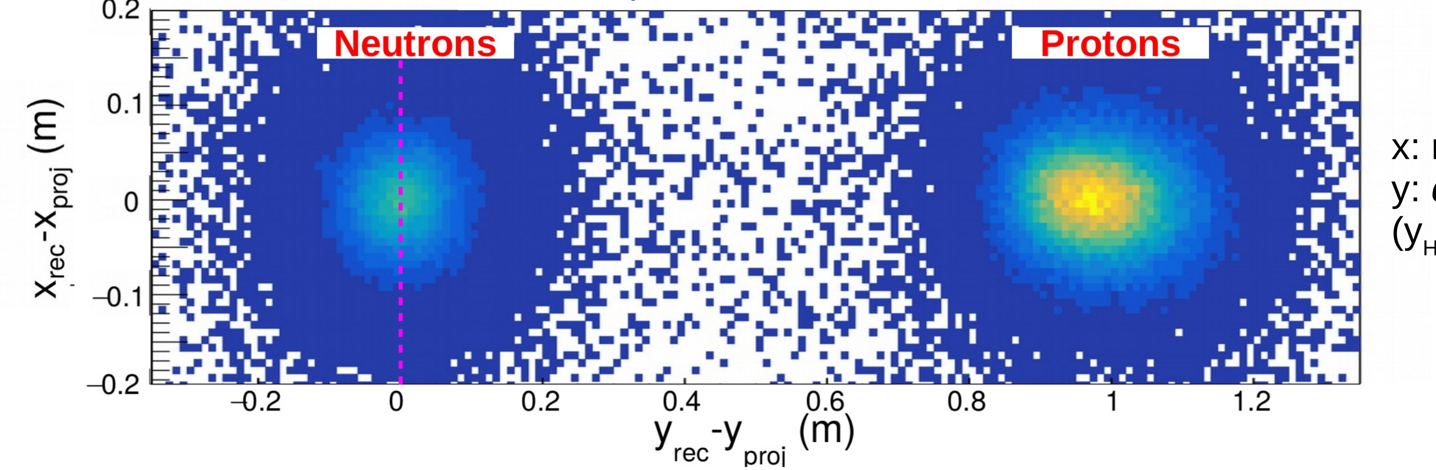
- Calorimeter threshold: **3.0 GeV** for 4.2 GeV mean elastic peak.
  => Projected single rates for BigBite: **8 kHz**

Key experimental parameters

- SBS: $\mathbf{\Delta\Omega_{SBS} = 71}$ **msr**; $\mathbf{\Delta\theta = \Delta\varphi = 5}$ **mrad**, $\mathbf{\Delta t / t = 0.5}$ **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

- Using $A=(\sigma_{en}/\sigma_{ep})_{\epsilon_1}/(\sigma_{en}/\sigma_{ep})_{\epsilon_2}$ the **experimental observable** and $B=\left(1+\epsilon_2 S^p\right)/\left(1+\epsilon_1 S^p\right)$, with $S^p=\sigma_L^p/\sigma_T^p\simeq 0.087\pm 0.01$ we find

$$A=B\times(1+\epsilon_1 S^n)/(1+\epsilon_2 S^n)\approx B\times\left(1+\Delta\epsilon\ S^n\right) \qquad \Delta\epsilon=\epsilon_1-\epsilon_2$$

