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

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On behalf of the nTPE collaboration

Hall A collaboration meeting,
Jefferson Lab

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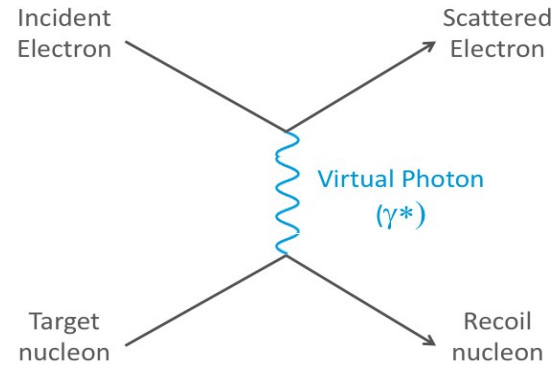
Elastic e-N Scattering, Rosenbluth (1950)

In the One-Photon Exchange (Born) approximation:

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

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



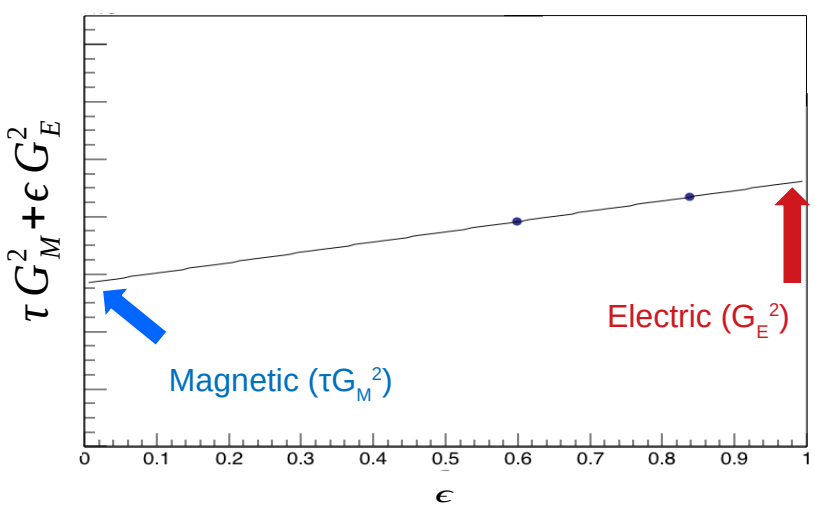
Rosenbluth technique: separate G_M^2 and G_E^2 based on the linear dependence in $\epsilon = \left[1+2(1+\tau)\tan^2\theta/2\right]^{-1}$

$$\sigma_r = (d\sigma/d\Omega)\cdot\epsilon(1+\tau)/\sigma_{Mott}$$

$$\tau G_M^2(Q^2) + \epsilon G_E^2(Q^2)$$

$$\sigma_T + \epsilon\,\sigma_L$$

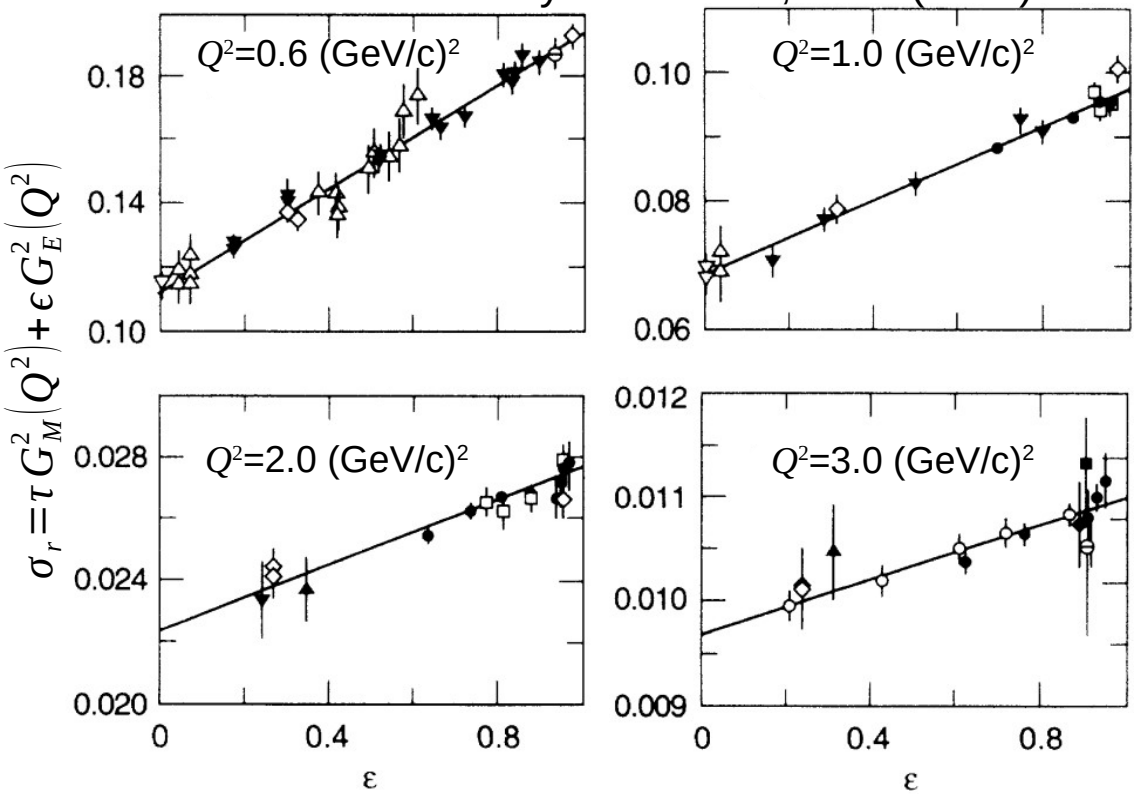
Two or more measurements, same Q^2, different E and θ (different ϵ)



