An Update on the Measurement of the Neutron Magnetic Form Factor G_M^n at CLAS

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Experimental technique

- Measure the ratio of quasi-elastic electron-neutron to electron-proton cross section on a deuterium target

$$R = \frac{\frac{d\sigma}{d\Omega}(D(e,e'n))}{\frac{d\sigma}{d\Omega}(D(e,e'p))} = a(Q^2)\frac{\frac{G_{En}^2+\tau G_{Mn}^2}{1+\tau} + 2\tau G_{Mn}^2 \tan^2(\frac{\Theta}{2})}{\frac{G_{Ep}^2+\tau G_{Mp}^2}{1+\tau} + 2\tau G_{Mp}^2 \tan^2(\frac{\Theta}{2})}$$

  This ratio is nearly equal to the ratio of *free* electron-neutron to electron-proton cross sections. Deviations from this assumption are parameterized in the factor $a(Q^2)$, which can be calculated from deuteron models, and are small at large Q^2.

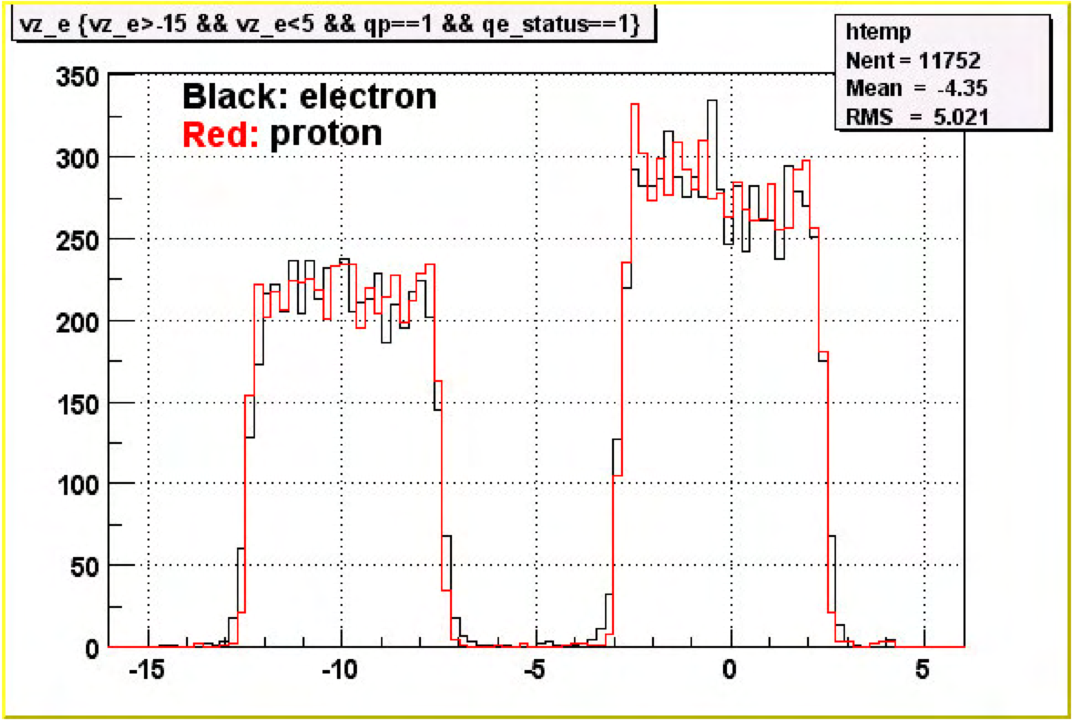
- Once the model corrections have been applied to R, the well-measured proton cross section can be used to extract G_M^n. The contribution to the cross-section from G_E^n is small relative to G_M^n, so although G_E^n is not known with high precision, it is a small source of uncertainty.

e5 experiment

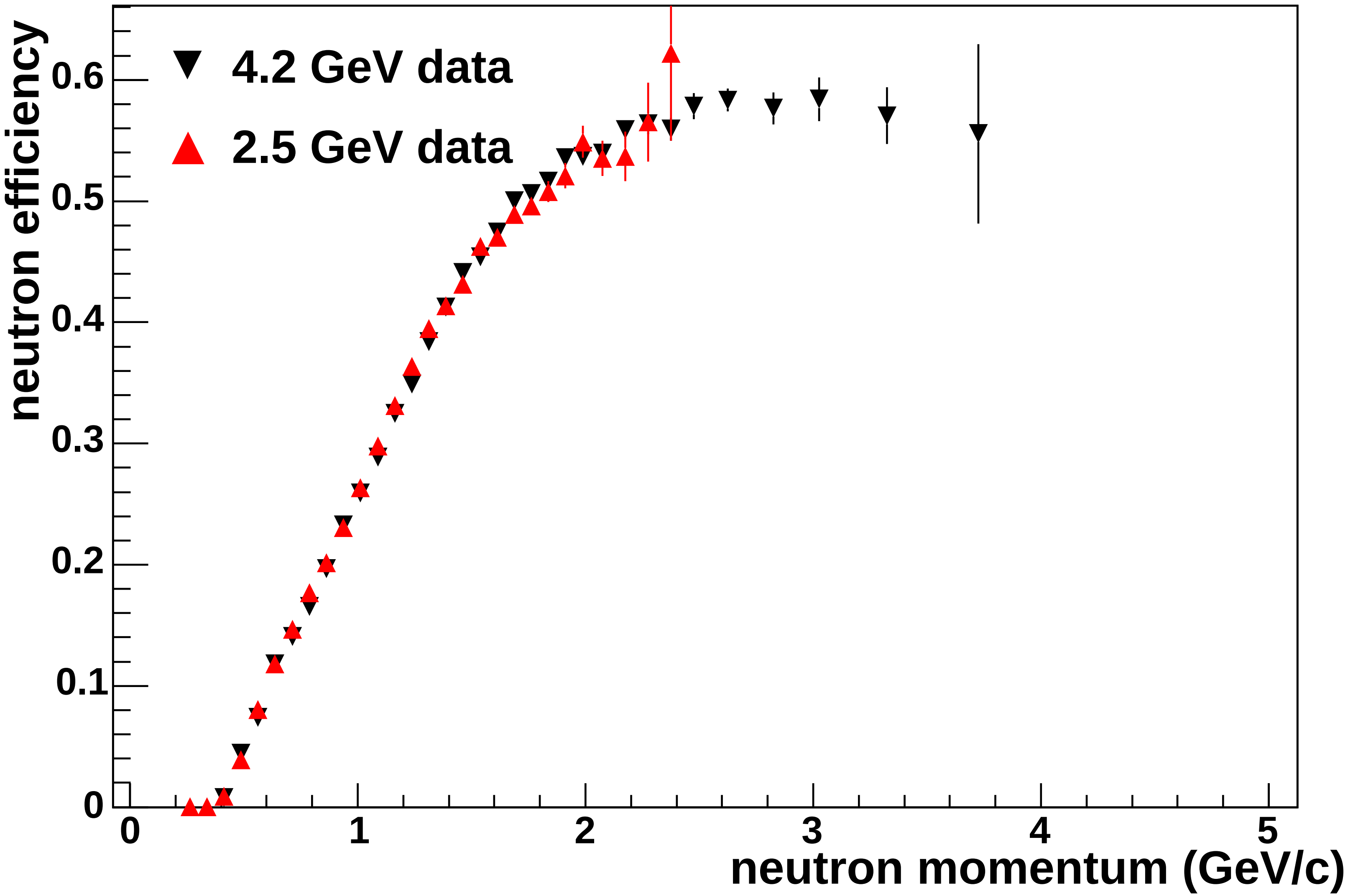
- Data Set:
  - Recorded $\approx$ 2.3 billion triggers
  - Q^2 range: 0.2 -5.0 $(GeV/c)^2$
  - Dual cell hydrogen/deuterium target
  - Hydrogen cell used as tagged neutron source ($ep \rightarrow e\pi^+n$) for calibration of neutron detection efficiency in EC,TOF and LAC

- Run Conditions:
  - E=4.2 GeV, I_{torus} = 3375A
  - E=2.5 GeV, I_{torus} = 2250A
  - E=2.5 GeV, I_{torus} = -2250A