$$\boxed{S^n=\frac{A-B}{B\Delta\epsilon}}$$

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%

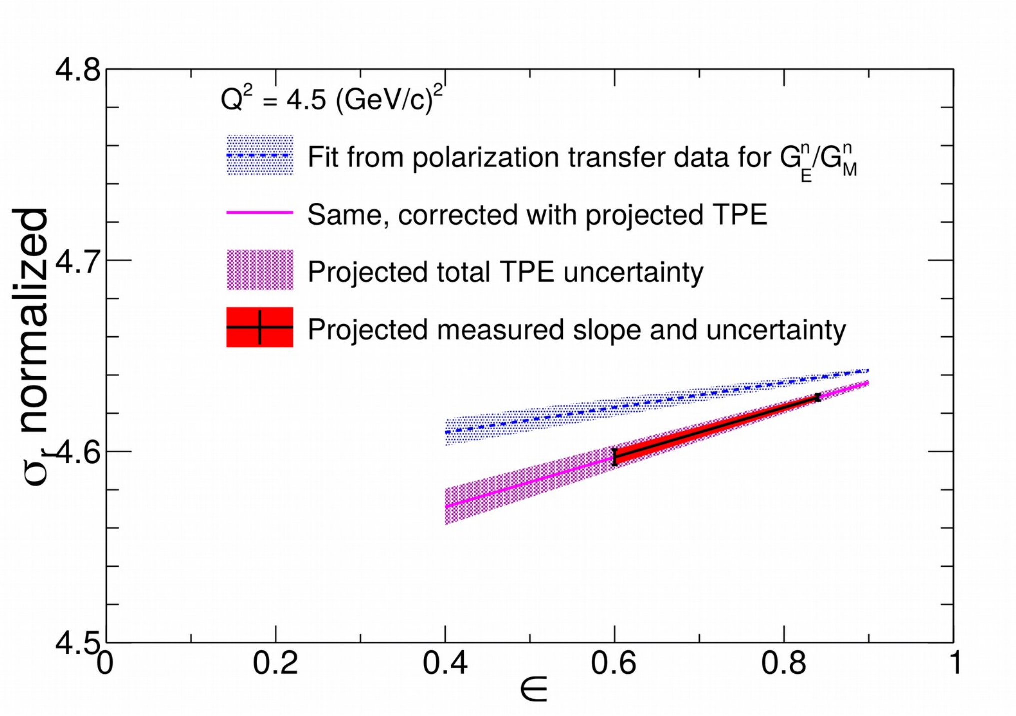
Syst. uncertainty on slope $S^p=\sigma_L^p/\sigma_T^p$	±0.01
Projected systematic uncertainty $S^n=\sigma_L^n/\sigma_T^n$	±0.01
$\mu_n G_E^n/G_M^n=0.55$, Eur. Phys. J. A51, 19 (2015)	±0.05
Combined uncertainty on TPE contribution to S^n	± 0.016

Beam request

Task	Target	I_{exp}	Time requested
Production	15 cm LD_2	30 μA	12 hours
Systematic check	15 cm “dummy”	30 μA	2 hours
Systematic check	Multifoil optics	10 μA	4 hours
Production	15 cm LD_2	15 μA	12 hours
Systematic check	15 cm “dummy”	15 μA	2 hours
Setting changes (BigBite move, beam pass change) Beam tune after pass change			8 hours 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)



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 $(\mathrm{GeV/c})^2$
- Result will help advancing theoretical understanding of TPE.
- two PAC days requested, **approved with A- rating**

  => will run with GMn (GEn-RP, WAPP)

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.

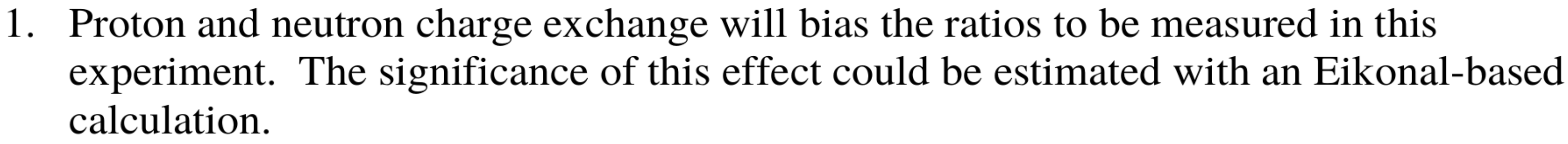
Summary

- 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

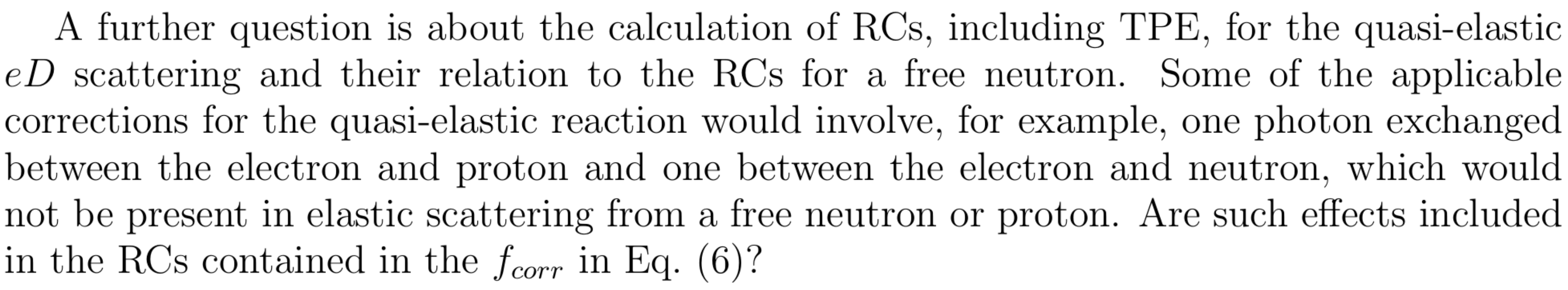


1. Proton and neutron charge exchange will bias the ratios to be measured in this experiment. The significance of this effect could be estimated with an Eikonal-based calculation.

