Measuring G_M^n in CLAS12

- Use the ratio $R = \frac{e-n}{e-p}$ in quasi-elastic kinematics to extract G_M^n.

$$R = \frac{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'n)_{QE}]}{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'p)_{QE}]} = \frac{\sigma^n_{mott}\left(G_E^{n\,2} + \frac{\tau_p}{\epsilon_p} G_M^{n\,2}\right)\left(\frac{1}{1+\tau_n}\right)}{\sigma^p_{mott}\left(G_E^{p\,2} + \frac{\tau_p}{\epsilon_p} G_M^{p\,2}\right)\left(\frac{1}{1+\tau_p}\right)}$$

- Data Set:
  1. Run Group B: Spring 2019, Fall 2019, Jan 2020
  2. Run Group A: Fall 2018, Spring 2019, used to extract CLAS12 neutron detection efficiency (NDE) for the $e = n$ events in R.
  3. Beam energies: 10.6 GeV and 10.2 GeV.
  4. Torus polarity: inbending and out bending.
- Outline:
  1. G_M^n: reaction, corrections
  2. NDE: reaction, event selection, method, preliminary results
  3. Acceptance Matching
  4. Quasielastic Event Selection - method, very preliminary results

Extracting G_M^n

Use the ratio $R = \frac{e-n}{e-p}$ in quasi-elastic kinematics to extract G_M^n.

$$R = \frac{\sigma^n_{mott}\left(G_E^{n2} + \frac{\tau_n}{\epsilon_n} G_M^{n\,2}\right)\left(\frac{1}{1+\tau_n}\right)}{\sigma^p_{mott}\left(G_E^{p2} + \frac{\tau_p}{\epsilon_p} G_M^{p\,2}\right)\left(\frac{1}{1+\tau_p}\right)}$$

where and

$$\tau = \frac{Q^2}{4M^2} \quad \epsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right)^{-1} \quad \sigma_{Mott} = \frac{\alpha^2 E' \cos^2(\frac{\theta_e}{2})}{4E^3 \sin^4(\frac{\theta_e}{2})}$$

Solving for G_M^n

$$G_M^n = \sqrt{\left[R\left(\frac{\sigma^p_{mott}}{\sigma^n_{mott}}\right)\left(\frac{1+\tau_n}{1+\tau_p}\right)\left(G_E^{p\,2} + \frac{\tau_p}{\epsilon_p} G_M^{n\,2}\right) - G_E^{n\,2}\right]\frac{\epsilon_n}{\tau_n}}$$

Corrections to R

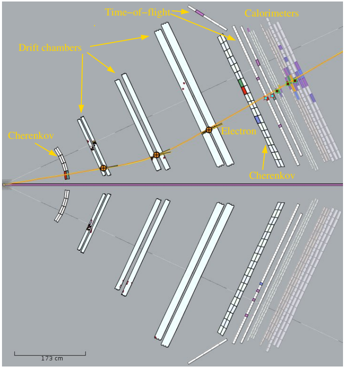
$$R(Q^2) = R_c(Q^2) = f_{NDE} f_{nuclear} f_{radiative} f_{fermi} \ldots R_{obs}$$

NDE*	acceptance matching
radiative effects	nuclear effects
fermi motion	θ_{pq} range
momentum corrections	angle corrections

* NDE - neutron detection efficiency

Neutron Detection Efficiency (NDE) - 1

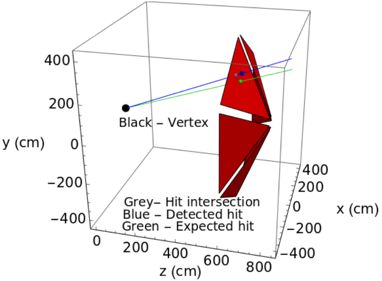
- Use the $^{1}\mathrm{H}(e, e'\pi^{+}n)$ reaction as a source of tagged neutrons.
- Event Selection
  1. Use standard CLAS12 reconstruction code and select $^{1}\mathrm{H}(e, e'\pi^{+})X_n$ events where X_n can be any number of neutrals, *i.e.* include all neutrals as neutron candidates.
  2. Use standard Run Group A cuts*:
     1. calorimeter fiducial cuts
     2. sampling fraction in calorimeter
     3. correlations in calorimeter
     4. deposited energy in calorimeter
     5. HTCC photoelectrons cut
     6. vertex cut
     7. $e - \pi^{+}$ vertex difference cut
     8. $\chi^2 PID$ cut.