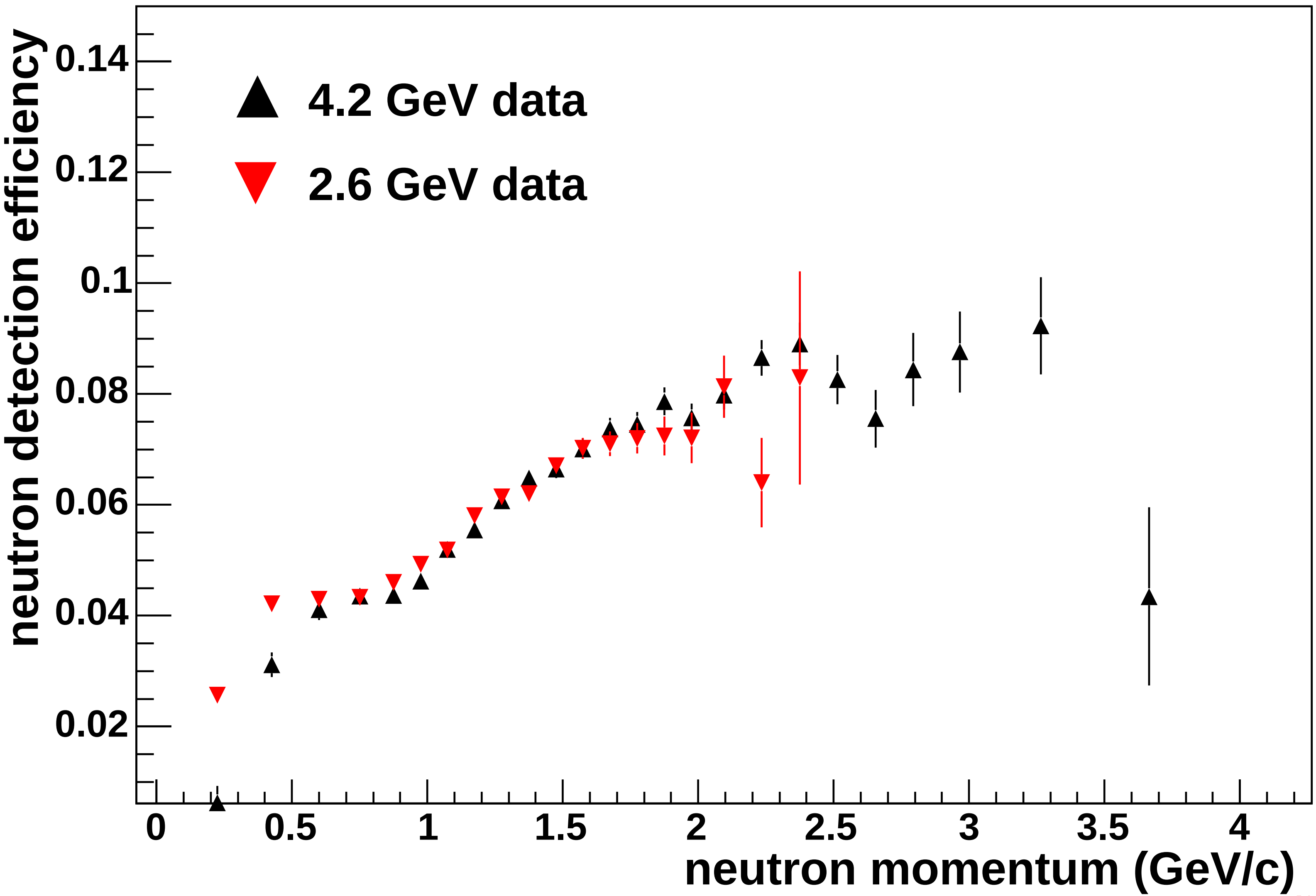
Dual Cell Cryotarget



Neutron Detection Efficiency Measurement (EC)

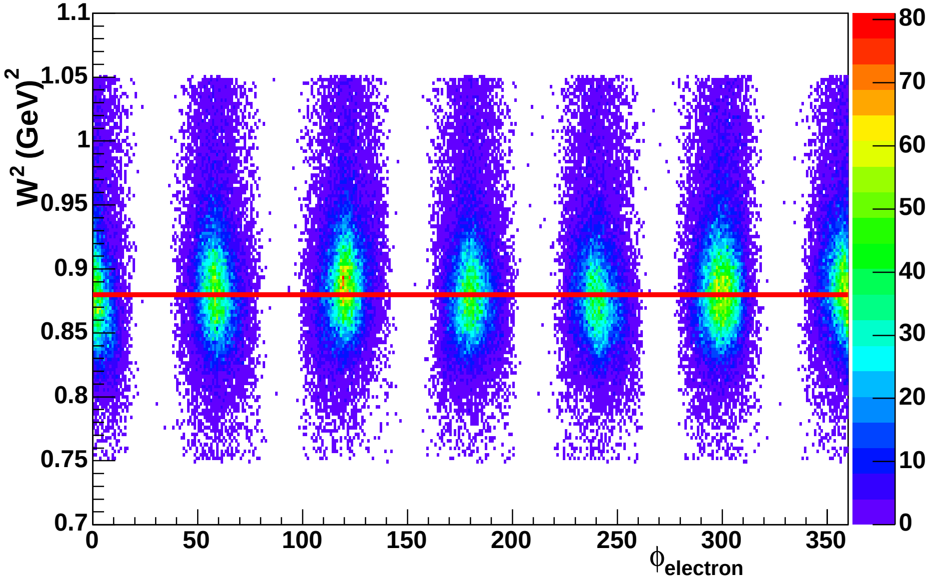


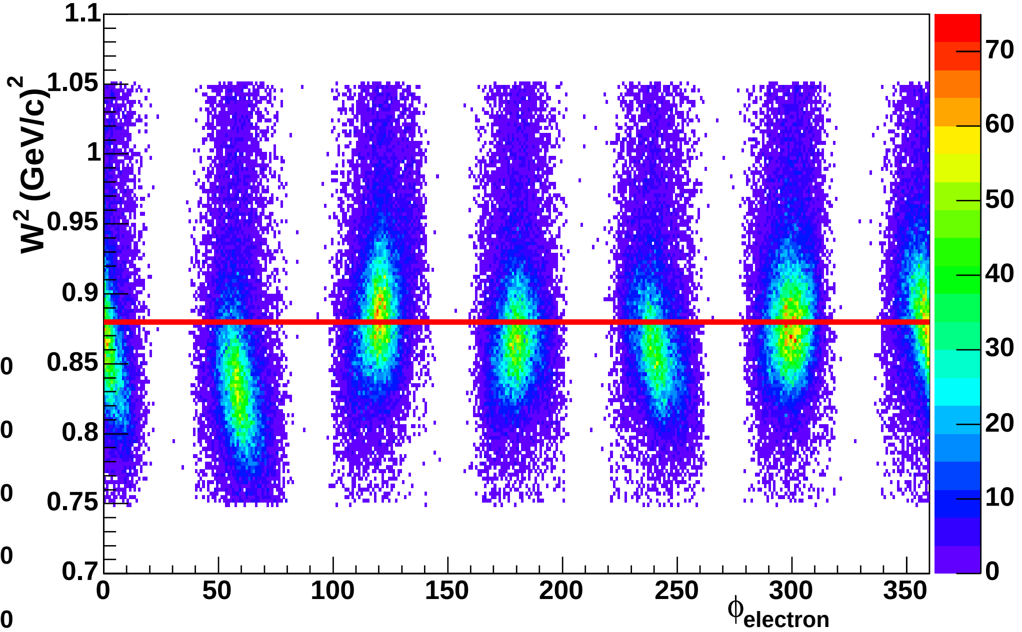
Neutron Detection Efficiency Measurement (SC)