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)

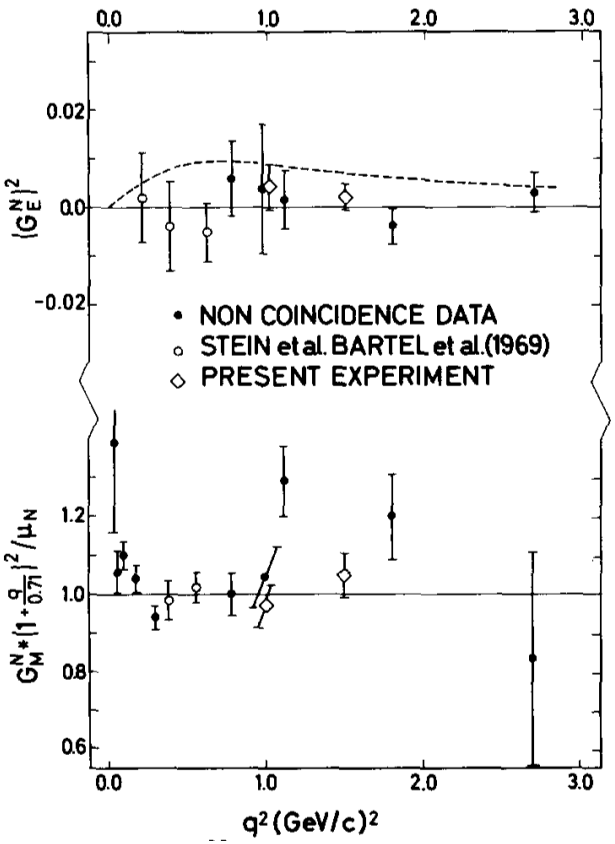


Linearity in ϵ well tested up to $Q^2 \leq 3$ (GeV/c)^2

Rosenbluth for *e-n* scattering

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

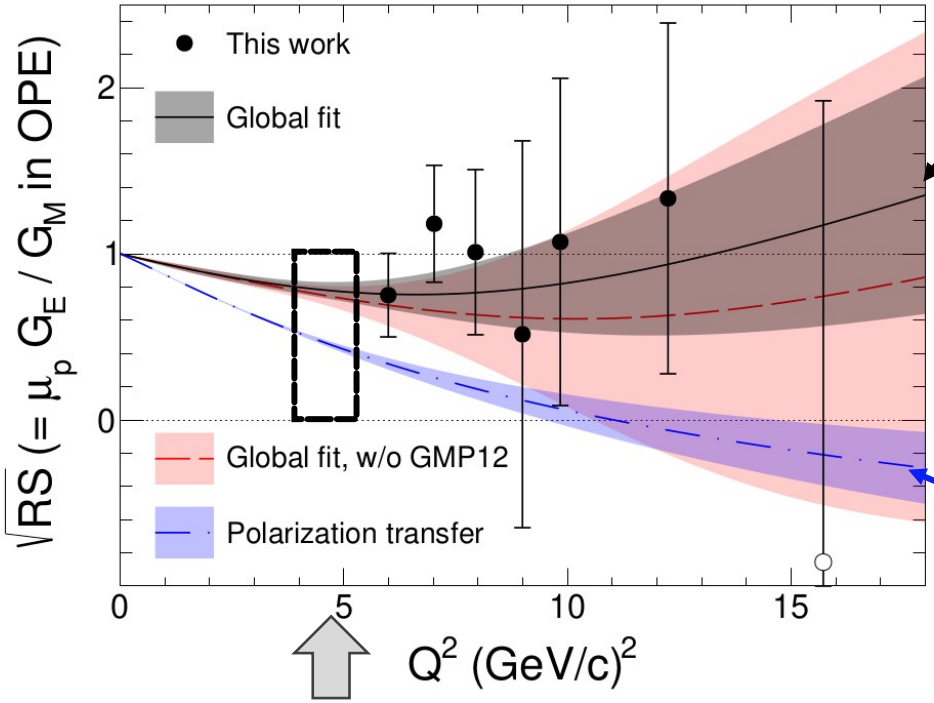
Bartel et al., Phys. Lett. 39B, 407 (1972)