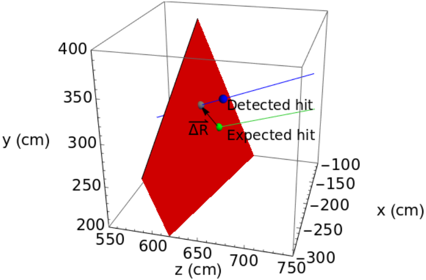


* CLAS12 RG-A - Analysis Note Overview and Procedures - Phase I, Towards SIDIS CLAS12 First Publications

Neutron Detection Efficiency (NDE) - 2

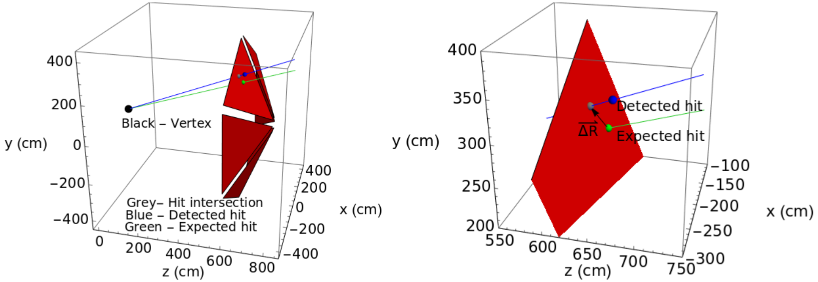
- Tagging Neutrons:
  1. Assume the reaction is $^1\mathrm{H}(e,e'\pi^+)n$ and use the e' and π^+ information to predict the trajectory of the assumed neutron.
  2. 'Swim' the neutron through the CLAS12 detector to see if strikes the fiducial region of the detector.
  3. If the 'swum' neutron DOES NOT strike CLAS12 drop the event.
  4. If the 'swum' neutron DOES strike CLAS12, continue. This is an expected neutron.





Red panels: ECAL front face, left - full size, right - close-up view

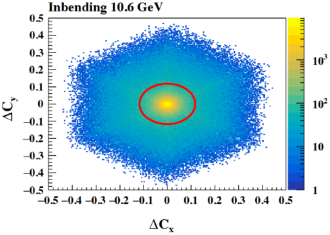
- Tagging Neutrons (continued):
  5. Now search the neutrals in the event to and see if one of those neutrals lies ‘near’ the predicted neutron track. See plot below. If a neutron is found this is a detected event.
  6. Geometry of neutron trajectories in CLAS12 for expected neutron (green) and a detected neutron (blue). Right-hand panel is a close-up.



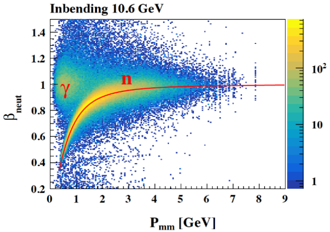
Red panels: ECAL front face, left - full size, right - close-up view

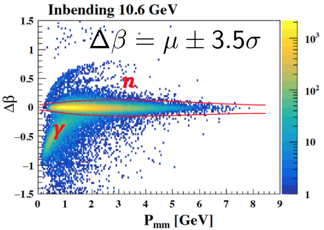
Neutron Detection Efficiency (NDE) - 4

- Tagging Neutrons (continued):
  7. Cut on 'nearby' tracks, $\Delta C_x \Delta C_y$ cut.