Momentum corrections

W^2 vs ϕ in ep elastic scattering, before momentum corrections



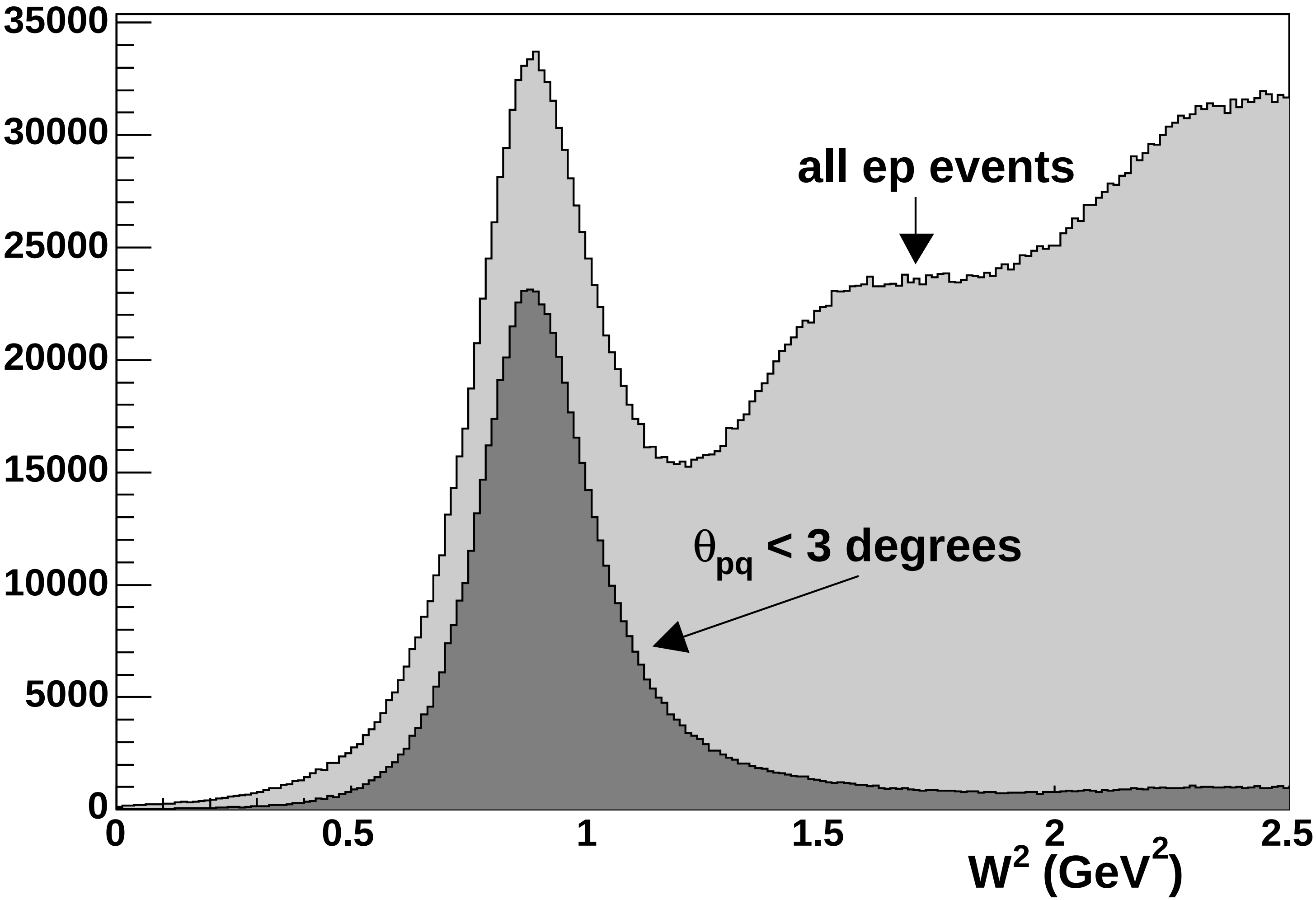


W^2 vs ϕ in ep elastic scattering, after momentum corrections

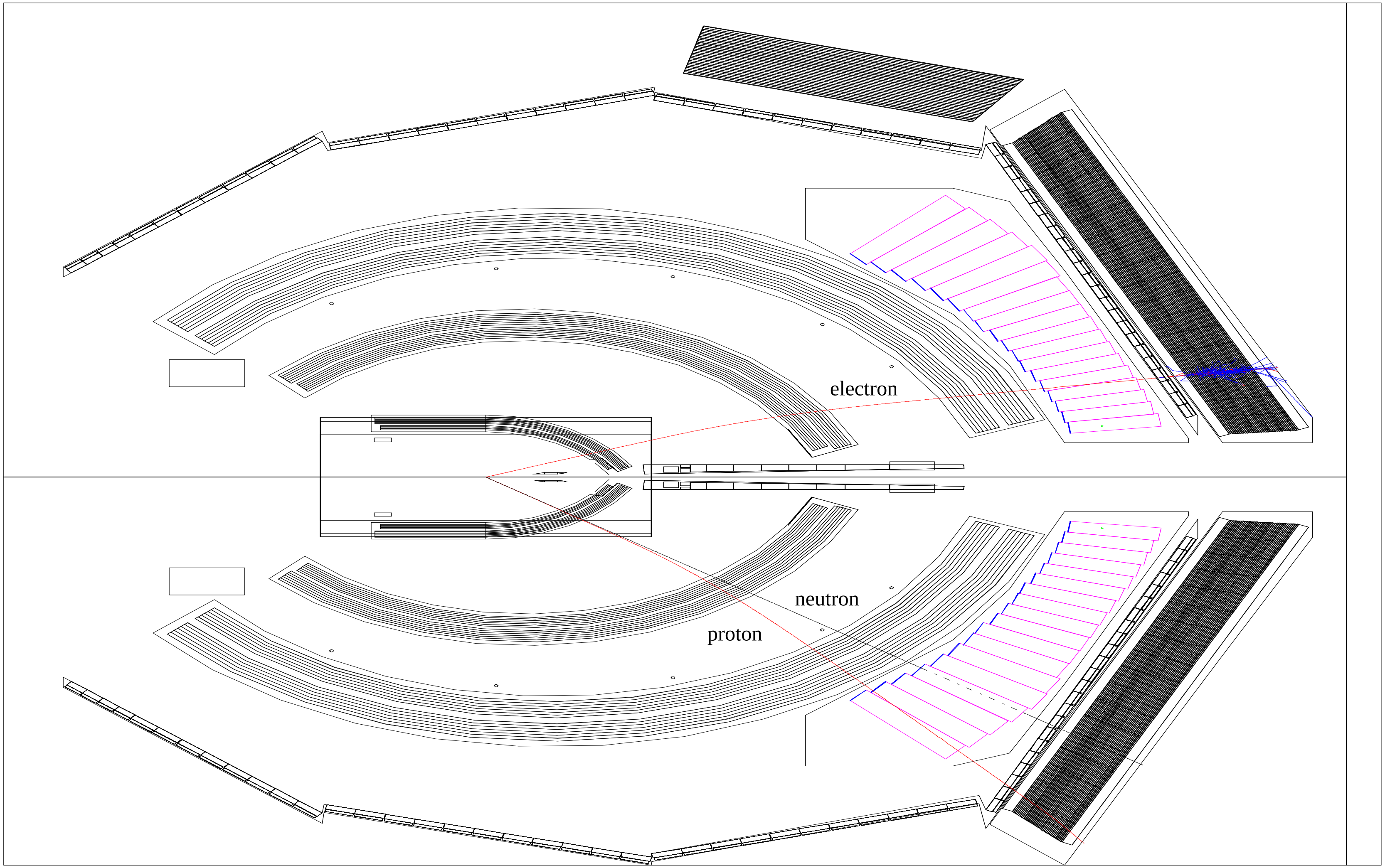
G_M^n measurement

- The same electron selection criteria as neutron detection efficiency measurement are used, except the vertex cut is shifted to $-12.9 < Z < -7.1cm$
- Quasi-elastic events are identified using a combination of cuts on W^2 and θ_{pq} (the angle between the virtual photon and the scattered nucleon).
- Efficiency corrections are applied on an event-by-event basis.
- A fiducial cut is applied to match the acceptance for e-n and e-p scattering

