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

On behalf of the nTPE spokespeople;

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Hall A/C Summer Meeting

July 17th, 2020

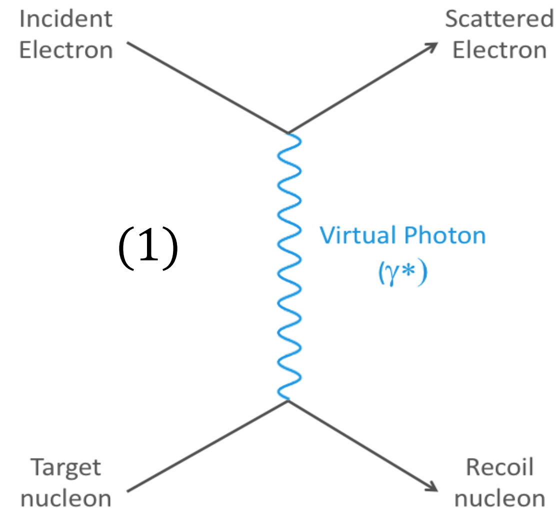
Talk Outline

- Theory Overview
- The nTPE Experiment
  - ✓ Collaborators
  - ✓ Scientific Significance
  - ✓ Technique
  - ✓ Proposed Measurements
  - ✓ Experimental Setup
  - ✓ Expected Results
  - ✓ Systematics

Theory Overview

Unpolarized Elastic e-N Scattering

- In the One-Photon Exchange (Born) approximation:



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

Magnetic (G_M^2) Electric (G_E^2)

- Rosenbluth technique: Separates the cross section into G_M^2 and G_E^2:

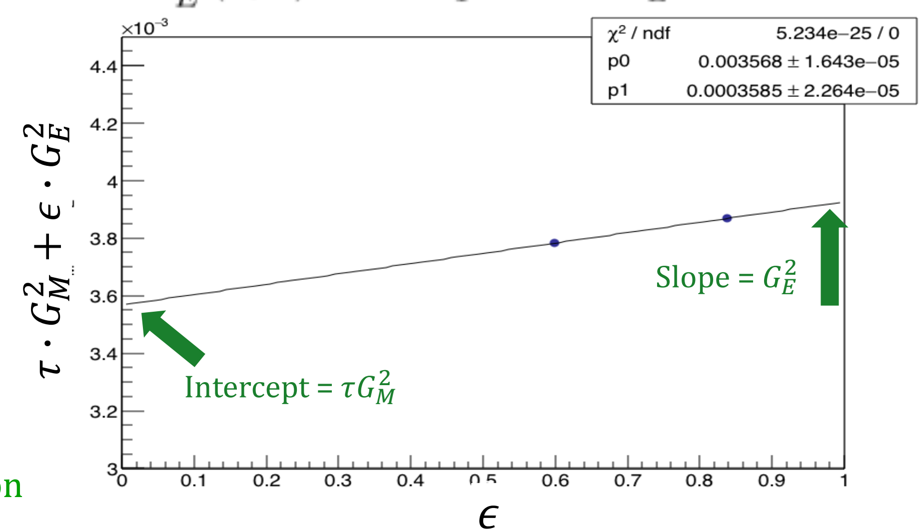
$$\sigma_r \equiv \left(\frac{d\sigma}{d\Omega}\right) \cdot \frac{\epsilon(1+\tau)}{\sigma_{Mott}} = \tau \cdot G_M^2(Q^2) + \epsilon \cdot G_E^2(Q^2) = \sigma_T + \epsilon \cdot \sigma_L \quad (2)$$