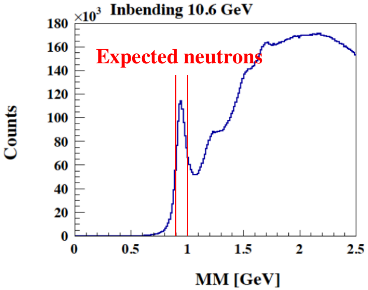


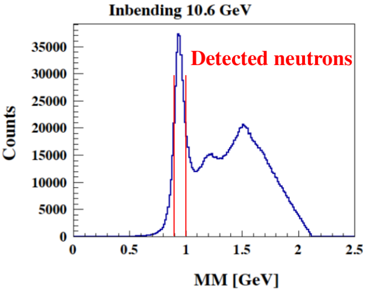
  8. Cut on $\Delta\beta = \frac{P_n}{E_{miss}} - \beta_n$ where $\beta_n = \frac{\ell_n}{c\Delta t_n}$. These are detected neutrons.





- Tagging Neutrons (continued):
  9. Cut on neutron missing mass peak $0.9\ \mathrm{GeV} < MM < 1.0\ \mathrm{GeV}$.

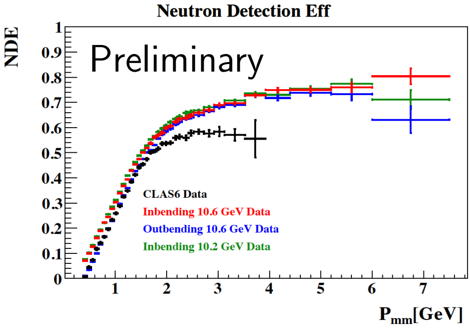




  10. Now studying fits to the missing mass and background subtraction.

Neutron Detection Efficiency (NDE) - 6

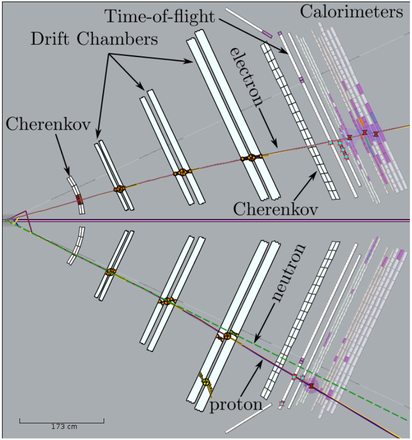
- Extracting the NDE
  1. Expected neutron events $^{1}\mathrm{H}(e, e'\pi^{+})X_n$ satisfy electron/pion cuts (from Run Group A) and expected neutron strikes calorimeter.
  2. Detected neutron events $^{1}\mathrm{H}(e, e'\pi^{+}n)$ satisfy electron/pion cuts (from Run Group A) and $\Delta C_x \Delta C_y$ and $\Delta\beta$ cuts.
  3. The NDE ϵ is the ratio of detected to expected neutrons $\epsilon = \frac{N_{detected}}{N_{expected}}$.



Acceptance Matching

Since we divide the number of $e - n$ event by the number of $e - p$ ones we must correct for the different acceptances of neutrons and protons in CLAS12.

1. Electron passes the selection cuts.
2. Using only the electron information, assume elastic scattering, predict the proton momentum, and swim it through CLAS12.
3. If the 'swum' proton track strikes the CLAS12 fiducial volume, continue. If it does not, then drop the event.
4. Using only the electron information, assume elastic scattering, predict the neutron momentum, and swim the proton track through CLAS12.
5. If the 'swum' neutron track strikes the CLAS12 fiducial volume, continue. If it does not, then drop the event.