Quasi-elastic event selection



Solid-angle matching

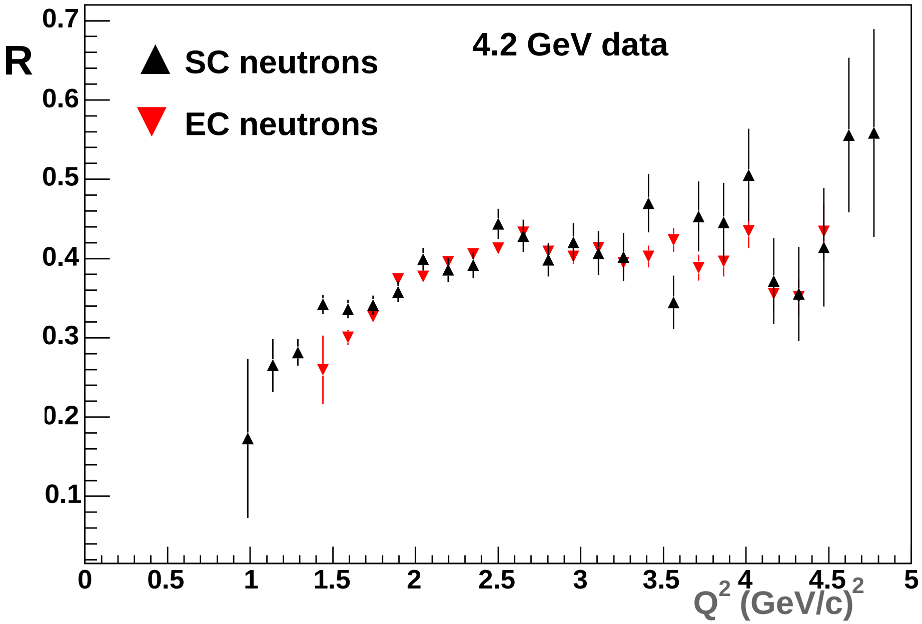


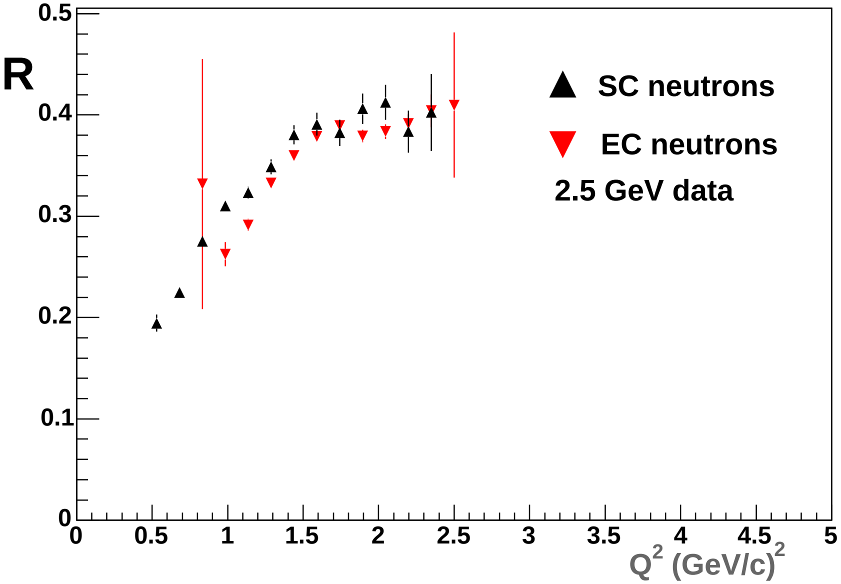
G_M^n *measurement*

- Simulation results are used to correct the ratio for losses near the edge of the acceptance caused by the Fermi-motion of the initial state nucleons.
- Radiative corrections are applied to the en/ep ratio.
- Theoretical corrections are applied to correct for deuteron wave function effects $a(Q^2)$.
- To extract G_M^n from the corrected ratio, the Kelly parametrization of the proton form factors is used along with the Galster fit for G_E^n

Fermi-Motion losses

The $\frac{\sigma_n}{\sigma_p}$ ratio at 4.2 GeV.

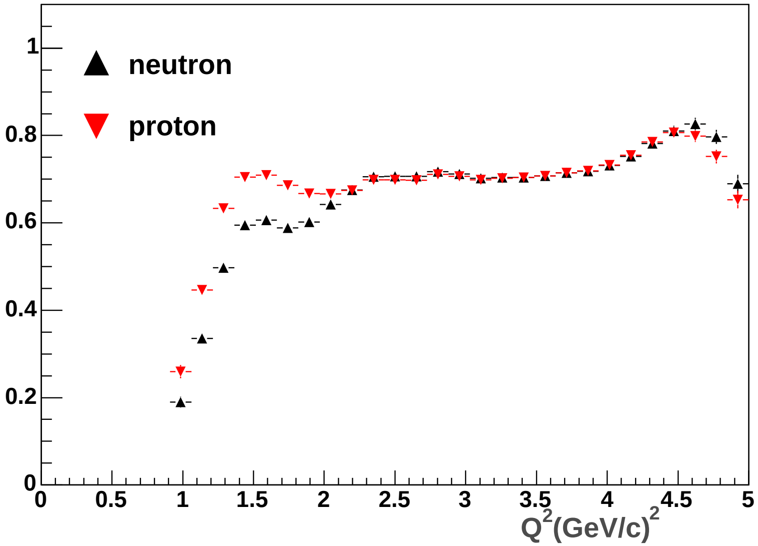




The $\frac{\sigma_n}{\sigma_p}$ ratio at 2.5 GeV.

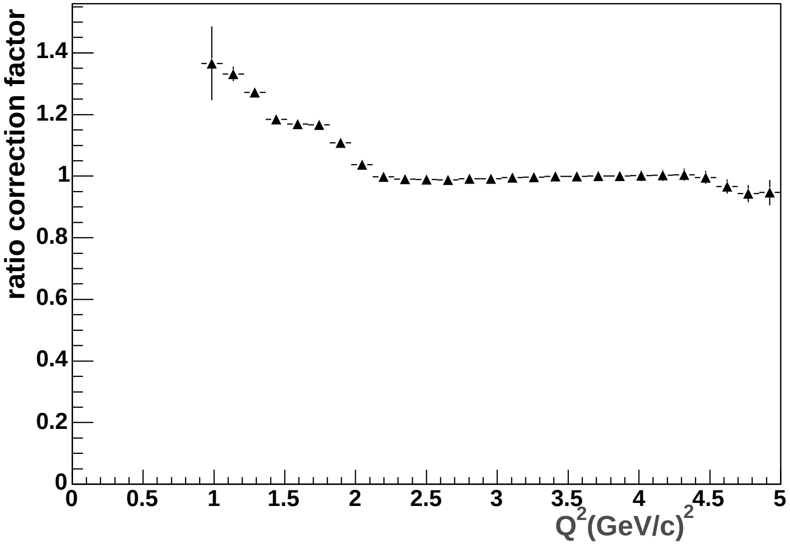
G_M^n

Fermi-motion Loss Corrections



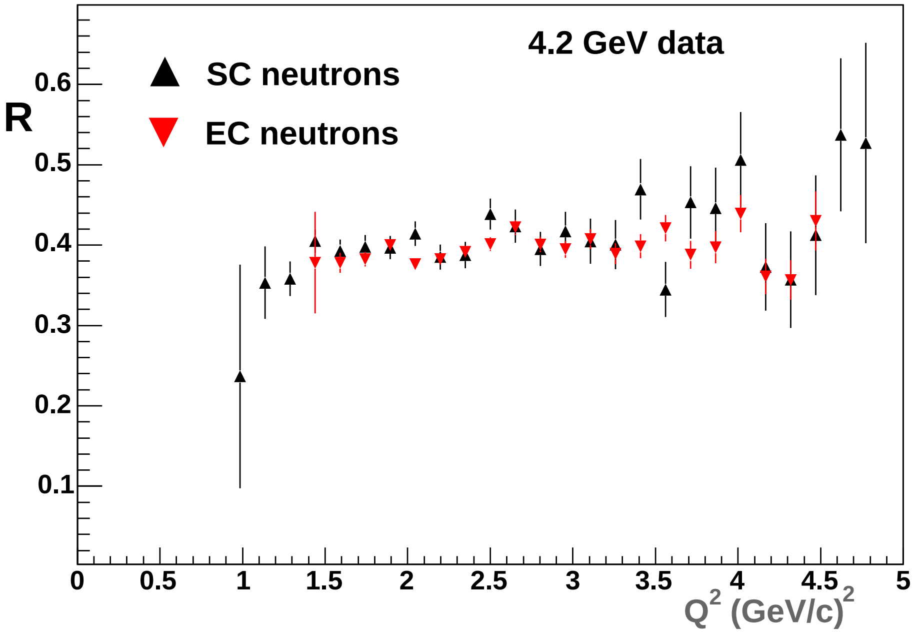
The fraction of nucleons scattered at the indicated Q^2 which scattered into the SC acceptance and satisfied the θ_{pq} cuts, as determined by the simulation.

