Elastic electron–proton scattering L/T separation at high Q^2

DIS in $D(e,e'n_s)$ / $H(e,e')$

Bogdan Wojtsekhowski

Elastic electron–proton scattering L/T separation at high Q^2

Why is L/T interesting to measure?

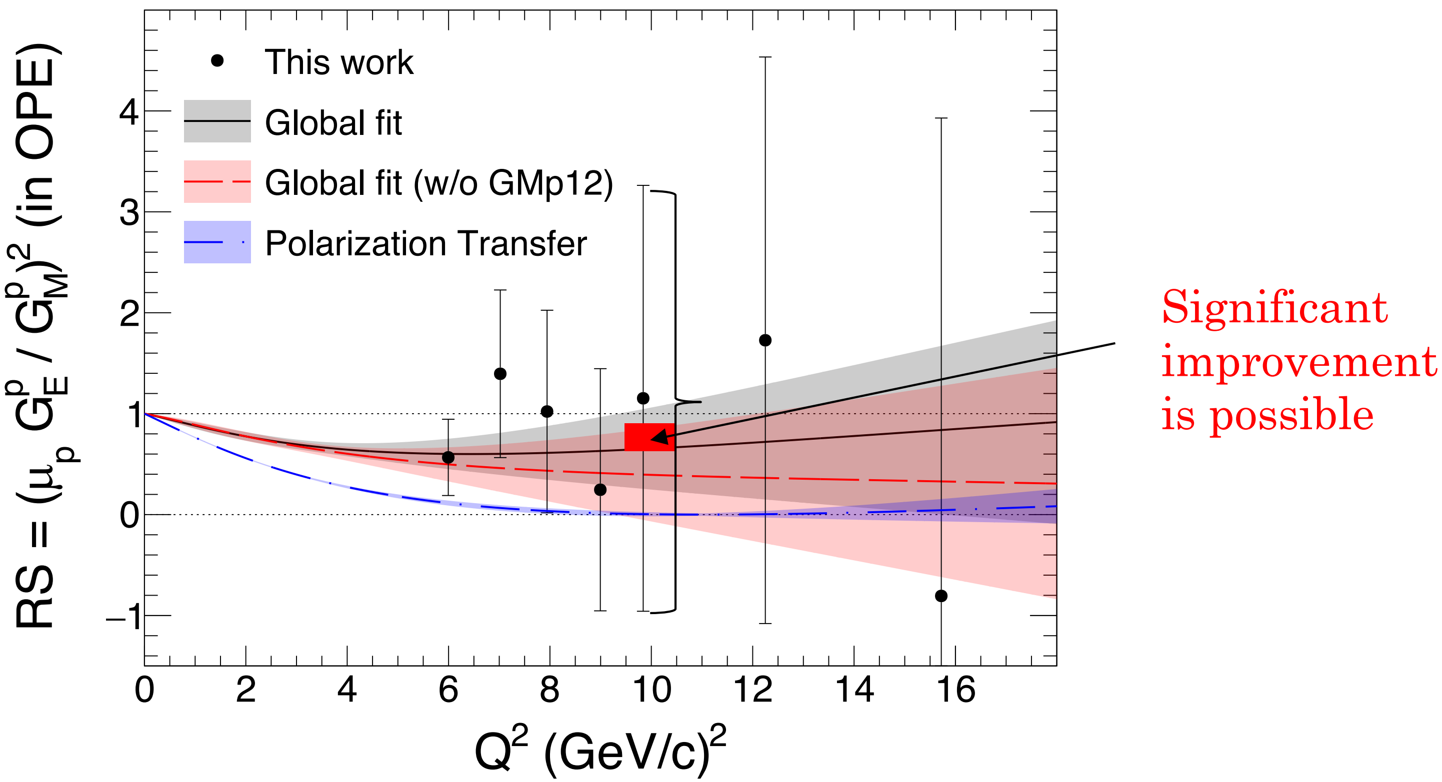
How can Hall C do such a measurement?

Projected accuracy in 10-day run

Projected accuracy L/T at high Q^2

$$\frac{\Delta\sigma}{\sigma} = 0.014 \times RS$$ Contribution of "GE" to cross section

In a 10-day run the relative statistical variation for cross section ~ 0.0014, so the variation of the relative value of the second term in cross section and δRS is 0.0014/2/0.014, so the accuracy for RS is +/- 0.05



Electro-Magnetic Form Factors

Rosenbluth (1950)

One-photon approximation, α_{em} = 1/137, hadron current

$$\mathcal{J}^{\mu}_{hadronic} = ie\overline{N}(p')\left[\gamma^{\mu}F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2M}F_2(Q^2)\right]N(p)$$

SLAC results for the proton Form Factors

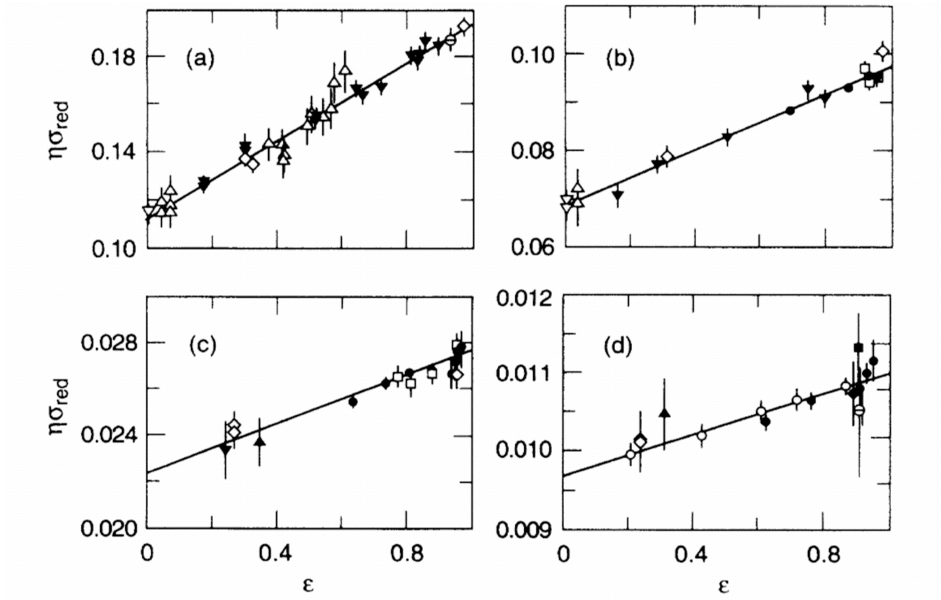
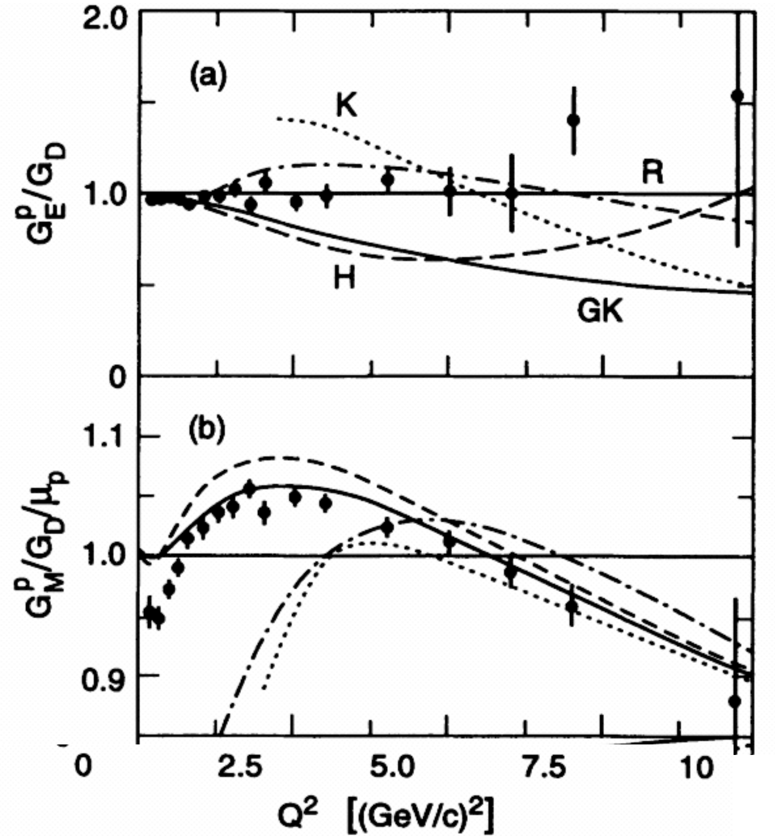