6. If both 'swum' tracks hit CLAS12, begin the nucleon analysis.

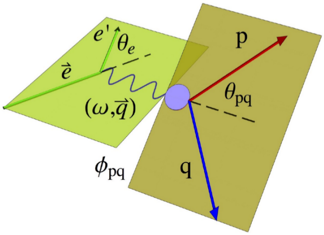
Quasielastic Event (QE) Selection - 1

1. The data can be used to calculate the incoming beam energy E_{beam} using different quantities. This feature give us the opportunity for cross-checks and corrections. See CLAS-NOTE-02-008.

$$E_{beam}^{angles} = M\left(\frac{1}{\tan\left(\frac{\theta_e}{2}\right)\tan\theta_N} - 1\right) \qquad E_{beam}^{mom} = p_e\cos\theta_e + p_N\cos\theta_N$$

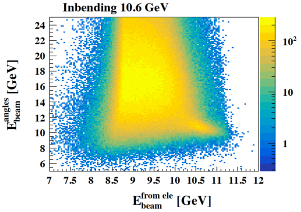
$$E_{beam}^{e} = \frac{E'}{1 + \frac{2E'}{m_N}\sin^2\left(\frac{\theta_e}{2}\right)}$$

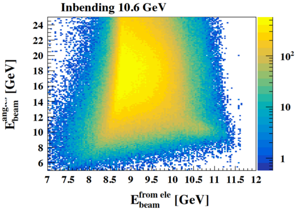
2. The angle θ_{pq} is the angle between the 3-momentum transfer and the direction of the struck nucleon. For QE events θ_{pq} should be small while inelastic events are emitted at larger angles.



Quasielastic Event (QE) Selection - 2

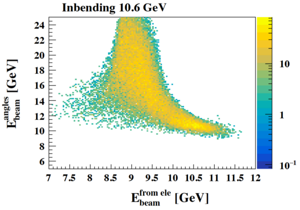
- Extract the known beam energy from the measured electron and nucleon (see CLAS-NOTE-02-008).
- 2D plots of E_{beam}^{angles} versus E_{beam}^{e}. No θ_{pq} cut.

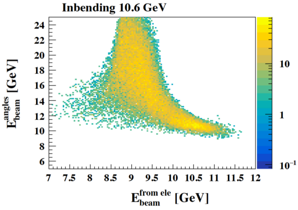




left column - $e - p$
right column - $e - n$

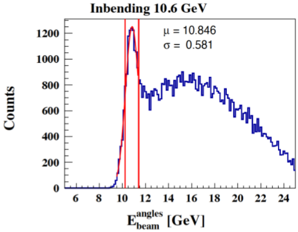
- 2D plots of E_{beam}^{angles} versus E_{beam}^{e}, $\theta_{pq} < 2.5^{\circ}$ cut.

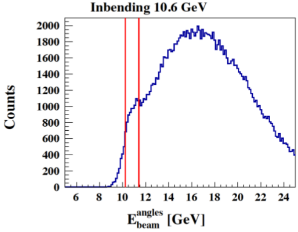




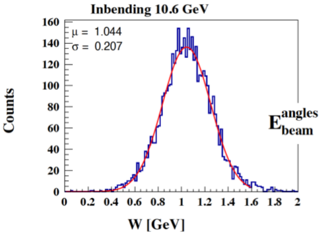
Quasielastic Event (QE) Selection - 3

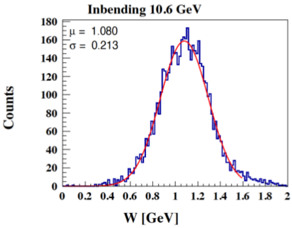
- Still significant background.





- Shows up in W.



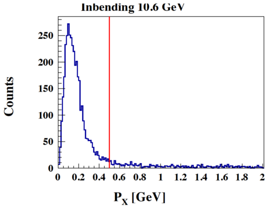


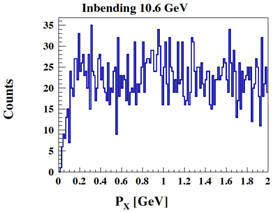
Quasielastic Event (QE) Selection - 4

- An additional QE selection cut - missing momentum.