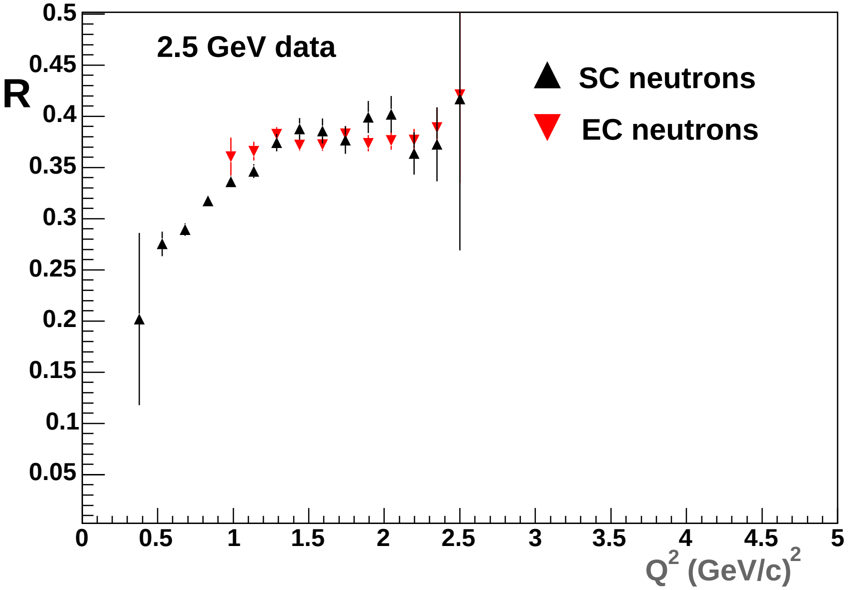
The correction factor to the e-n/e-p ratio for Fermi loss in the SC, for the 4.2 GeV data.



Fermi-Motion losses

The $\frac{\sigma_n}{\sigma_p}$ ratio at 4.2 GeV, after correction.

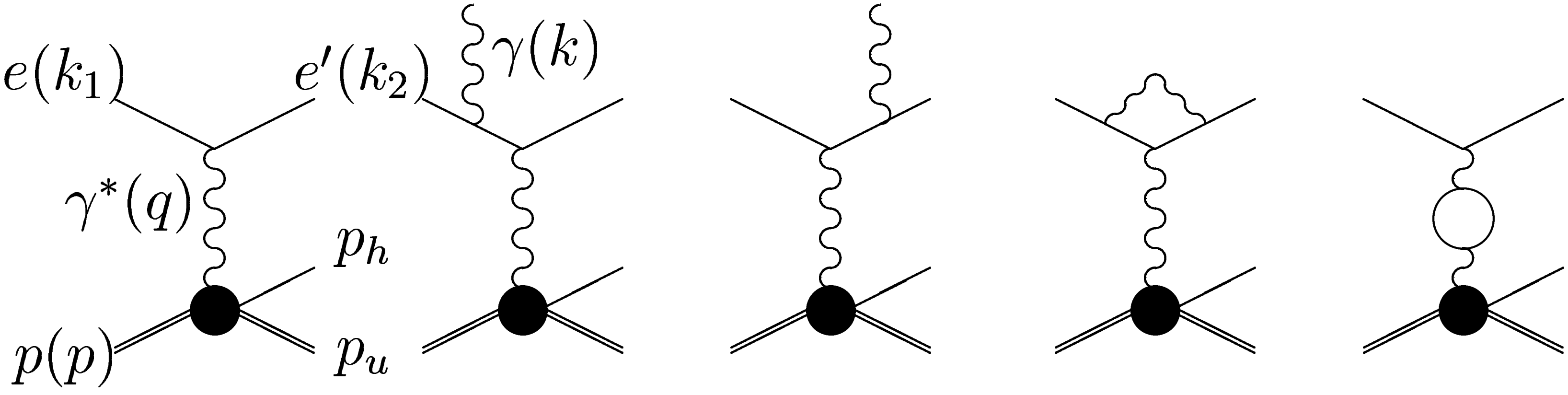




The $\frac{\sigma_n}{\sigma_p}$ ratio at 2.5 GeV, after correction.

Radiative Corrections

- A modification of the radiative correction code EXCLURAD (Afanasev, et al), originally developed for pion electronprodution is used.
- Diagrams included:



a) b) c) d) e)

Radiative Corrections

- The reactions of interest are d(e,e’p)n and d(e,e’n)p
- EXCLURAD was modified by changing the masses of the target, detected, and undetected scattered hadrons to values appropriate for quasi-elastic ed scattering.
- The relativistic impulse approximation DEEP code of Van Orden, et al, was installed to generate deuteron response funtions.
- Option to have detected hadron as either proton or neutron.
- Inputs to the code are $Q^2, W^2, \cos\theta_{pq}, \phi_{pq}$.
- Output: The ratio of the radiative cross-section to the PWIA result.

Radiative Corrections

Radiative corrections to e-n/e-p ratio for 2.5 GeV data.

Q^2	$1+\delta_n$	$1+\delta_p$	f_{rad}
1	0.7956	0.7957	0.9999
2.35	0.8273	0.8273	1.0000
2.45	0.8421	0.8424	0.9996
2.55	0.8568	0.8583	0.9983

Nuclear Corrections, $Q^2 > 1$ (GeV/c)^2

- For $Q^2 > 1$ (GeV/c)^2, the Jeschonnek model is used to determine the correction to the ratio due to nuclear effects.
- The model makes a non-relativistic reduction of the nucleon current operator. The AV18 deuteron wave function is used.
- Final-state interactions are implemented using a Glauber approach.
- The ratio $\sigma_{Full}/\sigma_{PWIA}$ is calculated for $e-p$ and $e-n$ scattering. The ratio of these two gives the correction applied to the measured $e-n/e-p$ ratio. The results are consistent with unity.

Nuclear Corrections, $Q^2 > 1$ *(GeV/c)*^{2}

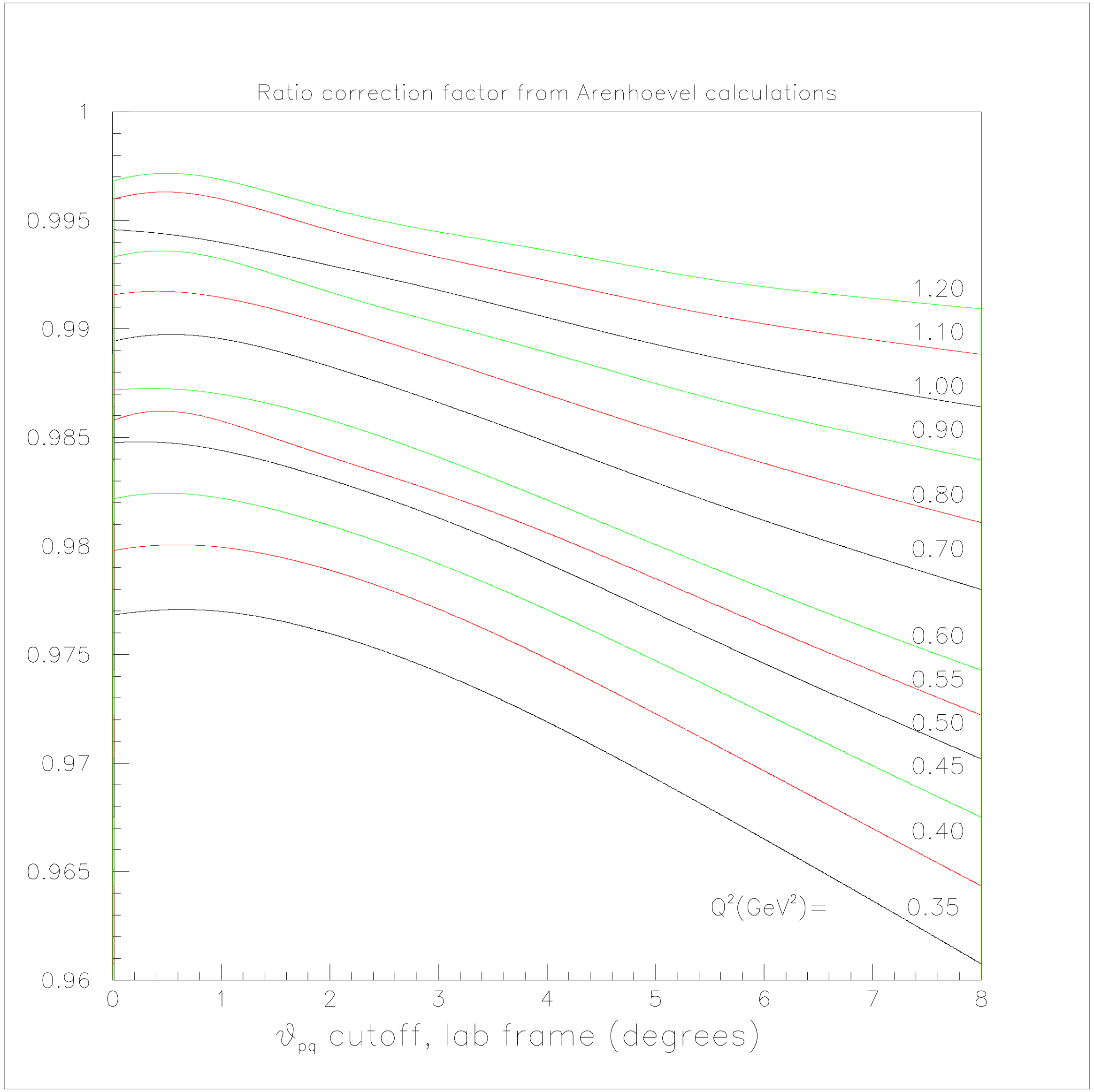
Nuclear corrections to the e-n/e-p ratio from the Jeschonnek model.