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

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

Global fit of polarization transfer data

At Q^2 = 4.5 (GeV/c)^2, the Rosenbluth slope is $S^p = \sigma_L^p / \sigma_T^p \simeq 0.087 \pm 0.01$

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)

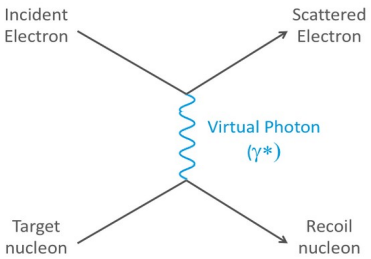
Until GEp-I at Jefferson Lab, Phys. Rev. Lett. 84, 1398 (2000),

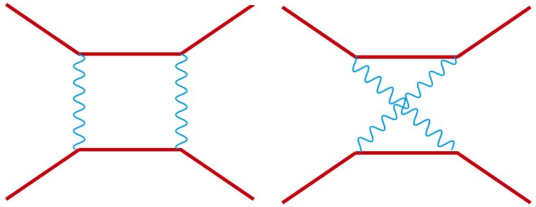
OPE accepted to be a sufficient approximation

Investigation of two-photon exchange is mandatory

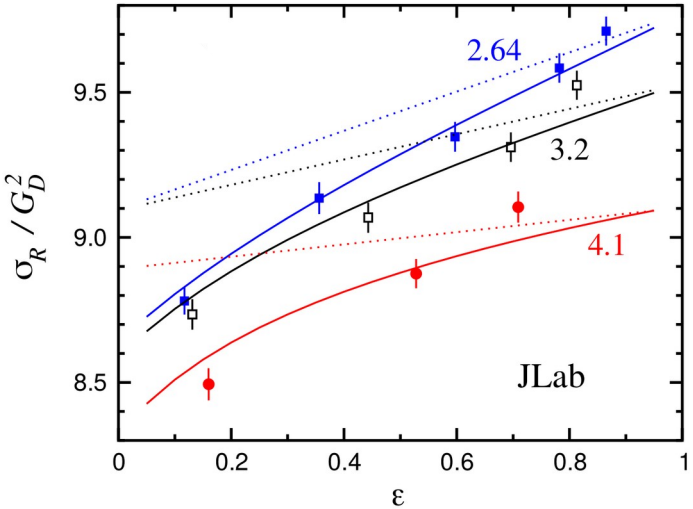
Many experiments were dedicated to measure two-photon exchange (TPE), including Rosenbluth and $e^{\pm}$-p scattering