Linear in ϵ

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

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

Longitudinal polarization of the virtual photon



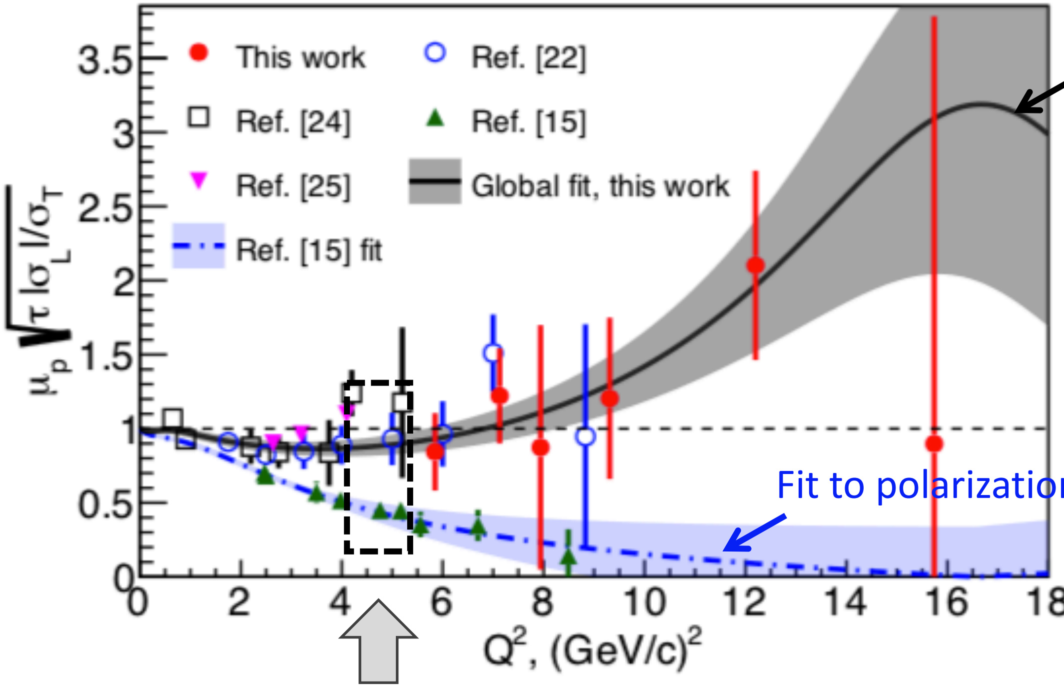
Rosenbluth vs. Polarization Transfer

- Rosenbluth technique (LT):
  - ✓ Need to make a clean separation of the form factors.
  - ✓ radiative corrections were believed to be well understood (OPE)
  - ✓ Large uncertainties
  - ✓ Used to extract proton form factors
  - ✓ Difficult for the neutron (no free neutron targets, the value of G_E^n is small)!
- Polarization transfer technique (PT):
  - ✓ measure the polarization of the recoiling hadrons
  - ✓ radiative corrections have very small effect

For many years, the proton form factors were extracted using both methods

The results should be the same (⇐ a naive guess!)

Rosenbluth vs. Polarization Transfer



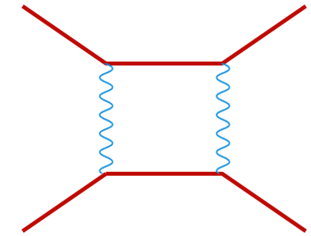
Fit to Rosenbluth slope

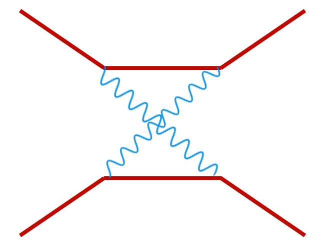
E. Christy et al., "Two-photon exchange in electron-proton elastic scattering at large four-momentum transfer", (2020), in preparation for publication in PRL