Q^2	$f_{nuclear}$
1	0.999796
2	0.999714
3	0.999655
4	0.999624
5	0.999619

Nuclear Corrections, $Q^2 < 1$ (GeV/c)^2

- For $Q^2 < 1$ (GeV/c)^2, the Arenhövel model is used to determine the correction to the ratio due to nuclear effects.
- Deuteron electro-distintegration is calculated in a non-relativistic Plane-Wave Born-Approximation, using the Bonn potential.
- Model includes relativistic corrections, meson-exchange currents, isobar configurations, final-state interactions.
- The ratio $\sigma_{Full}/\sigma_{PWIA}$ is calculated for $e-p$ and $e-n$ scattering. The ratio of these two gives the correction applied to the measured $e-n/e-p$ ratio.

Nuclear Corrections, $Q^2 < 1$ (GeV/c)^2



Nuclear Corrections, $Q^2 < 1$ *(GeV/c)*^{2}

Nuclear corrections to the e-n/e-p ratio from the Arenhövel model.

Q^2	$f_{nuclear}$
0.5	0.977
0.75	0.983
1.0	0.989
1.2	0.993

G_M^n extraction from Ratio

The corrected n/p ratio:

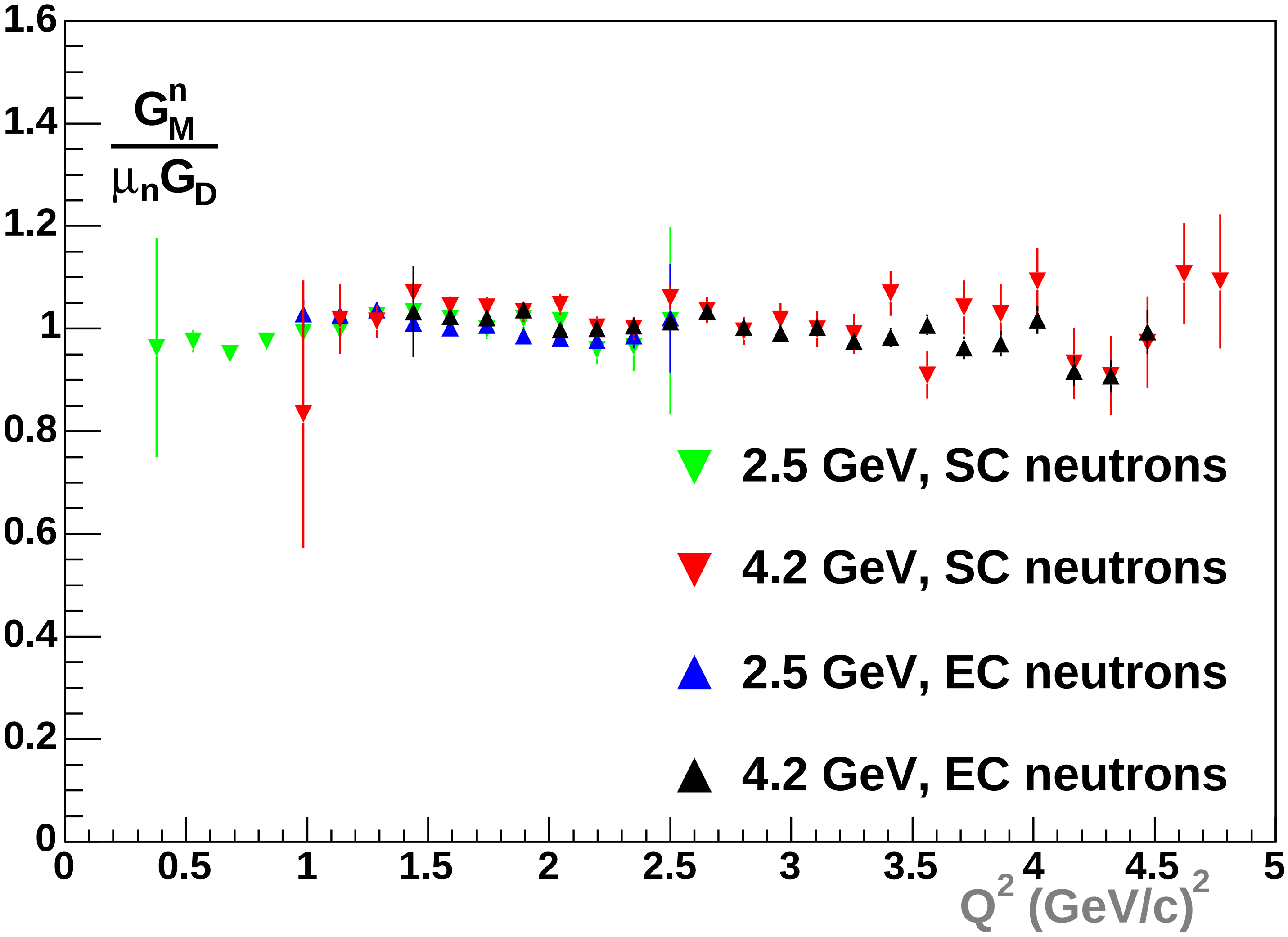
$$R_{corrected}(Q^2) = f_{nuclear}(Q^2) f_{radiative}(Q^2) f_{fermi}(Q^2) R_{observed}(Q^2)$$

is related to G_M^n through:

$$R_{corrected} = \frac{\sigma^n_{mott}\left(G^2_{E,n} + \frac{\tau_n}{\epsilon_n} G^2_{M,n}\right)\left(\frac{1}{1+\tau_n}\right)}{\sigma^p_{mott}\left(G^2_{E,p} + \frac{\tau_p}{\epsilon_p} G^2_{M,p}\right)\left(\frac{1}{1+\tau_p}\right)}$$

$$G_M^n = \sqrt{\left[R_{corrected}\left(\frac{\sigma^p_{mott}}{\sigma^n_{mott}}\right)\left(\frac{1+\tau_n}{1+\tau_p}\right)\left(G^2_{E,p} + \frac{\tau_p}{\epsilon_p} G^2_{M,p}\right) - G^2_{E,n}\right]\frac{\epsilon_n}{\tau_n}}$$

G_M^n *results*


$\frac{G_M^n}{\mu_n G_D}$
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
$Q^2\ (\mathrm{GeV}/c)^2$
▼ 2.5 GeV, SC neutrons
▼ 4.2 GeV, SC neutrons
▲ 2.5 GeV, EC neutrons
▲ 4.2 GeV, EC neutrons

Systematic Errors

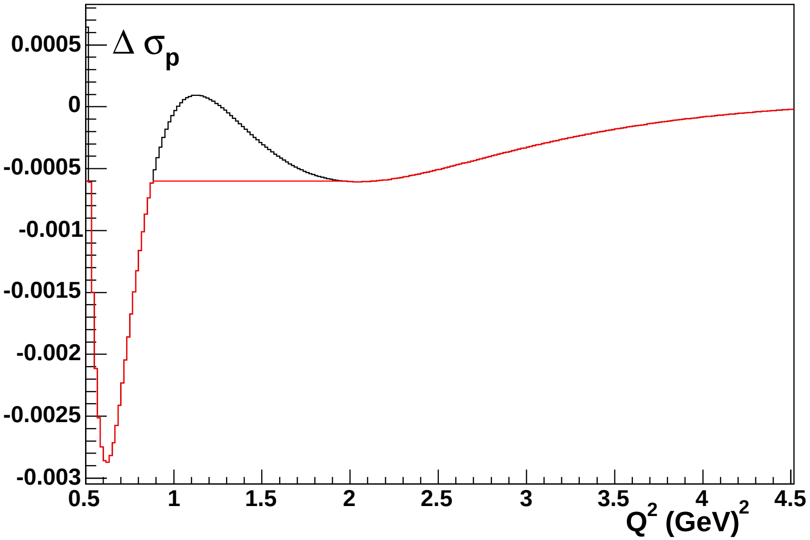
For the purpose of evaluating systematic errors, we make the approximation:

$$G_M^n = \sqrt{(\sigma_p R_c - G_{E,n}^2)\frac{\epsilon}{\tau}}$$

The standard propagation of errors formula is applied:

$$(\delta G_M^n)^2 = (\frac{\partial G_M^n}{\partial \sigma_p})^2(\delta\sigma_p)^2 + (\frac{\partial G_M^n}{\partial G_E^n})^2(\delta G_E^n)^2 + \sum_i(\frac{\partial G_M^n}{\partial f_i})^2(\delta f_i)^2.$$