FIG. 9. Four typical Rosenbluth fits for the form factor extraction from the global data set at (a) $Q^2 = 0.6$, (b) $Q^2 = 1.0$, (c) $Q^2 = 2.0$, and (d) $Q^2 = 3.0$ (GeV/c)^2.



Electro-Magnetic Form Factors

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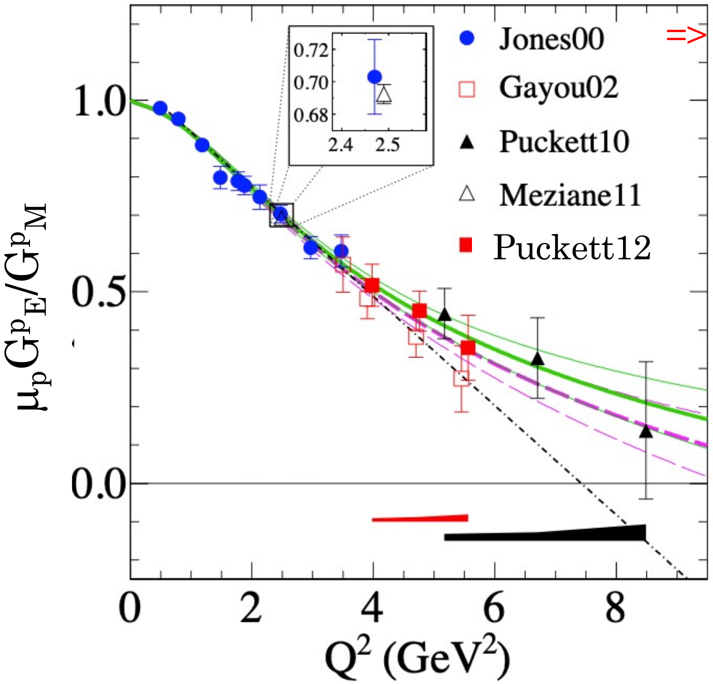
Rosenbluth (1950)

Akhiezer (1957)
Arnold, Carlson and Gross (1981)

At large Q^2, the study of G_E requires use of polarization observables => FFs at JLab

Perdrisat+



=> 1000 citations

Electro-Magnetic Form Factors

One-photon approximation, α_{em} = 1/137, hadron current

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At large Q^2, the study of G_E requires use of polarization observables => FFs at JLab

Akhiezer (1957)
Arnold, Carlson and Gross (1981)

1γ+2γ expression for M has three complex functions, F_1, F_2, F_3

$$\mathcal{M} = \frac{4\pi\alpha}{Q^2}\bar{u}'\gamma_{\mu}u \cdot \bar{N}'\left(\tilde{F}_1\gamma^{\mu} - \tilde{F}_2[\gamma^{\mu},\gamma^{\nu}]\frac{q_{\nu}}{4M} + \tilde{F}_3 K_{\nu}\gamma^{\nu}\frac{P^{\mu}}{M^2}\right)N$$

Guichon & Vanderhaeghen

$$\tilde{G}_M = \tilde{F}_1 + \tilde{F}_2 \qquad \tilde{G}_E = \tilde{F}_1 - \tau\tilde{F}_2$$

$\tilde{F}_i$ are functions of $(s-u)$ and t

$$d\sigma = d\sigma_{NS}\left\{\varepsilon(\tilde{G}_E + \frac{s-u}{4M^2}\tilde{F}_3)^2 + \tau(\tilde{G}_M + \varepsilon\frac{s-u}{4M^2}\tilde{F}_3)^2\right\}$$

$$\sigma_R = \varepsilon G_E^2 + \tau G_M^2 +$$
$$+2\tau G_M \mathcal{R}e\left(\delta\tilde{G}_M + \varepsilon\frac{s-u}{M^2}\tilde{F}_3\right) + 2\varepsilon G_E \mathcal{R}e\left(\delta\tilde{G}_E + \frac{s-u}{M^2}\tilde{F}_3\right)$$

Two-Photon Exchange

Electron-proton elastic cross section

$$\sigma_{Mott} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2 \sin^4\frac{\theta}{2}} \frac{E'}{E}. \qquad \frac{d\sigma}{d\Omega} = \sigma_{Mott}\left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2G_M^2 \tan^2\frac{\theta}{2}\right],$$