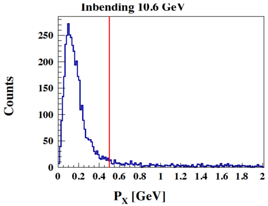
$$|\vec{P}_X| = P_{e'} + P_N - P_{beam}$$

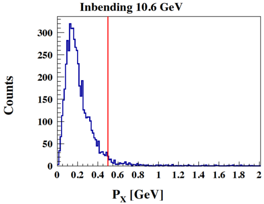
- The $e - p$ distribution looks good, the $e - n$ one not so much.





- Apply corrections to P_X and the distribution improves.





Quasielastic Event (QE) Selection - 5

- Neutron momentum correction

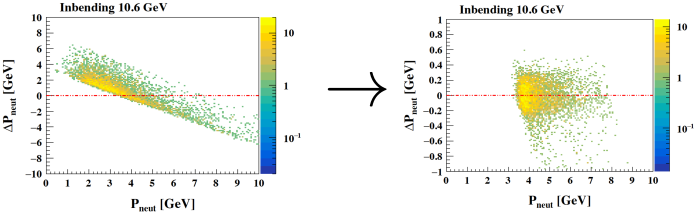
$$\Delta P_{neut} = p_{nfe} - p_n$$

where p_{nfe} is from the electron and p_n is from the neutron timing.

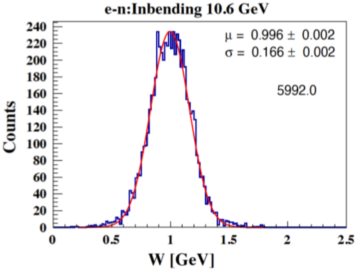
$$p_{nfe} = \sqrt{p_{beam}^2 - 2p_{beam}p_{e'}\cos\theta_e + p_{e'}^2}$$

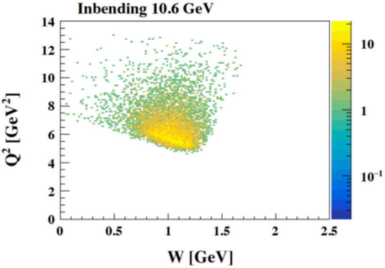
$$p_{e'} = \frac{p_{beam}}{1 + 2p_{beam}\sin^2\left(\frac{\theta_e}{2}\right)/m_N} \qquad p_n = \frac{m_n\beta_{neutral}}{\sqrt{1-\beta_{neutral}^2}} \qquad \beta_{neutral} = \frac{\ell_n}{c\Delta t}$$

- Results of corrections tp P_{neut} and θ_{neut}.

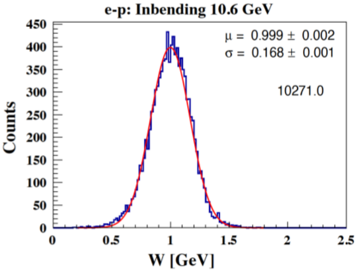


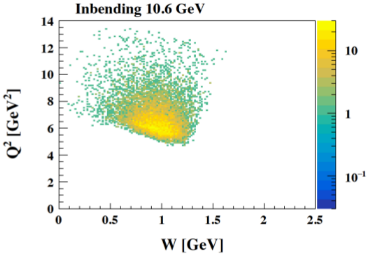
Current Status





e-n events





e-p events

63

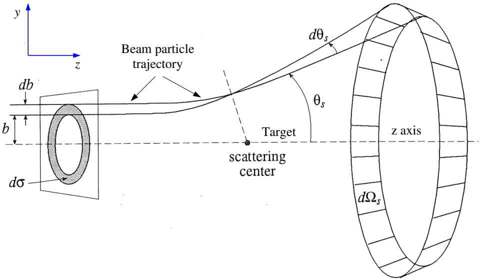
What is a Form Factor?