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

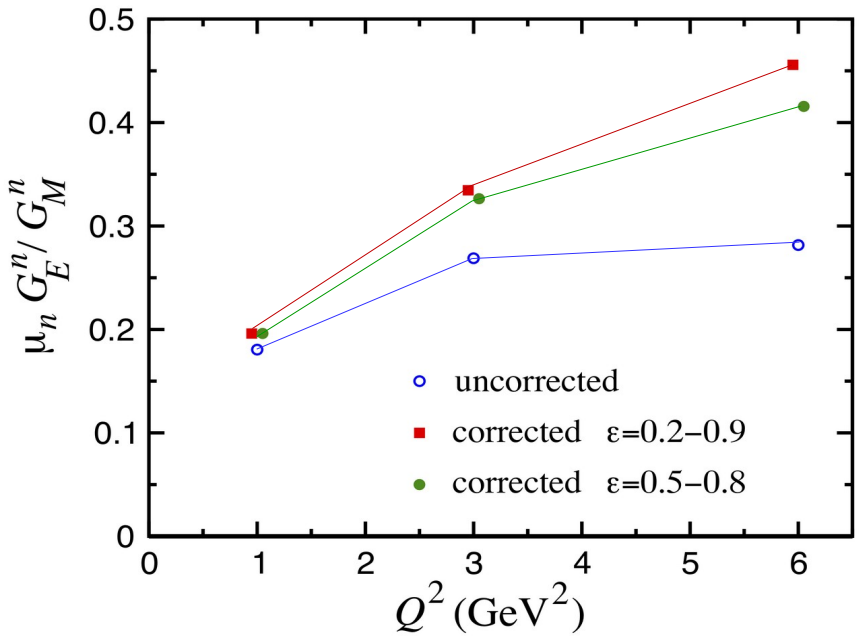
same, corrected with TPE contributions

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

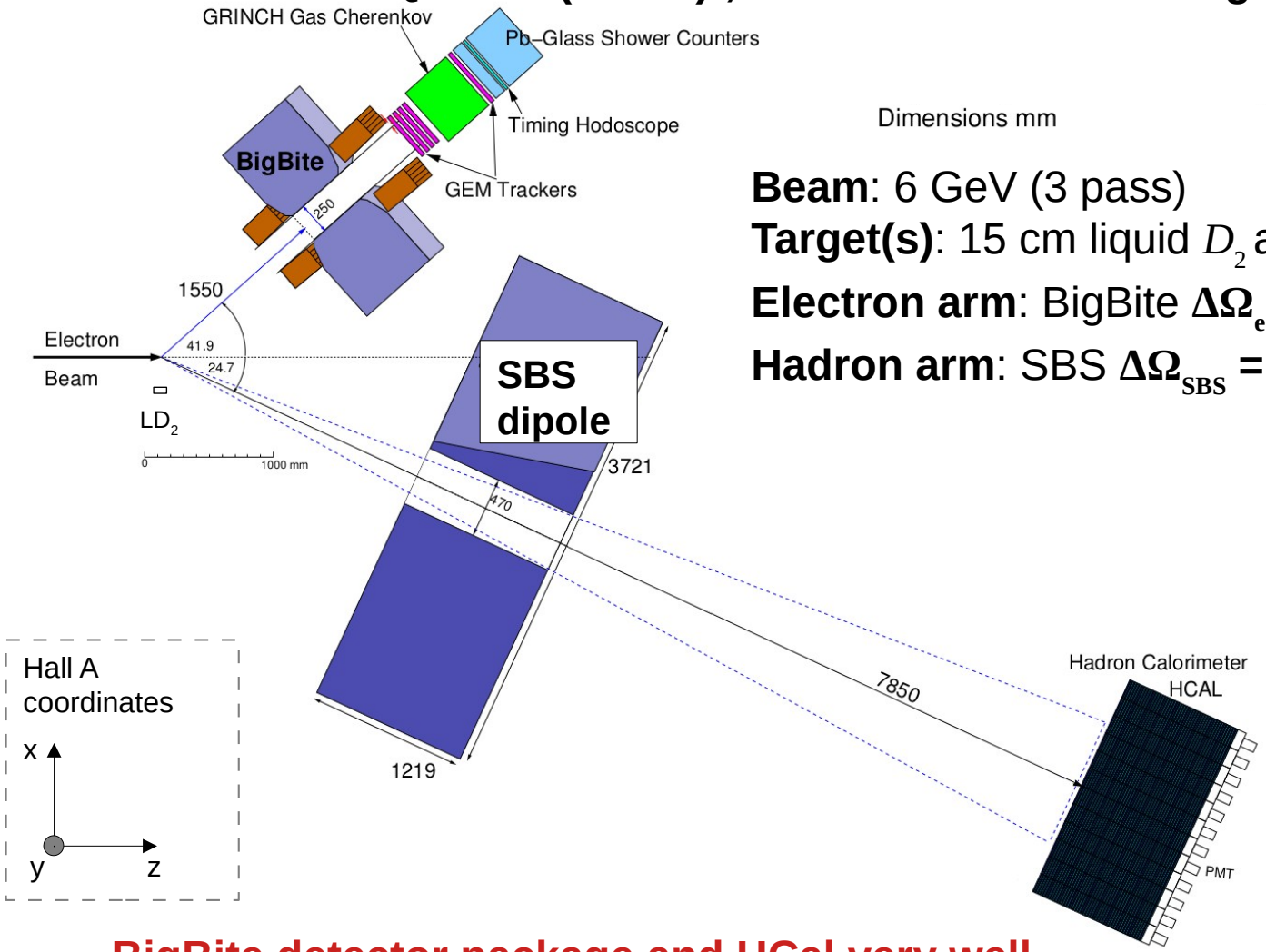
Means:

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	
SBS9	4.50	4.02	1.62	49.0	22.5	0.512	Approved E12-09-019
SBS8	4.51	5.97	3.56	26.5	29.9	0.797	Approved E12-20-010

Experimental Setup in Hall A

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



Dimensions mm

Beam: 6 GeV (3 pass)

Target(s): 15 cm liquid D_2 and H_2

Electron arm: BigBite $\Delta\Omega_e$ **= 32 msr**

Hadron arm: SBS $\Delta\Omega_{SBS}$ **= 71 msr**;

BigBite detector package and HCal very well presented in this afternoon session!