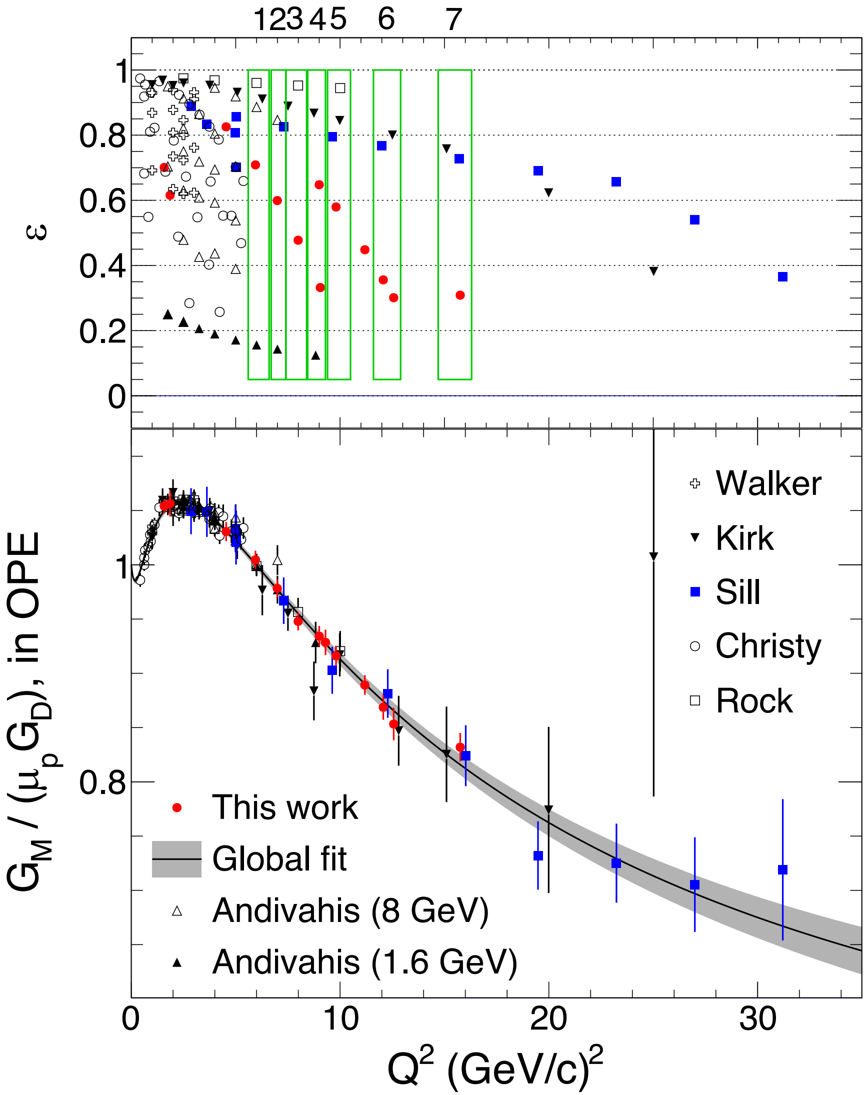
$$d\sigma/d\Omega \propto E_e^2/Q^4 \times 1/(Q^2)^4$$

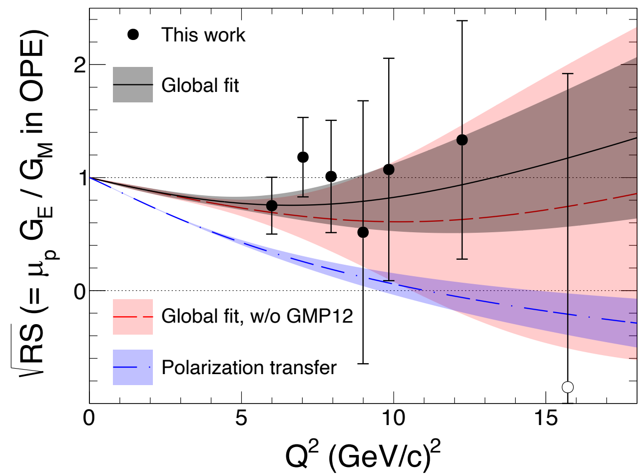
In the L/T experiment with detection of the scattered electron we need to measure very accurately:

- Beam charge
- Beam energy
- Target thickness
- Spectrometer momentum
- Spectrometer angle
- Spectrometer solid angle
- Detector efficiency

The GMp12 experiment (E12-07-108)

Phys.Rev.Lett. 128 (2022) 10, 102002





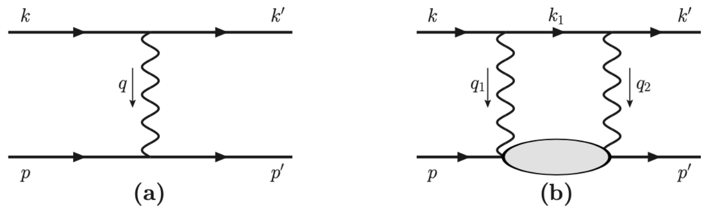
GMp12 fit:

$$G_M = \mu_p (1 + a_1 \tau)/(1 + b_1 \tau + b_2 \tau^2 + b_3 \tau^3),$$
$$\mathrm{RS} = 1 + c_1 \tau + c_2 \tau^2.$$

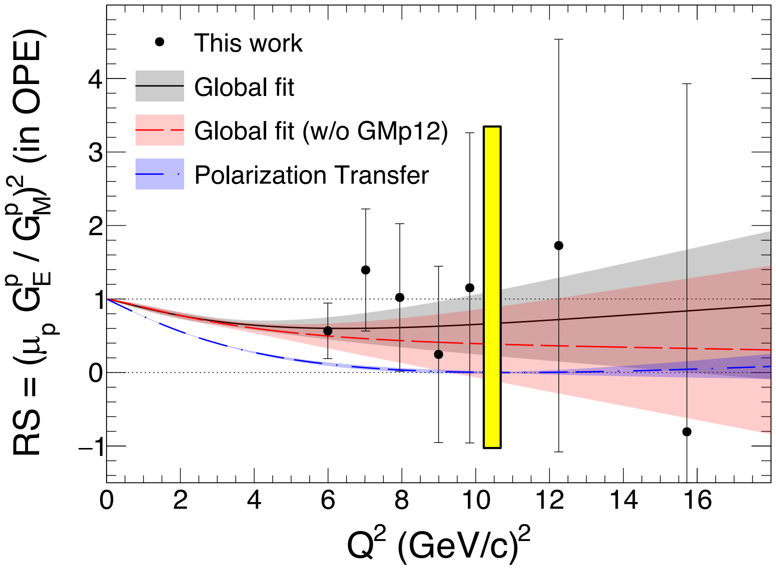
a_1	b_1	b_2	b_3	c_1	c_2
0.072(22)	10.73(11)	19.81(17)	4.75(65)	-0.46(12)	0.12(10)

courtesy of A. Gramolin and A. Puckett

Proton E/M from cross section



$$\sigma_R = \tau\, G_M^2(Q^2) + \varepsilon\, G_E^2(Q^2) = \sigma_T + \varepsilon\, \sigma_L$$
$$= G_M^2(Q^2)(\tau + \varepsilon\, RS(Q^2)/\mu_p^2),$$