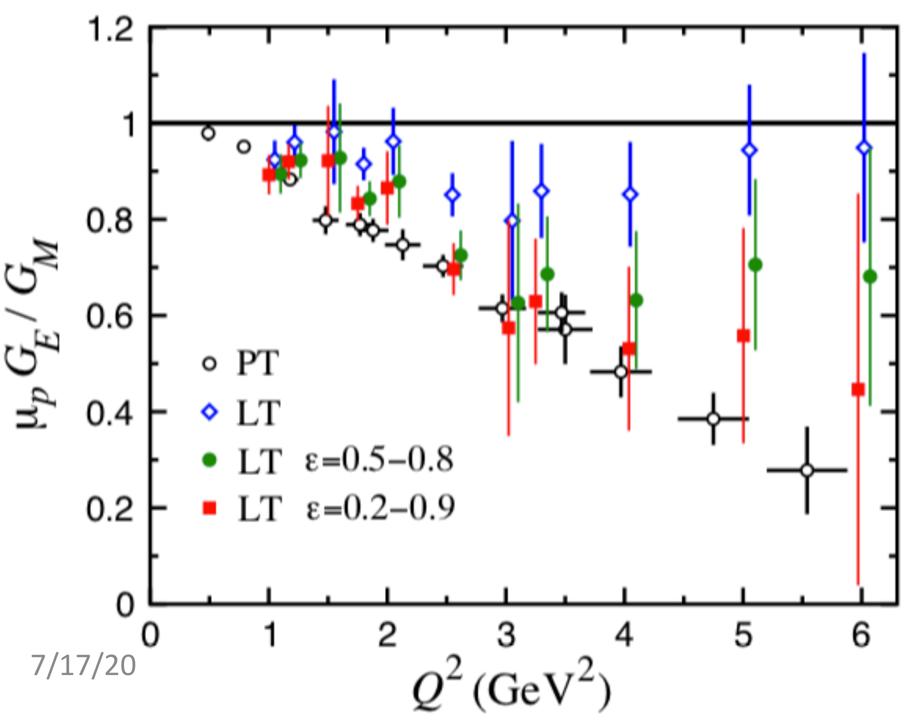
- At Q^2 of 4 -5 (GeV/c)^2, the Rosenbluth slope is 3-4 times larger than expected in OPE.
- The results of the two methods do not agree ⇒ Hint of a missing correction!

Two-Photon Exchange Correction (Proton)

- The Two-Photon Exchange (TPE) correction can explain the discrepancy between the Rosenbluth (LT) and the Polarization transfer (PT) measurements.
- Several attempts to measure the TPE for proton.
- TPE has a bigger impact on G_E than G_M (small ϵ-dependant TPE correction can yield large correction to G_E)







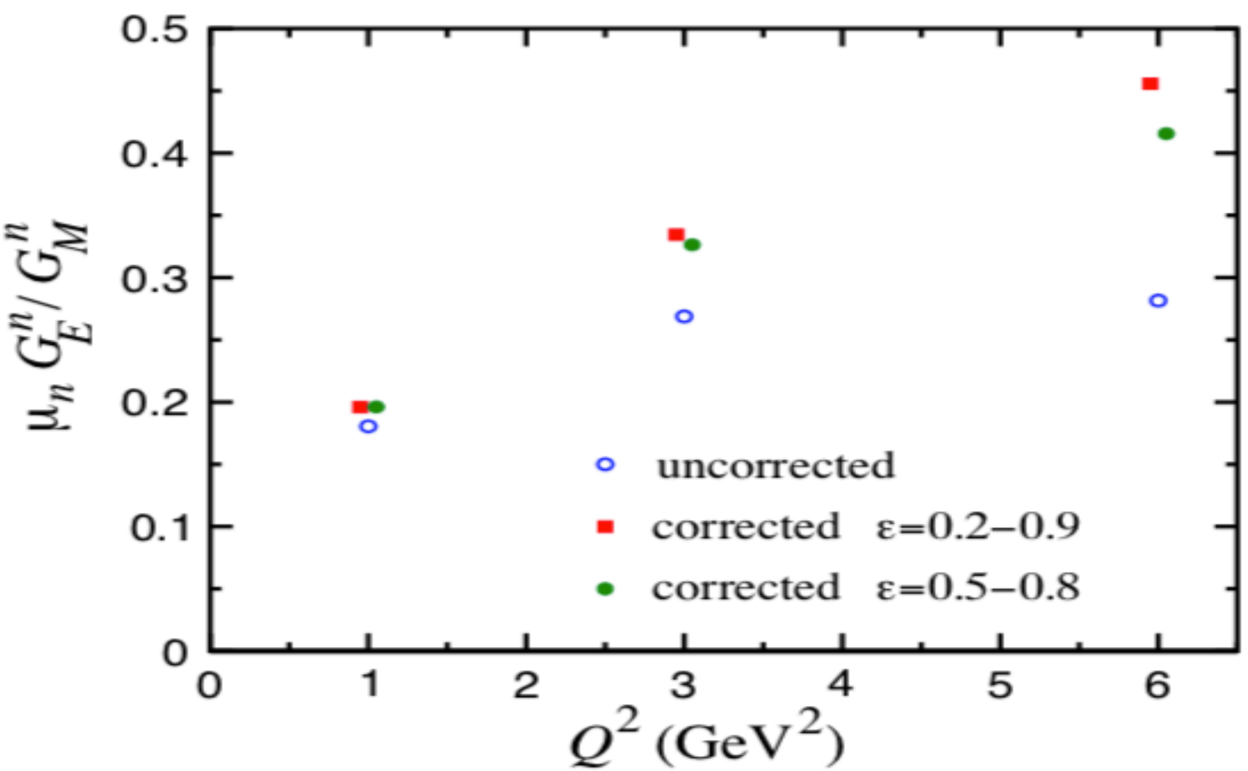
Blunden, Melnitchouk and Tjon
[Phys. Rev. C72, 034612 (2005)]