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

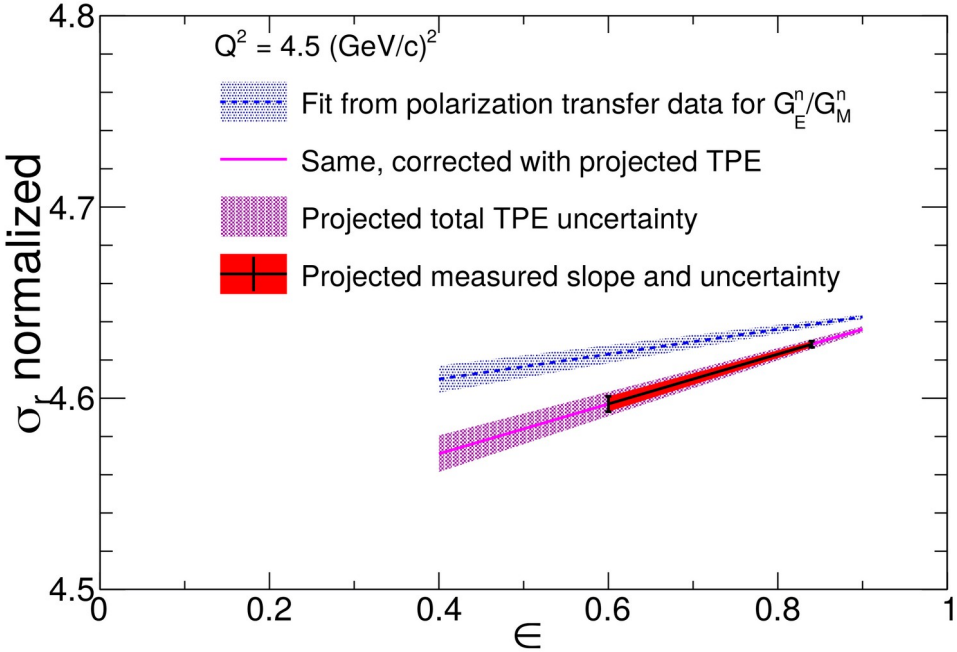
- Using $A=\left(\sigma_{en}/\sigma_{ep}\right)_{\epsilon_1}/\left(\sigma_{en}/\sigma_{ep}\right)_{\epsilon_2}$ the **experimental observable** and $B=\left(1+\epsilon_2 S^p\right)/\left(1+\epsilon_1 S^p\right)$, with $S^p=\sigma_L^p/\sigma_T^p \simeq 0.087 \pm 0.01$ we find

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

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) *as per the proposal*

Additional GEn data points (i.e. GEn-RP @ Q^2 = 4.5 GeV^2) *may* improve the systematics



Status

Data taken for *both* kinematics this winter:

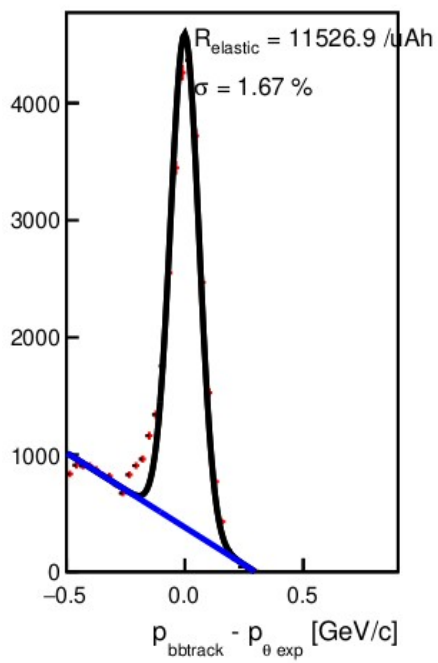
SBS8 from 1/21 to 1/31: estimated ~1.40 C collected on LD2 => **est.** 550k QE *e-n*

+ 0.87 C collected LH2, Dummy;

SBS9 from 2/01 to 2/07: estimated ~2.64 C collected on LD2 => **est.** 317k QE *e-n*

+ 0.81 C collected on LH2, Dummy;

(a larger proportion of LH2 data was collected for SBS8 for HCal systematic studies)



Elastic yield per unit of charge on LH2 for SBS8:
=> 11.5k/ uAh = 3200 *e-p*/mC on LH2
(Plot credit D. Hamilton)

Estimations (combining data and MC + 0.5 safety factor):
~400 QE *e-n* /mC on LD2 for SBS8
~120 QE *e-n* /mC on LD2 for SBS9
(full analysis necessary for definitive numbers)