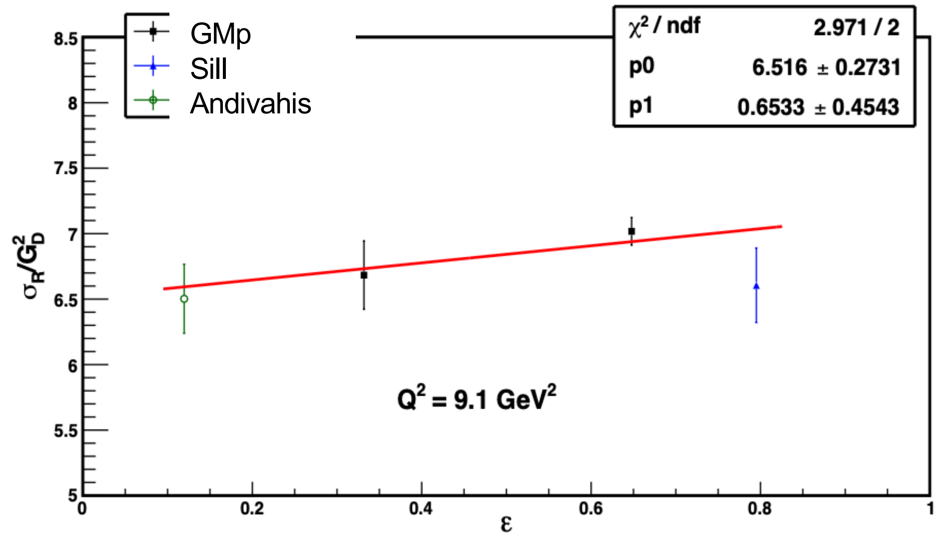
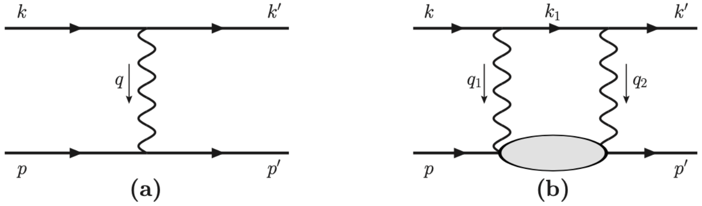


Figure 5.7. Reduced cross section normalized by G_D^2 versus ε at Q^2 =9.1 GeV^2.

$$d\sigma/d\Omega \propto E_e^2/Q^4 \times 1/(Q^2)^4$$

Proton E/M from cross section



$$\sigma_R = \tau\, G_M^2(Q^2) + \varepsilon\, G_E^2(Q^2) = \sigma_T + \varepsilon\, \sigma_L$$
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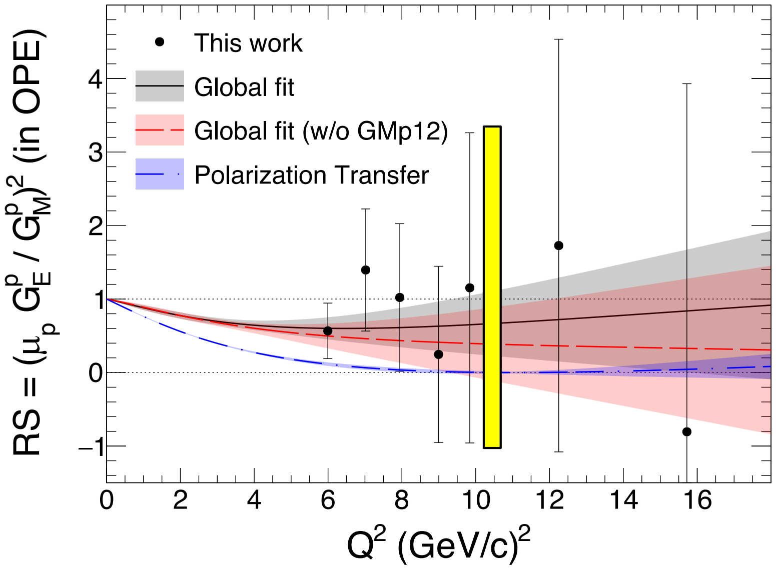

$$d\sigma/d\Omega \propto E_e^2/Q^4 \times 1/(Q^2)^4$$

TABLE III. Rosenbluth separation results for the data groupings shown in the top panel of Fig. 1, after centering to the average Q_c^2. The quoted values of σ_L and σ_T as defined in Eq. (2), and $G_M/(\mu_p G_D)$ and $\mu_p G_E/G_M$ are obtained assuming validity of the OPE approximation. For the largest Q^2, where $\sigma_L < 0$, we quote $-\sqrt{|RS|}$.

Q_c^2 $(\mathrm{GeV}/c)^2$	$\sigma_T \times 10^5$	$\sigma_L \times 10^5$	$G_M/(\mu_p G_D)$ (OPE)	$\mu_p G_E/G_M$ (OPE)
5.994	167 ± 4	7.1 ± 4.6	1.000 ± 0.011	0.75 ± 0.25
7.020	104 ± 3	9.3 ± 5.3	0.967 ± 0.015	1.18 ± 0.35
7.943	71.0 ± 2.7	4.1 ± 3.9	0.943 ± 0.018	1.0 ± 0.5
8.994	49.8 ± 1.7	0.7 ± 3.0	0.934 ± 0.016	0.5 ± 1.2
9.840	36.9 ± 2.4	1.9 ± 3.5	0.909 ± 0.029	1.1 ± 1.0
12.249	18.0 ± 0.8	1.2 ± 1.8	0.858 ± 0.019	1.3 ± 1.1
15.721	8.6 ± 0.5	-0.2 ± 1.2	0.840 ± 0.025	(-0.9 ± 2.8)

Landau textbook on electron-hadron

Поэтому имеем

$$-t = \frac{4\varepsilon_e^2 \sin^2\frac{\vartheta}{2}}{1+\frac{2\varepsilon_e}{M}\sin^2\frac{\vartheta}{2}}, \qquad (139,7)$$

$$\pi d|t| = \frac{\varepsilon_e^2 do'_e}{\left(1+\frac{2\varepsilon_e}{M}\sin^2\frac{\vartheta}{2}\right)^2}, \qquad (139,8)$$

где $do'_e = 2\pi \sin\vartheta\, d\vartheta$. В формуле (139,4) можно везде опустить массу электрона m; выразив все величины через t и $s - M^2 = 2M\varepsilon_e$, получим

$$d\sigma = \frac{\pi\alpha^2 d|t|}{\varepsilon_e^2 t^2}\left\{F_e^2(t)\left[\frac{(4M\varepsilon_e+t)^2}{4M^2-t}+t\right] - \frac{t}{4M^2}F_m^2(t)\left[\frac{(4M\varepsilon_e+t)^2}{4M^2-t}-t\right]\right\},$$

will allow improved acceptance determination as well as Q^2 matching between the points at the level of the HRHh spectrometer resolution ($\approx 10^{-4}$) since this spectrometer's magnetic field setting will be constant. While we expect the coincident measurement will provide the most accurate measurement of G_{E_p}/G_{M_p}, the singles measurement will provide a consistency