- ○ Polarization Transfer measurements
- ◇ Rosenbluth measurements
- ● Corrected Rosenbluth measurement
- ■ Corrected Rosenbluth measurement

(What about neutron?)

Two-Photon Exchange Correction (Neutron)

- The Two-Photon Exchange (TPE) correction was never studied 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 the LT (Rosenbluth) method.



The nTPE Experiment

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.

Scientific Significance

Goals:

- Extract G_E^n by applying the Rosenbluth technique (for the first time!!)
- Study the two-photon exchange contribution on elastic e-n scattering (also, for the first time!!)

Current Status:

- Proposed for PAC 48
- Should run concurrently with two approved experiments (E12-09-019 and E12-17-004)

Technique

- G_E is extracted from the **ratio** of quasi-elastic yields ⇒ reduced uncertainties

(Technique introduced by Bogdan Wojtsekhowski: arXiv:1706.02747)

$$R_{n/p} \equiv R_{observed} = \frac{N_{e,e'n}}{N_{e,e'p}} \qquad (3)$$

- The corrected ratio $R_{corr} = f_{corr} \times R_{Observed}$ can be written as:

$$R_{corrected} = \frac{\sigma^n_{Mott} \cdot (1+\tau_p)}{\sigma^p_{Mott} \cdot (1+\tau_n)} \times \frac{\epsilon\sigma^n_L + \sigma^n_T}{\epsilon\sigma^p_L + \sigma^p_T} \qquad (4)$$

- Making the measurements for two epsilon points (ϵ_1 , ϵ_2):

$$R_{corrected,\epsilon_1} = R_{Mott,\epsilon_1} \times \frac{\epsilon_1\sigma^n_L + \sigma^n_T}{\epsilon_1\sigma^p_L + \sigma^p_T} \qquad R_{corrected,\epsilon_2} = R_{Mott,\epsilon_2} \times \frac{\epsilon_2\sigma^n_L + \sigma^n_T}{\epsilon_2\sigma^p_L + \sigma^p_T}$$

- Taking the ratio of the two measurements:

$$A = B \times \frac{1+\epsilon_1 S^n_c}{1+\epsilon_2 S^n_c} \approx B \times (1 + \Delta\epsilon \cdot S^n_c) \qquad (5)$$

$S_c^{n(p)} = \sigma_L^{n(p)} / \sigma_T^{n(p)}$ $\qquad$ $B = R_{Mott,\epsilon_1}/R_{Mott,\epsilon_2} \times (1+\epsilon_2 S_c^p)/(1+\epsilon_1 S_c^p)$ measured!