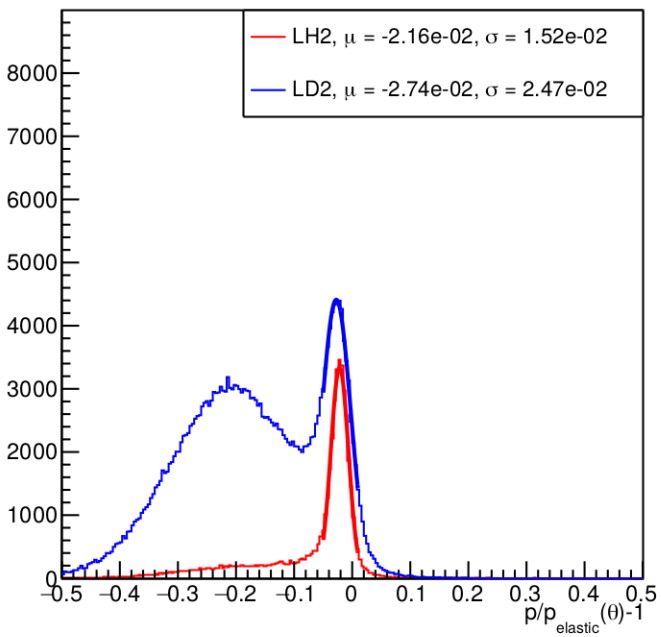
Analysis : first look

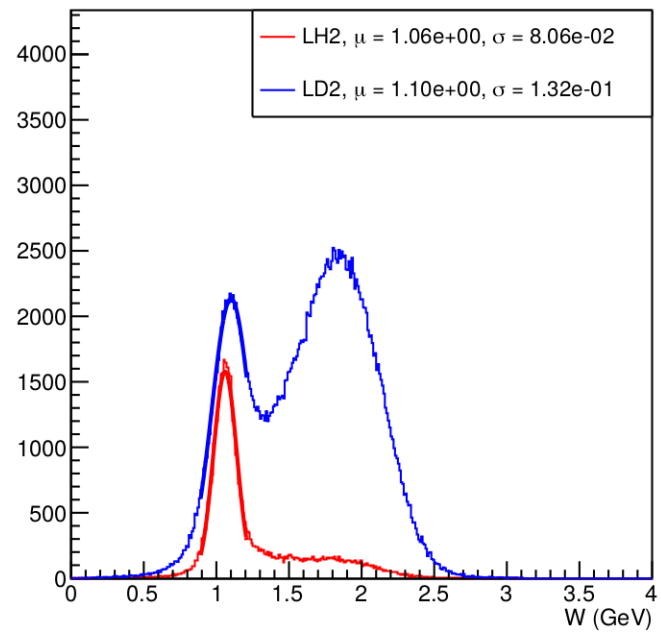
SBS8 (high ε)

Elastic selection:

* Ntrks>0
* E_{PS}>0.15 GeV
* $1-(E_{PS}+E_{SH})/p_e < 0.25$
* LD2: $(x_{Hcal}-x_{expect\_Hcal}-0.862)^2/0.236^2 + (y_{Hcal}-y_{expect\_Hcal}-0.133)^2/0.294^2 < \mathbf{1.0}^2$
* LH2: $(x_{Hcal}-x_{expect\_Hcal}-0.866)^2/0.149^2 + (y_{Hcal}-y_{expect\_Hcal}-0.133)^2/0.0863^2 < \mathbf{1.0}^2$

=> resolution in $W = \sqrt{(M_N^2+2M_N(E-E')-Q^2)}$ of the quasi-elastic peak: 0.13 GeV