- Start with the cross section.

$$\frac{d\sigma}{d\Omega} = \frac{\text{scattered rate/solid angle}}{\text{incident rate/surface area}}$$

- For elastic scattering use the Rutherford cross section.

$$\frac{d\sigma}{d\Omega} = \frac{Z_{tgt}^2 Z_{beam}^2 \alpha^2 (\hbar c)^2}{16E^2 \sin^4(\theta/2)}$$



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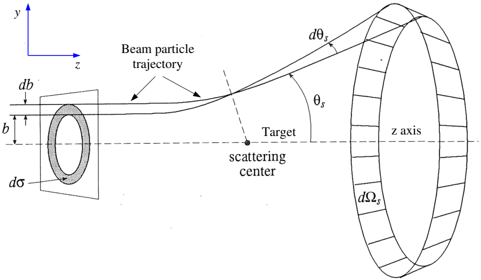

- Cross section for elastic scattering by point particles with spin.

$$\frac{d\sigma}{d\Omega} = \frac{Z_{tgt}^2 Z_{beam}^2 \alpha^2 (\hbar c)^2}{16 E^2 \sin^4(\theta/2)} \left(1 - \beta^2 \sin^2 \frac{\theta}{2}\right) \quad \text{(Mott cross section)}$$

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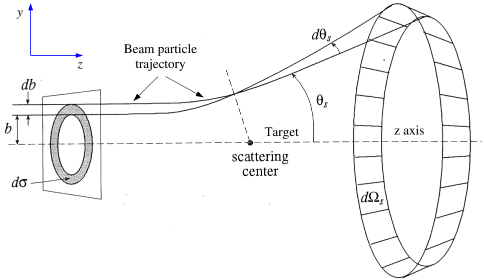

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- What happens when the beam is electrons and the target is not a point?

$$\frac{d\sigma}{d\Omega} = \frac{Z_{tgt}^2 \alpha^2 (\hbar c)^2}{16E^2 \sin^4(\theta/2)} \left(1 - \beta^2 \sin^2 \frac{\theta}{2}\right) |F(Q^2)|^2$$

where Q^2 is the 4-momentum transfer.

What is a Form Factor?

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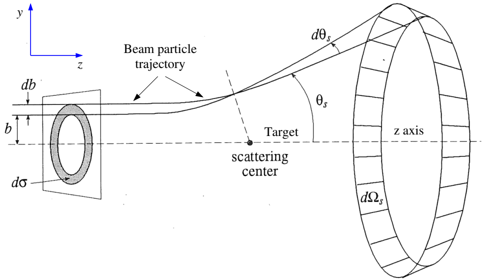

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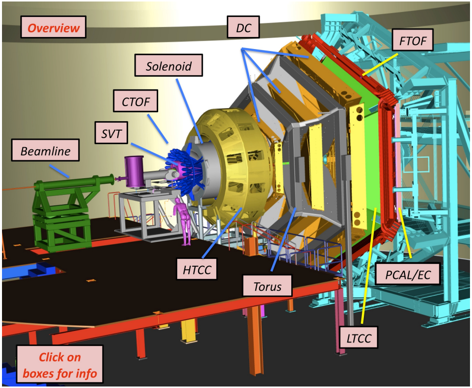
$$\frac{d\sigma}{d\Omega} = \frac{Z_{tgt}^2 \alpha^2 (\hbar c)^2}{16E^2 \sin^4(\theta/2)} \left(1 - \beta^2 \sin^2 \frac{\theta}{2}\right) |F(Q^2)|^2$$

where Q^2 is the 4-momentum transfer.

THE FORM FACTOR!

How Do We Measure G_M^n on a Neutron? (Step 2)

- Add one 45-ton, \$80-million radiation detector: the CEBAF Large Acceptance Spectrometer (CLAS12).
- CLAS covers a large fraction of the total solid angle at forward angles.
- Has about 62,000 detecting elements in about 40 layers.