Projected accuracy L/T at high Q^2

the beam energy uncertainty contribution:

$$d\sigma = \frac{\pi\alpha^2 d|t|}{\varepsilon_e^2 t^2}\left\{F_e^2(t)\left[\frac{(4M\varepsilon_e+t)^2}{4M^2-t}+t\right]-\frac{t}{4M^2}F_m^2(t)\left[\frac{(4M\varepsilon_e+t)^2}{4M^2-t}-t\right]\right\}$$

$$\frac{\partial\sigma}{\partial E_e} = -\frac{2\cdot\sigma}{E_e} + 0.21\cdot\sigma \approxeq \frac{0.34\cdot\sigma}{E_e}$$

$$\frac{\delta\sigma}{\sigma} = 0.34 \times \frac{\delta E_e}{E_e}$$

It is small

How to do accurate L/T at high Q^2

$$d\sigma = \frac{\pi\alpha^2 d|t|}{\varepsilon_e^2 t^2}\left\{F_e^2(t)\left[\frac{(4M\varepsilon_e+t)^2}{4M^2-t}+t\right]-\frac{t}{4M^2}F_m^2(t)\left[\frac{(4M\varepsilon_e+t)^2}{4M^2-t}-t\right]\right\}$$

Proton spectrometer controls *t and* d/*t*/, beam energy is less important

In Hall C using SHMS and HMS, 6 GeV/c recoiled proton in Ω = 10+ msr

for $-t = Q^2 = 10\,GeV^2$ or $-\tau = \frac{Q^2}{4M^2} = 2.82$
using $E_e = 11GeV$ got $\theta_p = 21.0$ deg. and $\epsilon = 0.76$ ← Rate is 12 Hz
using $E_e = 7.5GeV$ got $\theta_p = 14.6$ deg. and $\epsilon = 0.46$ ← Rate is 1.5 Hz

What will experimental accuracy will be for realistic $\Delta\varepsilon = 0.3$:

$$\sigma \propto \tau + \frac{\epsilon}{\mu_p^2}(\mu_p G_E/G_M)^2 => 1 + \frac{\epsilon}{\tau\mu_p^2} \times RS$$

$$\frac{\Delta\sigma}{\sigma} = 0.014 \times RS$$

In 10 days statistics is 10^6 events
for each beam energy

High accuracy L/T, 1998

Letter –of-Intent: LOI-99-003

Title: A Precision Measurement of G^E_p/G^M_p at Q^2 = 2.0 and 4.0 GeV^2

Spokespersons: B. Wojtsekhowski, W. Bertozzi, K. Fissum, D. Rowntree

Precision measurements of G^E_p are of great interest for providing information on the proton's

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Precision measurements of G^E_p are of great interest for providing information on the proton's substructure. New precision measurements using recoil polarization from Hall A experiment 93-027 indicate a decreasing ratio of G^E_p/G^M_p with Q^2, contradicting some of the previous measurements using a Rosenbluth separation. This LOI discusses a new precision measurement in Hall A using the Rosenbluth technique. It would require control and understanding of systematic effects at the level of 1% in measurements of relative cross sections. The PAC acknowledges the interesting suggestions for limiting potential systematic errors presented in this letter but is not convinced that this 1% level can be achieved. In addition, as a cross-check on the recoil polarization technique a polarized beam-polarized target measurement would be more straightforward than the extremely challenging high-precision Rosenbluth separation discussed here. Also, while the PAC appreciates the importance of demonstrating the potential for doing high-precision Rosenbluth measurements with regard to future possible measurements (e.g. Coulomb Sum Rule), the PAC is not convinced that the physics motivation discussed in the present letter warrants the significant effort required to carry out such a difficult experiment.

PAC18 report

Proposal: E-01-001

Scientific Rating: A^-

Title: New measurement of G_E/G_M for the proton.

Spokesperson: R. E. Segel and J. Arrington

Motivation: The disagreement between the Rosenbluth method and the polarization transfer method of existing determinations of G_E/G_M motivates this experiment to make a new Rosenbluth measurement with several improvements to the experimental method. It is of great importance to determine if there is a fundamental problem with either the Rosenbluth or polarization transfer methods, as they are also used for many other experiments.

Measurement and Feasibility: The new measurement will detect protons, which have fixed momentum at fixed Q^2, independent of epsilon. By simultaneously making measurements at very low Q^2, where there is no controversy, systematic errors are reduced compared to the previous Rosenbluth measurements, which detected electrons over a wide range of momentum at fixed Q^2, and did not have a simultaneous low Q^2 measurement. Radiative corrections are also smaller using protons. The experiment uses standard equipment and methods, and appears to be straightforward to carry out.

Issues: The PAC believes it would be of higher scientific value to emphasize more precise measurements at the lower values of Q^2 , where the Rosenbluth method and polarization transfer already have a significant difference. It will be very important to check the assumed linearity of the Rosenbluth separation with respect to epsilon at the optimal Q^2 values by taking data at more epsilon points than proposed.

Recommendation: Approve for 10 days in Hall A.

Summary

- Accurate measurement of the L/T ratio at high Q^2 will significantly boost understanding of the basic process.

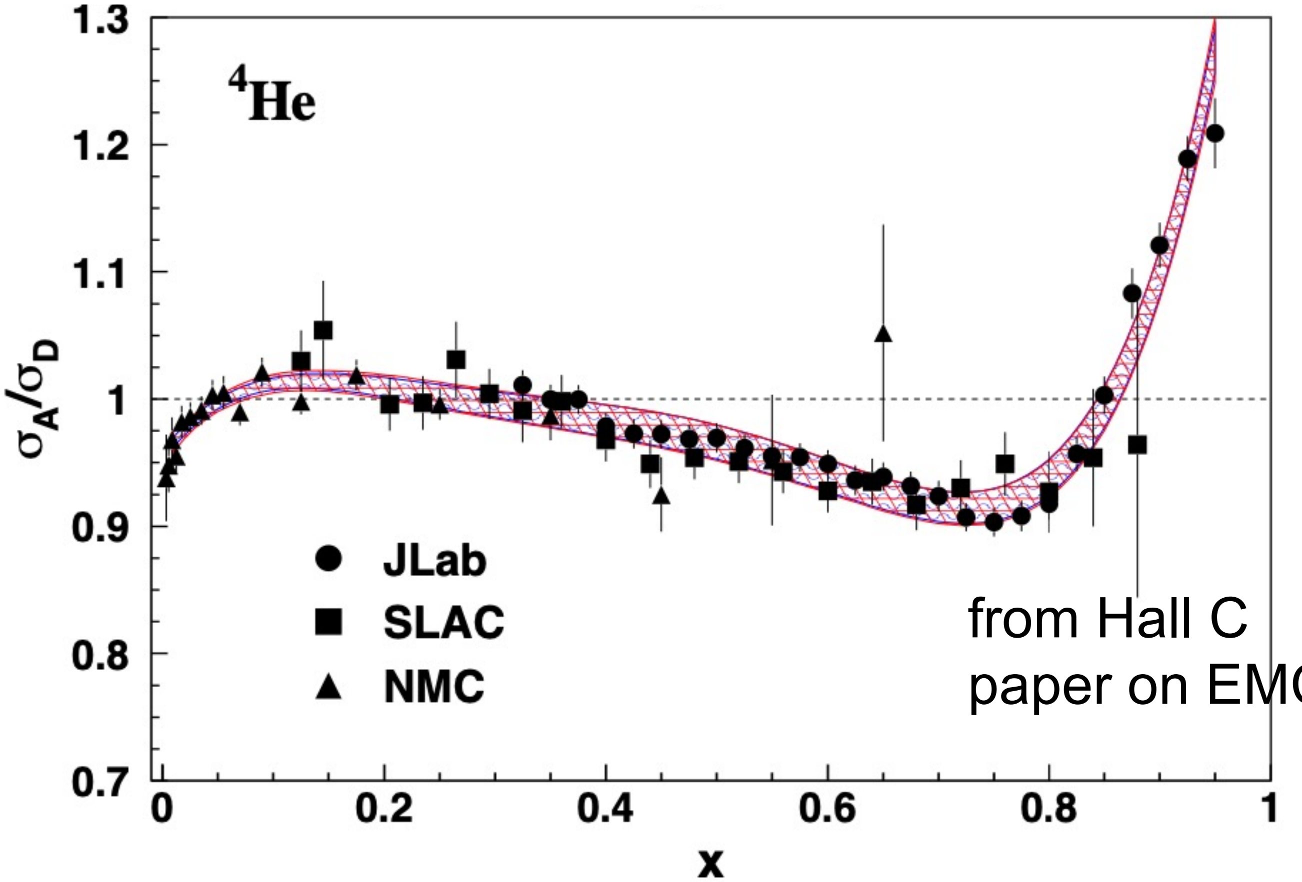
- Accurate measurement of the L/T ratio at high Q^2 is possible using a fixed momentum proton spectrometer.