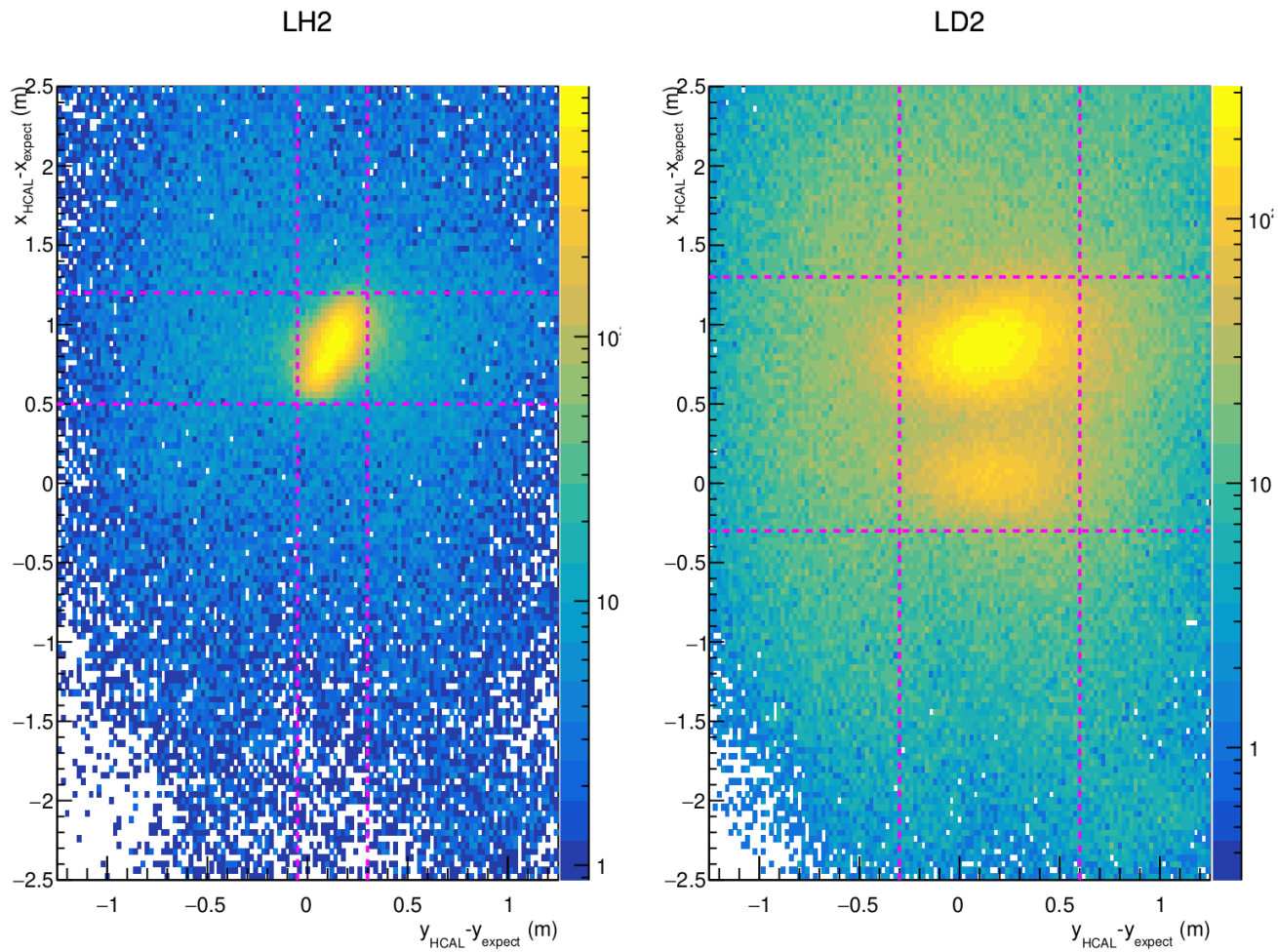
Analysis : first look

SBS8 (high ε)

Nucleon identification by reconstructed vs projected position in Hcal

* Ntrks>0
* E_{PS}>0.15 GeV
* $1-(E_{PS}+E_{SH})/p_e < 0.3$
* 0.6 < W (GeV) < 1.2
* -0.06 < dpel < 0.06