Proposed Measurements

Point	Q^2 $(\mathrm{GeV/c})^2$	E (GeV)	E′ (GeV)	θ_{BB} degrees	θ_{SBS} degrees	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

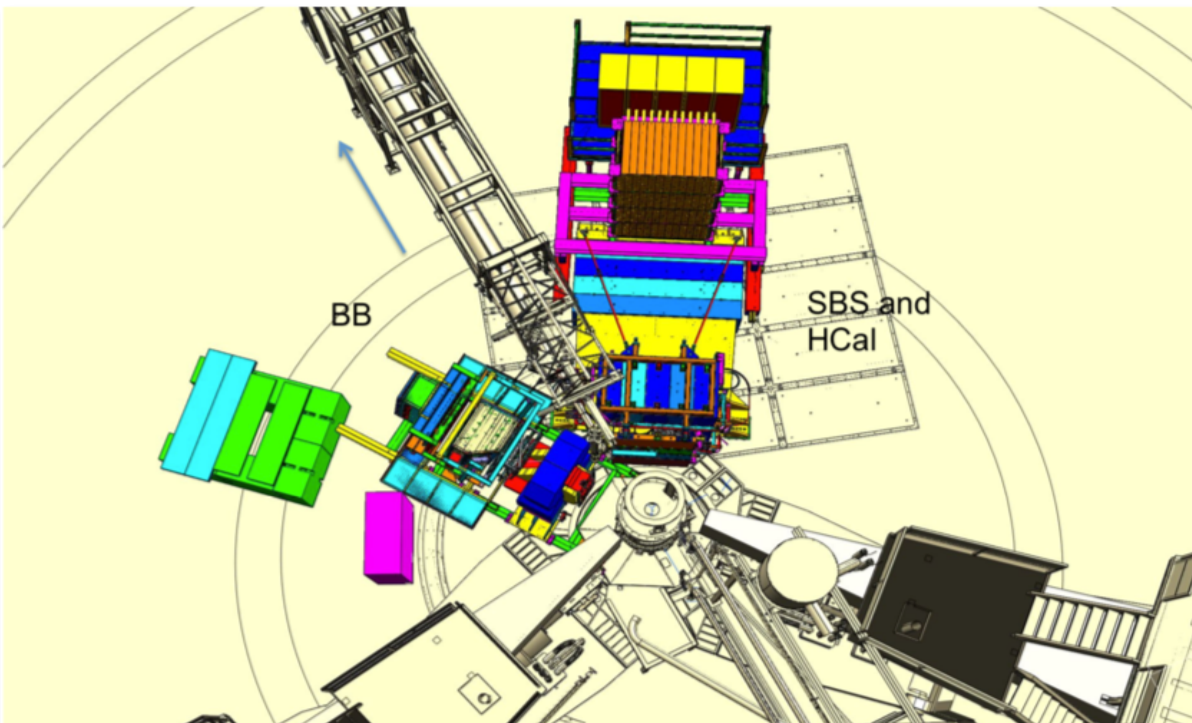
An existing measurement of the approved E12-09-019 (point 1)

nTPE proposed measurement (point 2)

More data points could be obtained if PAC allocate a full week!

Experimental Setup

- **Hall:** A
- **Target**: 15 cm LD2 target.
- **Spectrometers:** BigBite (electrons) and Super-BigBite (hadrons)