- HMS and SHMS with 6-7 GeV/c allow us to do this experiment in 10 days for $Q^2 = 10$ GeV^2 to accuracy $\delta(\mu G_E)/G_M < 10\%$

- L/T-10 will provide essential constraints on two-photon exchange contribution functions.

"EMC" in $D(e,e'n_s)$ / $H(e,e')$

EMC effect



from Hall C paper on EMC

Proposal 05-014 for D(e,e'n_s)

(A New Proposal to Jefferson Lab PAC27)
Neutron Tagged bound proton structure to probe the Origin of the EMC Effect

G.D. Cates, D. Day, N. Liyanage (Spokesperson and contact person),
R. Lindgren, V. Nelyubin, B. Norum, O. Rondon K. Slifer, A. Tobias, K. Wang,
S. Tajima, B. Craver, R. Chang
University of Virginia, Charlottesville, VA 22904

J.P. Chen, P. Degtiarenko, E. Chudakov, J. Gomez, O. Hansen, D. Higinbotham, B. Reitz,
B. Wojtsekhowski (Spokesperson)
Jefferson Lab, Newport News, VA 23606

PAC27 report

Proposal: PR-05-014

Scientific Rating: N/A

Title: Neutron Tagged Bound Proton Structure to Probe the Origin of the EMC Effect

Spokespersons: Nilanga Liyanage, Bogdan Wojtsekhowski

Motivation: The determination of the ratio F_2^n/F_2^p and the *d/u* quark momentum distributions at large *x* in the proton suffer from uncertainties due to our lack of understanding of the EMC effect in the deuteron. Different classes of models lead to very different results at large *x* making the extraction of the neutron structure function from the deuteron ambiguous. The proposed experiment aims to probe the EMC effect from a barely bound to a strongly bound proton by means of deep inelastic scattering off the proton in the deuteron and by tagging the spectator neutron. This would allow discrimination between different models of the EMC effect.