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



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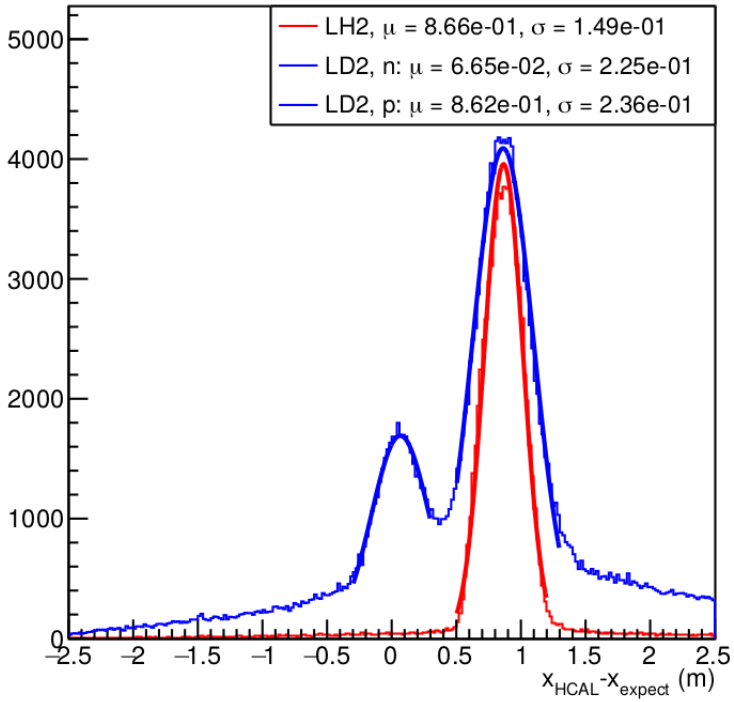
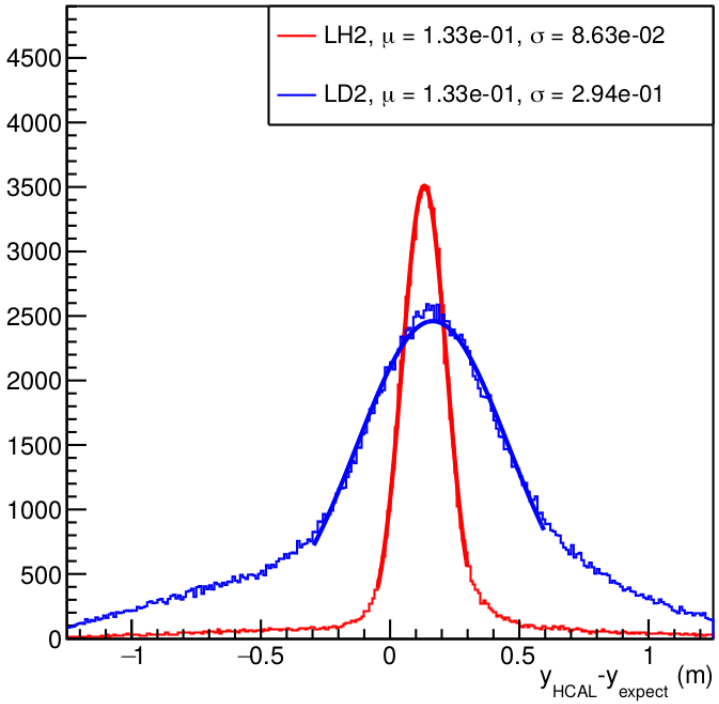
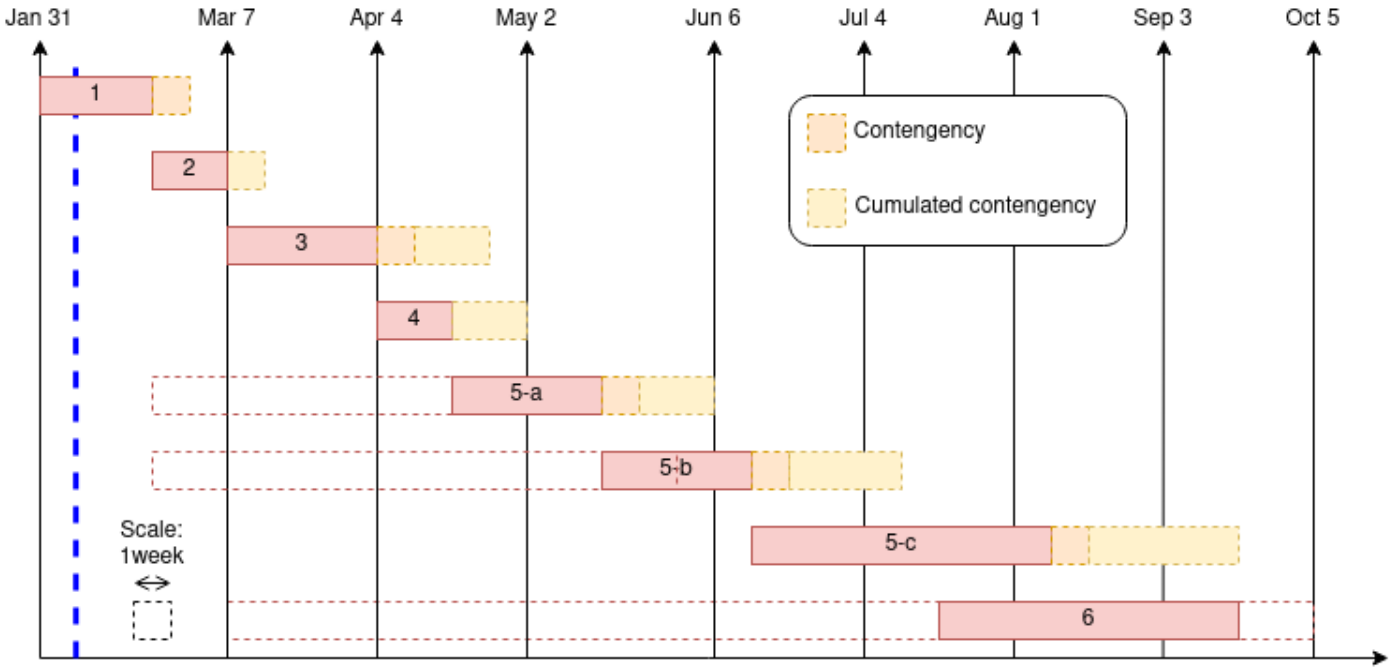




Analysis TODO and *tentative* timeline

1) 1st pass Calibration: Optics, BBCal, HCal calibration coefficients for each setting (2-3 weeks)
2) 1st pass mass replay analysis: (2 weeks)
3) Refined calibration: Optics, BBCal, HCal refined calibration coefficients for each setting (3-4 weeks)
4) 2nd pass mass replay analysis: (2 weeks)
5) Physics analysis:
    a) finalizing HCal response uniformity study and other systematics effects (3-4 weeks)
    b) finalizing selection of quasi-elastics: (3-4 weeks)
    c) combination of the two kinematics; extraction of the experimental observables (6-8 weeks)
6) preparation of the publication; time estimate: (6-8 weeks - doesn't account for the approval of the publication by the collaboration, etc) Note: first publication will probably not wait for GEn-RP results to be published; GEn-RP results will trigger a second analysis with another publication.



Outlook

* First measurement of two-photon exchange on neutron!

* Data taken, analysis just started;
will setup dedicated analysis meeting with students (Sebastian, John B?, Zeke?)
=> stay tuned for more!

THANK YOU for everyone participating to the nTPE/GMn effort:
- Hall A engineering staff for the experiment design;
- Hall A tech staff for installation/setting changes
(and god knows they were many!);
- Hall A, physics division, accelerator and Jefferson lab leaderships for giving more time for both experiments to run;
- run coordinators for litterally giving one week of their life to coordinate all activities;
- subsystem experts for tirelessly maintaining all detectors in a functioning state;
- shift takers for spending countless hours monitoring data and being on the frontline for problem detection;
- spokespeople and lead coordinator for steering the whole experiment over the whole period (and stuffing the counting house with food);