Systematic Errors

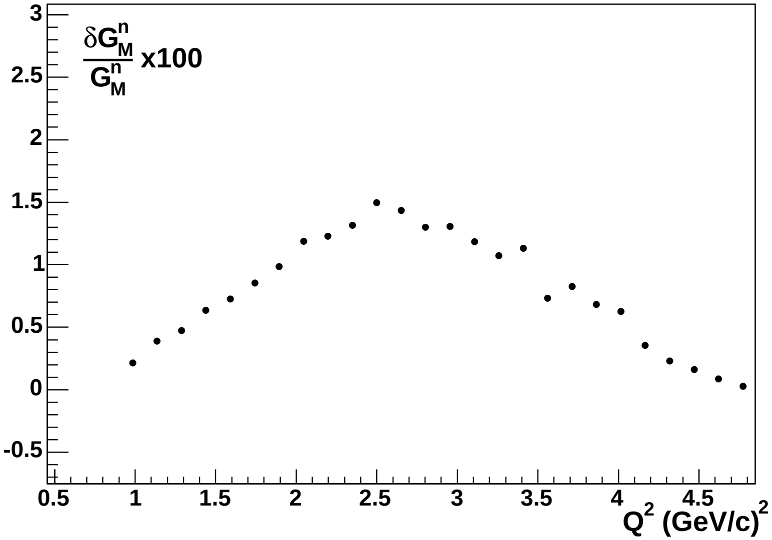


The difference between the Kelly and Bosted parametrizations of σ_p. This is used along with:

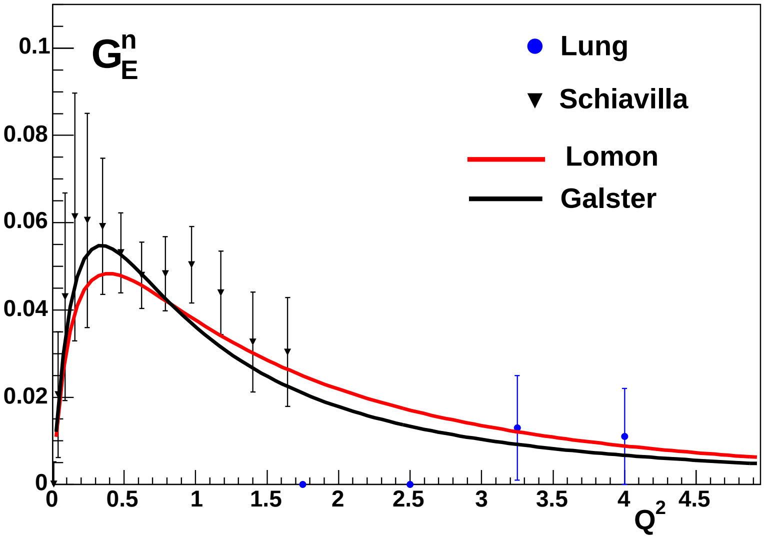
$$\frac{\partial G_M^n}{\partial \sigma_p} = \frac{1}{2}\frac{1}{G_M^n} R_c \frac{\epsilon}{\tau}$$

to evaluate the estimated systematic error.

The estimated systematic error on G_M^n due to uncertainties in the reduced proton cross-section, for the 4.2 GeV data.



Systematic Errors

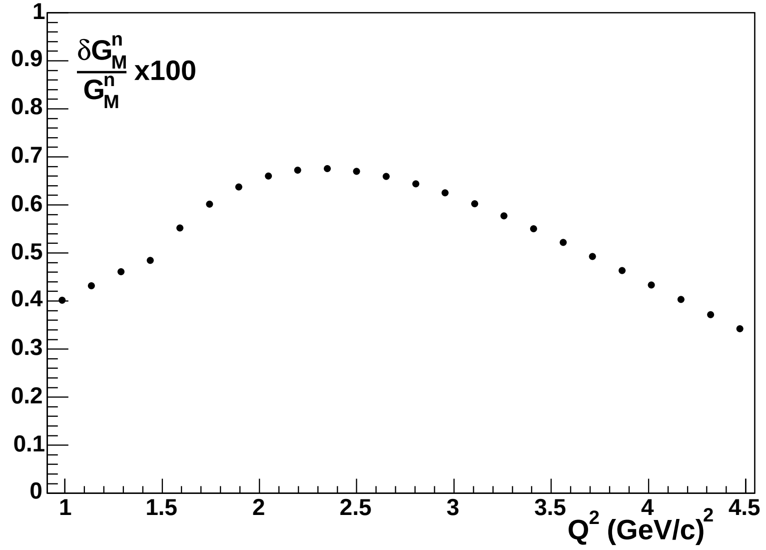


The difference between the Galster fit and Lomon parametrizations of G_E^n. This is used along with:

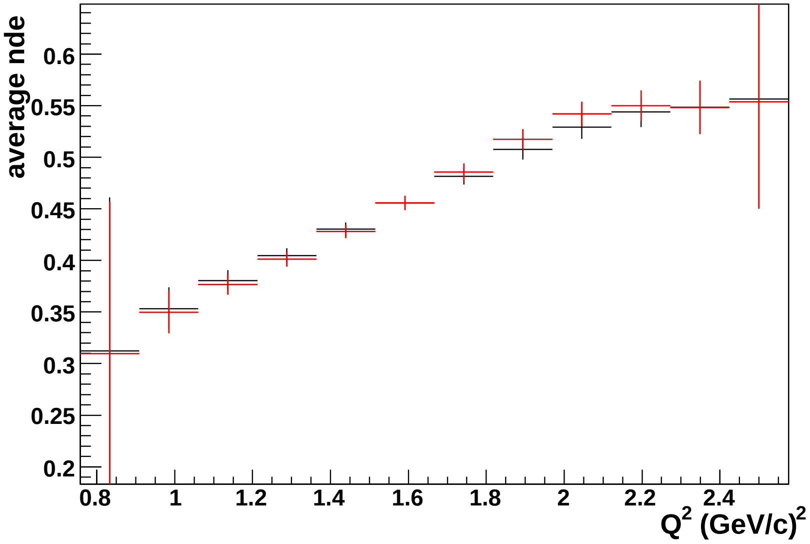
$$\frac{\partial G_M^n}{\partial G_E^n} = \frac{G_E^n}{G_M^n}\frac{\epsilon}{\tau}$$

to evaluate the estimated systematic error.

The estimated systematic error on G_M^n due to uncertainties in G_E^n, for the 4.2 GeV data.



Systematic Errors

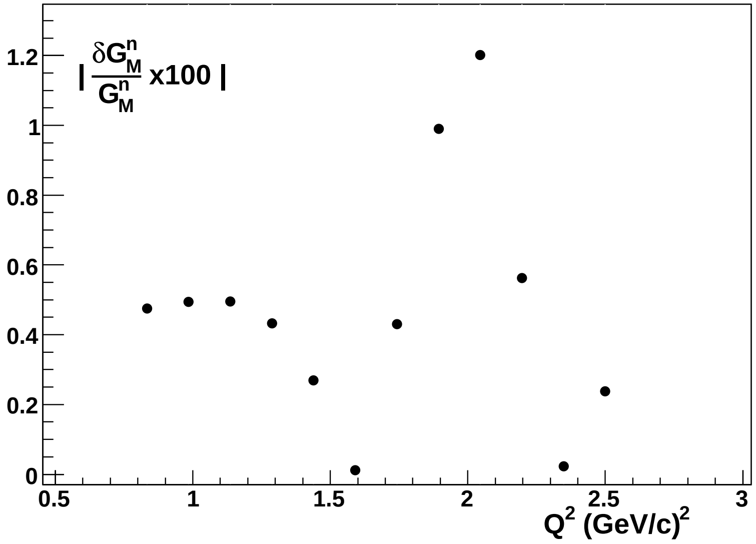


The standard fit to the EC neutron detection efficency, and the perturbed fit. The difference between the fits is used along with:

$$\left(\frac{\delta G_M^n}{G_M^n}\right)^2 = \left(\frac{\sigma_p \epsilon}{2\mu_n^2 G_D^2 \tau}\right)^2 (\delta R_c)^2$$

to evaluate the estimated systematic error.