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 theory comments



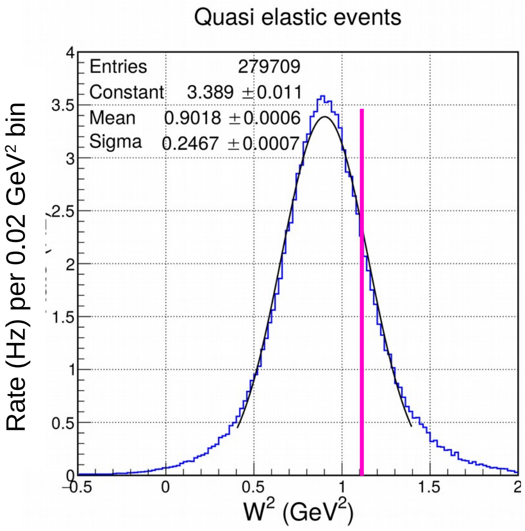
A further question is about the calculation of RCs, including TPE, for the quasi-elastic eD scattering and their relation to the RCs for a free neutron. Some of the applicable corrections for the quasi-elastic reaction would involve, for example, one photon exchanged between the electron and proton and 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)?

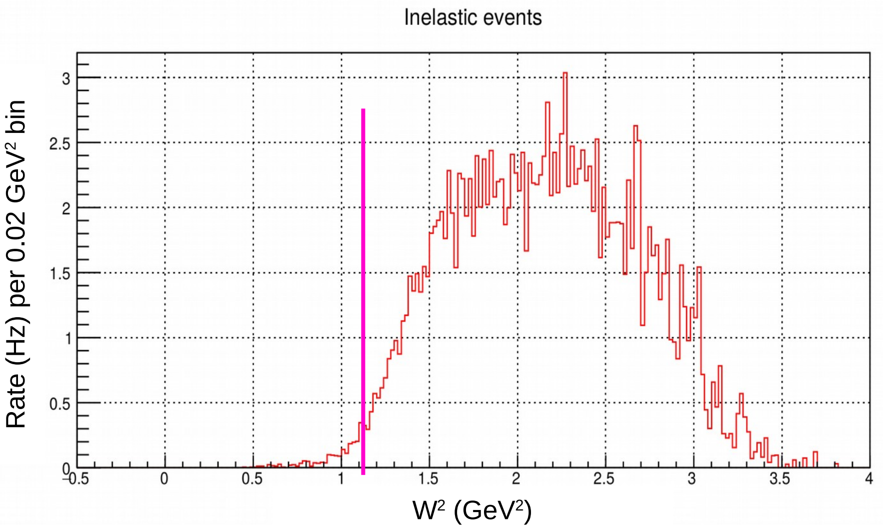
Yes, this effect is included in the radiative correction procedure. Such an inclusion is possible for our data due to the kinematical cuts which will be applied to the missing momentum, $p_{\perp miss}$, a difference between the high energy nucleon momentum and electron missing momentum.
The projected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

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 GeV^2**
  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)

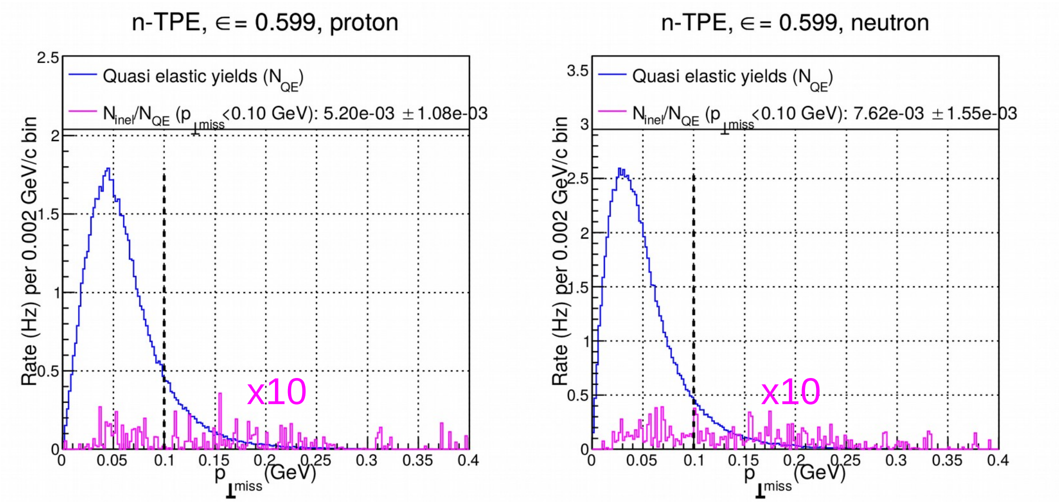
- **Nucleon momentum reconstruction** in SBS coordinates system:

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

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