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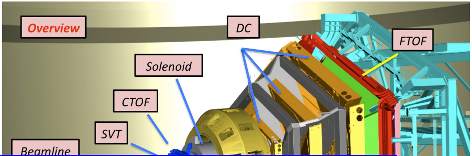

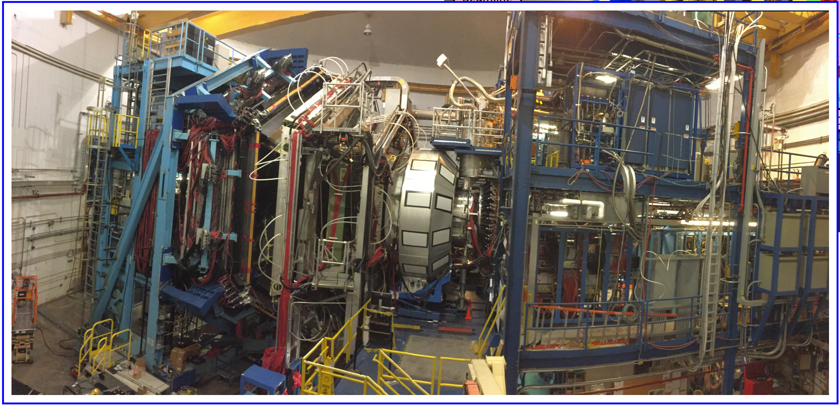

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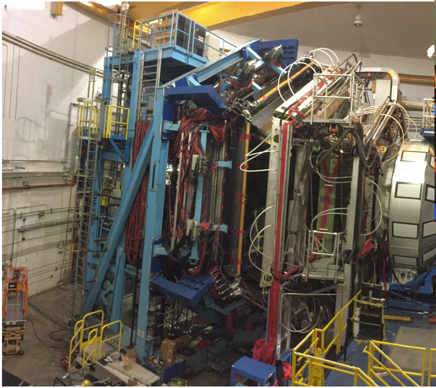
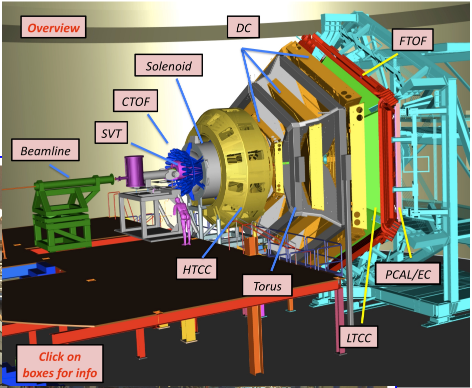
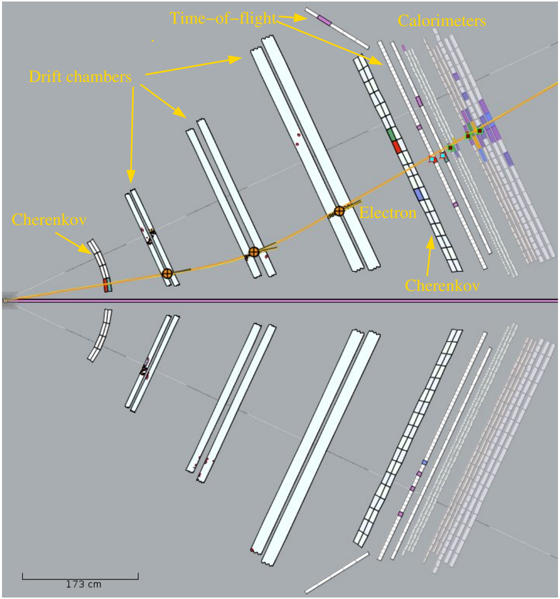
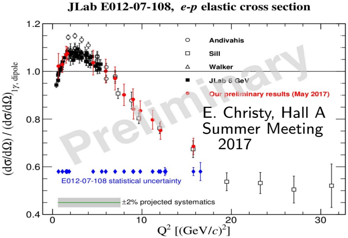