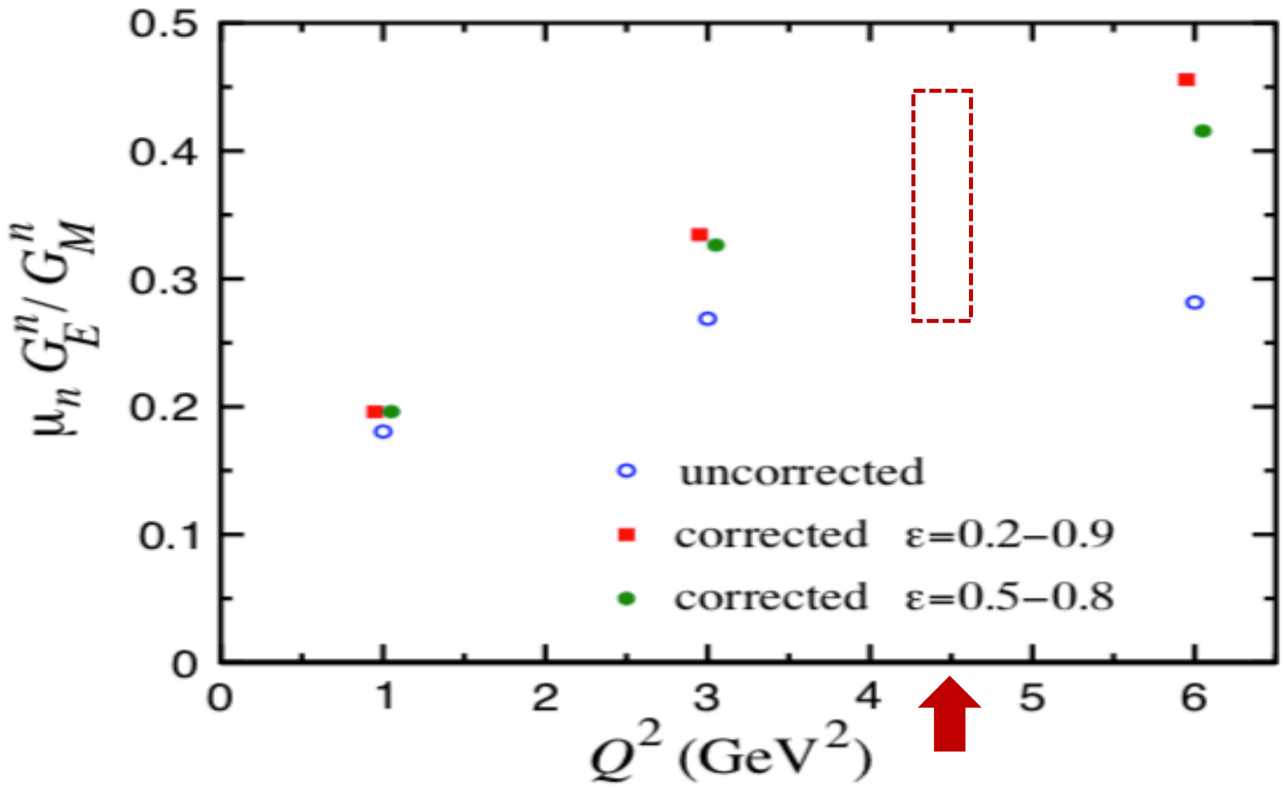


Experimental Setup

Task	Target	I_{exp}	time requested
Data taking (Prod.)	15 cm LD_2	30 μA	12 hours
Data taking (Syst.)	15 cm "Dummy"	30 μA	4 hours
Data taking (Prod.)	15 cm LD_2	15 μA	12 hours
Data taking (Syst.)	15 cm "Dummy"	15 μA	4 hours
Setting changes (BigBite move, beam pass change)			8 hours
Beam tune after beam pass change			8 hours
Total			**48 hours**

Expected Results

Considering the predictions of Blunden, Melnitchouk and Tjon [Phys. Rev. C**72**, 034612 (2005)] , our measurement of the nTPE could be $0.069 \pm 0.012\ (sys) \pm 0.01\ (stat)$



Systematics

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

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

Conclusions

- The nTPE experiment will provide the first measurement of the TPE in the e-n elastic scattering.
- The nTPE experiment will allow measure the G_E^n using Rosenbluth technique for the first time!
- The kinematics of the nTPE measurements emphasize the same Q^2 range where the TPE in e-p elastic scattering was observed to dominate in Rosenbluth slope.
- The knowledge of the TPE is essential to shape our understanding of the elastic electron nucleon scattering and hadron structure.

Thanks!

Backup Slides

Counting Rates

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 (*)
Total ($\sum_{\pi(Wiser)}$ for HCal)	1.37×10^4	3.39×10^6 / (1.22×10^7)	8.17×10^3	3.32×10^6 / (1.11×10^7)
Coincidence rate ($\sum_{\pi(Wiser)}$ for HCal)	1.39×10^3 (5.01×10^3)		8.14×10^2 (2.72×10^3)	

Experimental Setup

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