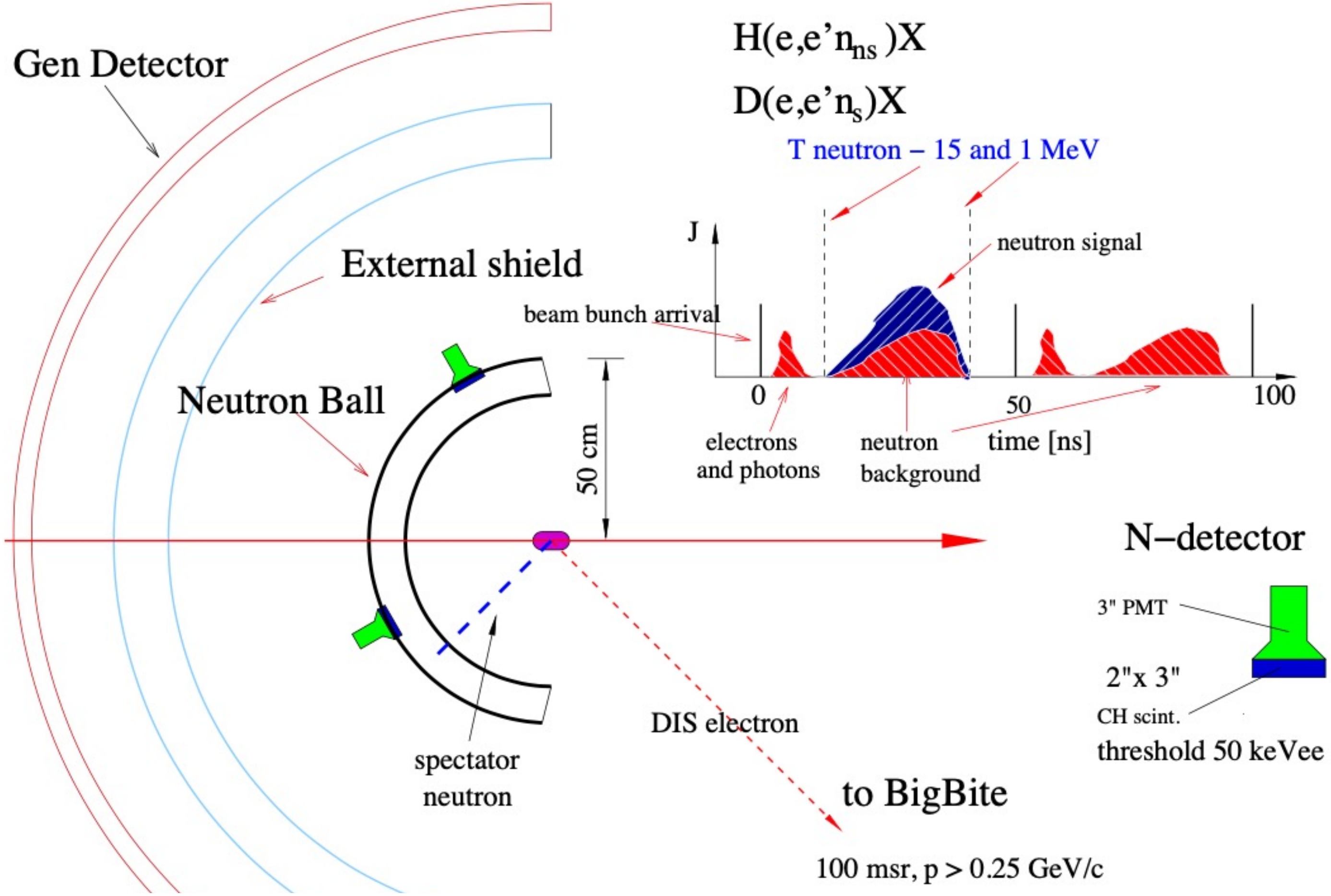
PAC27 report

Measurement and Feasibility: In the proposed experiment the ratio $\sigma[D(e,e'N)X]_{(x',\alpha^{sp},p_t,Q^2)}/\sigma[p(e,e')X]_{(x',Q^2)}$ is measured at values of *x'* from 0.11 up to 0.6 and spectator momentum fraction $1.04 \leq \alpha^{sp} \leq .4$ where $\sigma[D(e,e'N)X]_{(x',\alpha^{sp},p_t,Q^2)}$ is normalized to the inclusive *D(e,e')* cross section. An absolute measurement of this ratio is performed at each of the proposed α^{sp} by using the reaction *D(e,e'pn)* to calibrate the neutron detector efficiency to about 3%. Furthermore, to improve on the relative uncertainty in the determination of this ratio as a function of α^{sp}, it is normalized at each value of *x'* by its measured value at *x'*=0.2 leading to the determination of the ratio $G=\sigma[D(e,e'N)X]_{(x'_1,\alpha^{sp},p_t,Q_1^2)}/\sigma[D(e,e'N)X]_{(x'_2=0.2,\alpha^{sp},p_t,Q_2^2)}$. The experiment makes use of the BigBite spectrometer to detect electrons. The spectator neutrons are detected by using the neutron detector of the G_E^n experiment (E02-013) for the largest momenta and a new specially designed low energy neutron detector. The method takes advantage of the beam time structure as used in the G0 experiment in order to reduce the electromagnetic background and determine the shape of the neutron background with precision.

Issues: While the PAC is in principle very positive about this method, some issues remain to be addressed. The sensitivity of this experiment is at the 4σ level, which is marginal. The rate of accidental coincidences in the neutron detectors needs to be investigated by a test measurement, as already considered by the proponents, in order to optimize the luminosity of the experiment. A more complete estimate of the resulting systematic errors must be performed and must include the effect of $R=\sigma_L/\sigma_T$, as well as the possible uncertainty resulting from the normalization of the deuteron coincidence cross section to the inclusive one when the spectator is far off-shell.

Recommendation: Defer

2004 proposal for D(e,e'n$_s$)



EIC plan for D(e,e'n_s/p_s)

PHYSICAL REVIEW C **104**, 065205 (2021)

estion

Deep-inelastic electron-deuteron scattering with spectator nucleon tagging at the future Electron Ion Collider: Extracting free nucleon structure

Alexander Jentsch,[1,*] Zhoudunming Tu,[1,2,†] and Christian Weiss[3,‡]

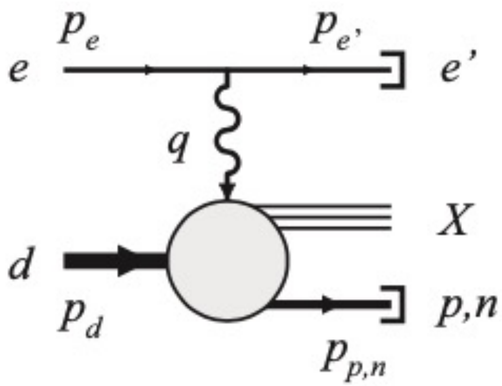
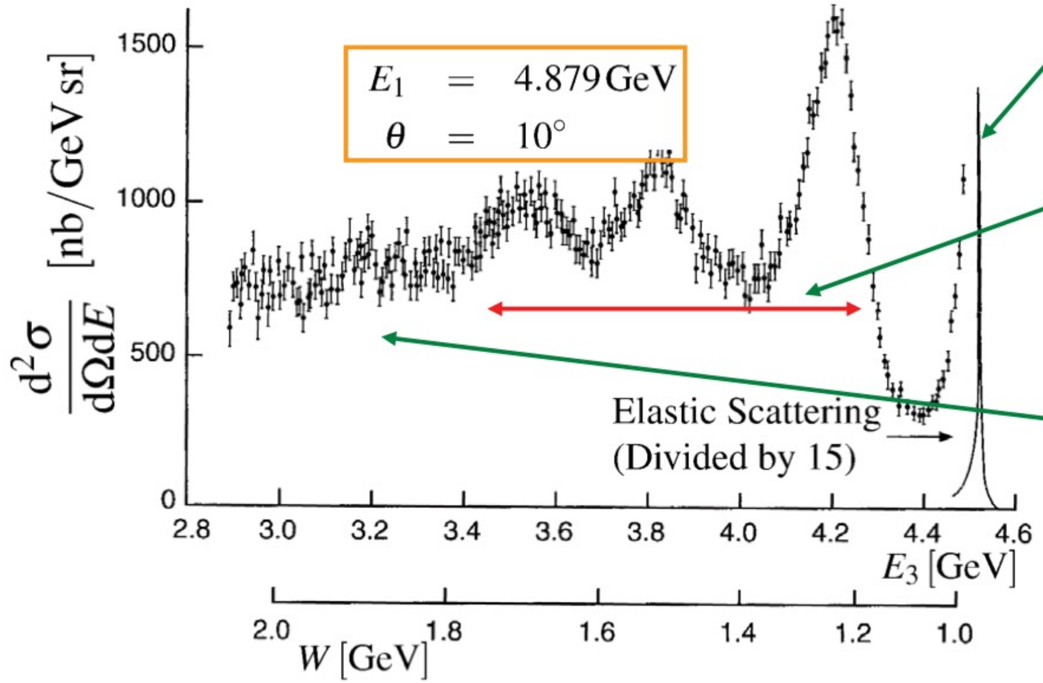


FIG. 1. DIS on the deuteron with detection of a proton (or neutron) in the nuclear fragmentation region, $e + d \rightarrow e' + X + p(n)$ ("tagged DIS").