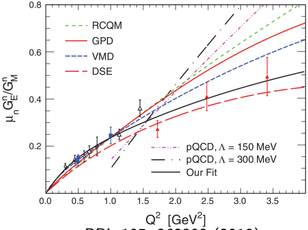
A CLAS12 Event



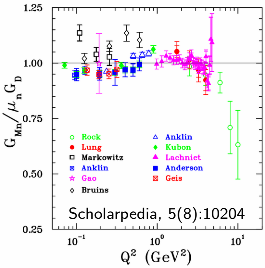
- G_M^p well known over large Q^2 range.
- The ratio G_E^p/G_M^p from polarization transfer measurements diverged from previous Rosenbluth separations.
  - Two-photon exchange (TPE).
  - Effect of radiative corrections.

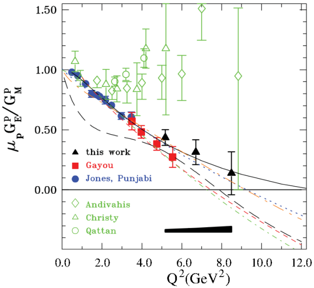


- Neutron magnetic FF G_M^n still follows dipole.
- High-Q^2 G_E^n opens up flavor decomposition.



PRL 105, 262302 (2010)





PRL **104**, 242301 (2010)

How Do We Measure G_M^n on a Neutron? (Step 3)

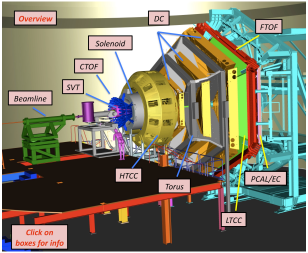
- E12-07-104 in Hall B (Gilfoyle, Hafidi, Brooks).
- Ratio Method on Deuterium:

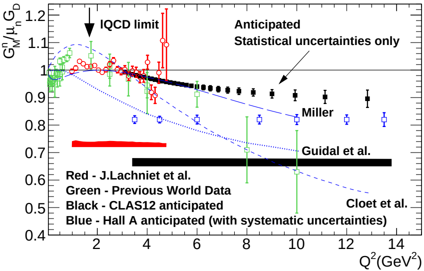
$$R = \frac{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'n)_{QE}]}{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'p)_{QE}]}$$

$$= a \times \frac{\sigma_{Mott}\left(\frac{(G_E^n)^2+\tau(G_M^n)^2}{1+\tau}+2\tau\tan^2\frac{\theta_e}{2}(G_M^n)^2\right)}{\frac{d\sigma}{d\Omega}[^1\mathrm{H}(e,e')p]}$$

where a is nuclear correction.

- Precise neutron detection efficiency needed to keep systematics low.
    - tagged neutrons from $^2\mathrm{H}(e,e'pn)$.
    - LH_2 target.
- Kinematics: $Q^2 = 3.5 - 13.0\ (\mathrm{GeV/c})^2$.
- Beamtime: 40 days.
- Systematic uncertainties $<$ 2.5% across full Q^2 range.
- Half of Run Group B done January, 2020.





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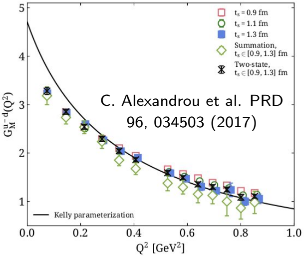

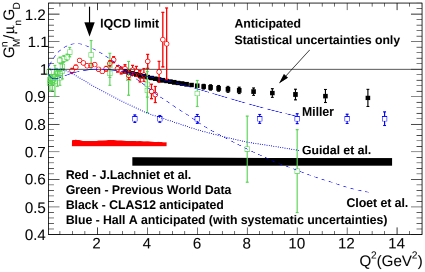

Anticipated Results