DIS event rate



- **Elastic Scattering**
  proton remains intact
  $W = M$
- **Inelastic Scattering**
  produce "excited states" of proton e.g. $\Delta^+(1232)$
  $W = M_\Delta$
- **Deep Inelastic Scattering**
  proton breaks up resulting in a many particle final state

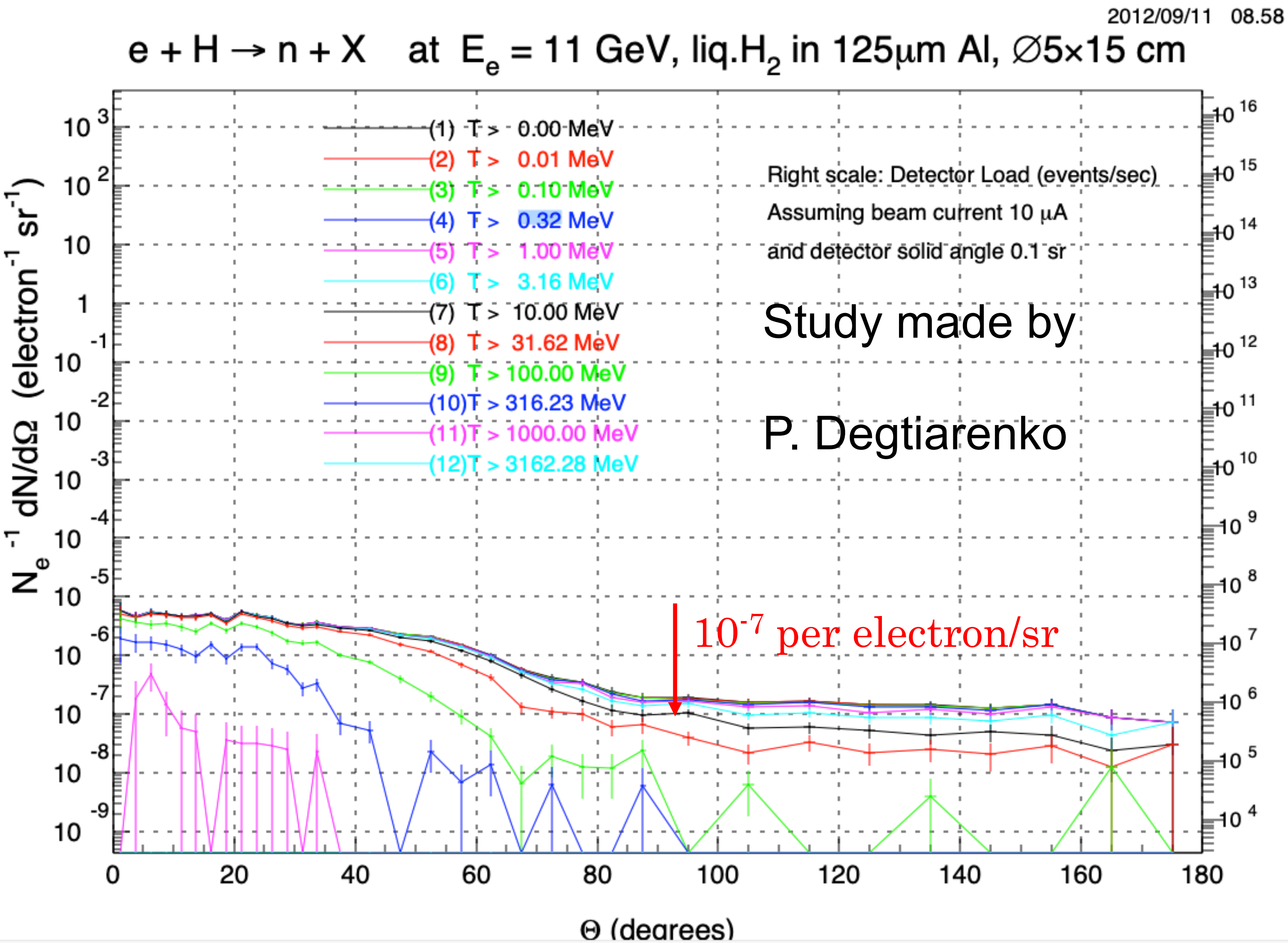
DIS = large W

$$\frac{d^2\sigma}{dE_3 d\Omega} = \frac{\alpha^2}{4E_1^2 \sin^4\theta/2}\left[\frac{1}{\nu}F_2(x,Q^2)\cos^2\frac{\theta}{2} + \frac{2}{M}F_1(x,Q^2)\sin^2\frac{\theta}{2}\right]$$

~ 0.3

$F_2(x) = 2xF_1(x)$

Detector rate vs angle



Detector rates at L = 3 x 10^{37}
(10 μA x 5 cm LD2)

- Neutron energy of 5 MeV (p = 100 MeV/c) and angle > 100 deg
- Rate of n ~ 0.3 $\times 10^{-6}$ per electron/sr = 20 MHz/sr for 10 μA x 5 cm LD2
- Those soft neutrons are from the many-particle final state processes
- DIS rate: E = 11 GeV beam at 15 deg on the proton target (see also a plot).
- The DIS rate with SBS = > 0.05 sr x 1×10^{-32} cm^2/sr x 3×10^{37} cm^{-2}/s = 1.5×10^4 Hz

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- For each e,e' event there is 1/12 probability of a correct hit in the neutron detector
- For 1 sr neutron detector Signal (e,e'n_s) rate is $N_{DIS}/4\pi$ ~1/12 => 1.2x10^{3} Hz
- In each e,e' event there will be some extra hits in the neutron detector:

  neutron rate e,e' rate
- For 32 ns beam RF the probability is 20 MHz x 0.032 μs = 0.64 => 15 kHz x 0.64 = 9.6 kHz background events with a potential neutron in one RF bucket.

=> Signal/Background (accidental) = 1.2 kHz / 9.6 kHz = 1/8

EMC signal size

The window 10 ns wide for 32 ns RF structure allows us to remove high speed particles

For 1 m from the target => 33 ns (for 5 MeV) => +/-50% energy window (3 to 8 MeV)

The Signal (DIS + neutron) statistics in 20 days ~ 2.1×10^8 +/- 1.4×10^4

Need to measure accidental Background with high accuracy

and in 100 RF buckets = windows will collect the accidental Background
mostly originating from the reaction D($\gamma_{q\text{-real}}$, n)X

Hit rate in the neutron detector (in such a wide window and detector of 10% efficiency) is 100 x 0.64 = 6.4 per e,e' event. It will have a total statistics of 1.7×10^{11} with +/- 4×10^5

Only 1/100 of these events will be in the correct RF bucket, so background will be
1.7×10^9 +/- 4×10^3 inside the bucket with the Signal

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Need to measure accidental Background with high accuracy

and in 100 RF buckets = windows will collect the accidental Background
mostly originating from the reaction $D(\gamma_{q\text{-real}}, n)X$

Hit rate in the neutron detector (in such a wide window and detector of 10% efficiency) is
100 x 0.64 = 6.4 per e,e' event. It will have a total statistics of 1.7×10^{11} with +/- 4×10^5

Only 1/100 of these events will be in the correct RF bucket, so background will be
1.7×10^9 +/- 4×10^3 inside the bucket with the Signal

The Signal statistics is 2×10^8 +/- 1.5×10^4.

The 1% size EMC effect (it corresponds to 2×10^6 events) will be well visible

$2 \times 10^6 / 1.5 \times 10^4 \sim 130 / 1$

Summary

- We propose to investigate the EMC effect in a deuteron: a ratio of the DIS on a free proton and DIS on a barely bound slow proton in the deuteron.
- This is a natural part of the SBS program at Hall C.
- The understanding of EMC will be advanced in a 20-day run.