The estimated systematic error on G_M^n due to uncertainties in the EC neutron detection efficiency parametrization, for the 2.5 GeV data.



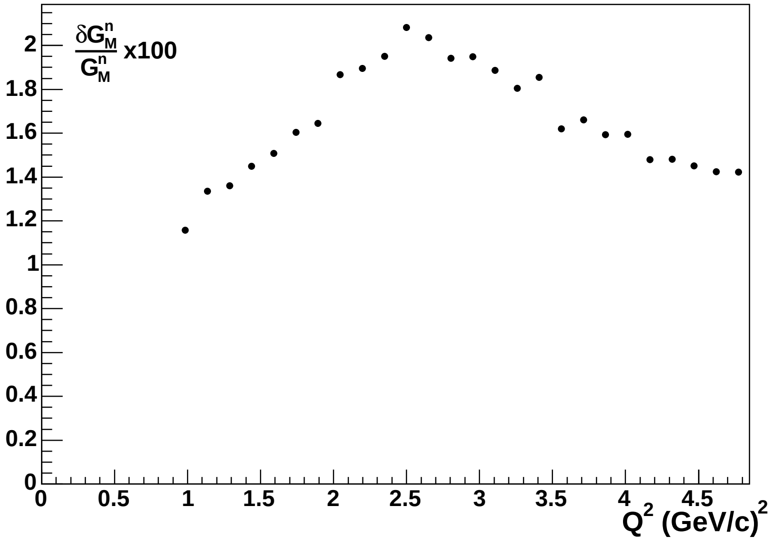
Systematic Errors

Other sources of systematic error considered were:

- Accidental background in neutron detection efficiency measurement
- Location of missing mass cut in neutron selection
- Location of ΔR cut in EC neutron selection
- Proton detection efficiency
- Sensitivity of Fermi-correction to deuteron momentum distribution
- Location of θ_{pq} cut
- Radiative/Nuclear corrections

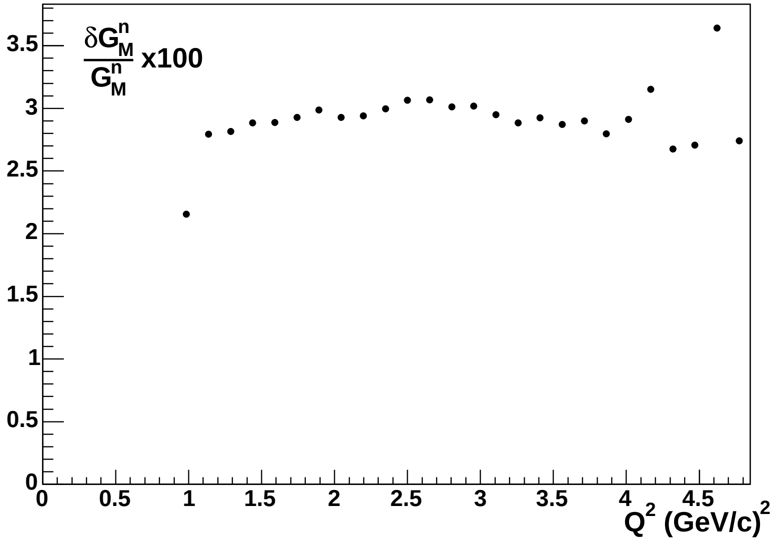
Each of these contributed at the sub-1% level.

Systematic Errors



The combined systematic error for the 4.2 GeV data, with EC neutron detection.

The combined systematic error for the 4.2 GeV data, with SC neutron detection.



Combined G_M^n and systematic error

The four separate G_M^n measurements were combined by minimizing:

$$\chi^2 = \sum_j \frac{(x_j - \overline{x})^2}{\sigma_j^2}$$

$$\overline{x} = \frac{\sum_j \frac{x_j}{\sigma_j^2}}{\sum_j \frac{1}{\sigma_j^2}}$$

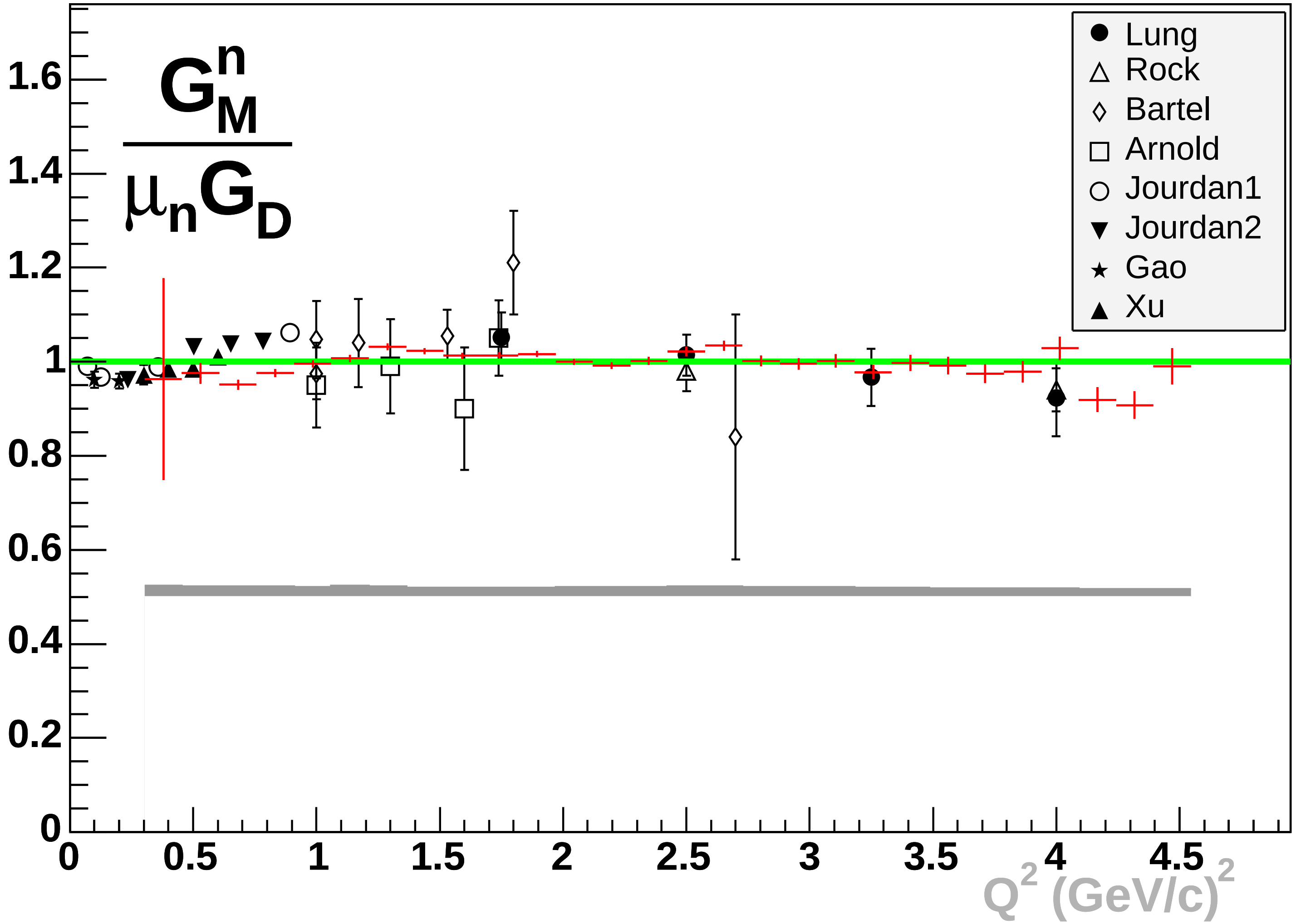
The statistical error on each point was found from:

$$\begin{aligned} \sigma_{\overline{x}}^2 &= \sum_j \left(\frac{\partial \overline{x}}{\partial x_j}\right)^2 \sigma_j^2 \\ &= \frac{1}{\sum_j \frac{1}{\sigma_j^2}} \end{aligned}$$

The systematic errors were combined using the same weighting as the G_M^n values.

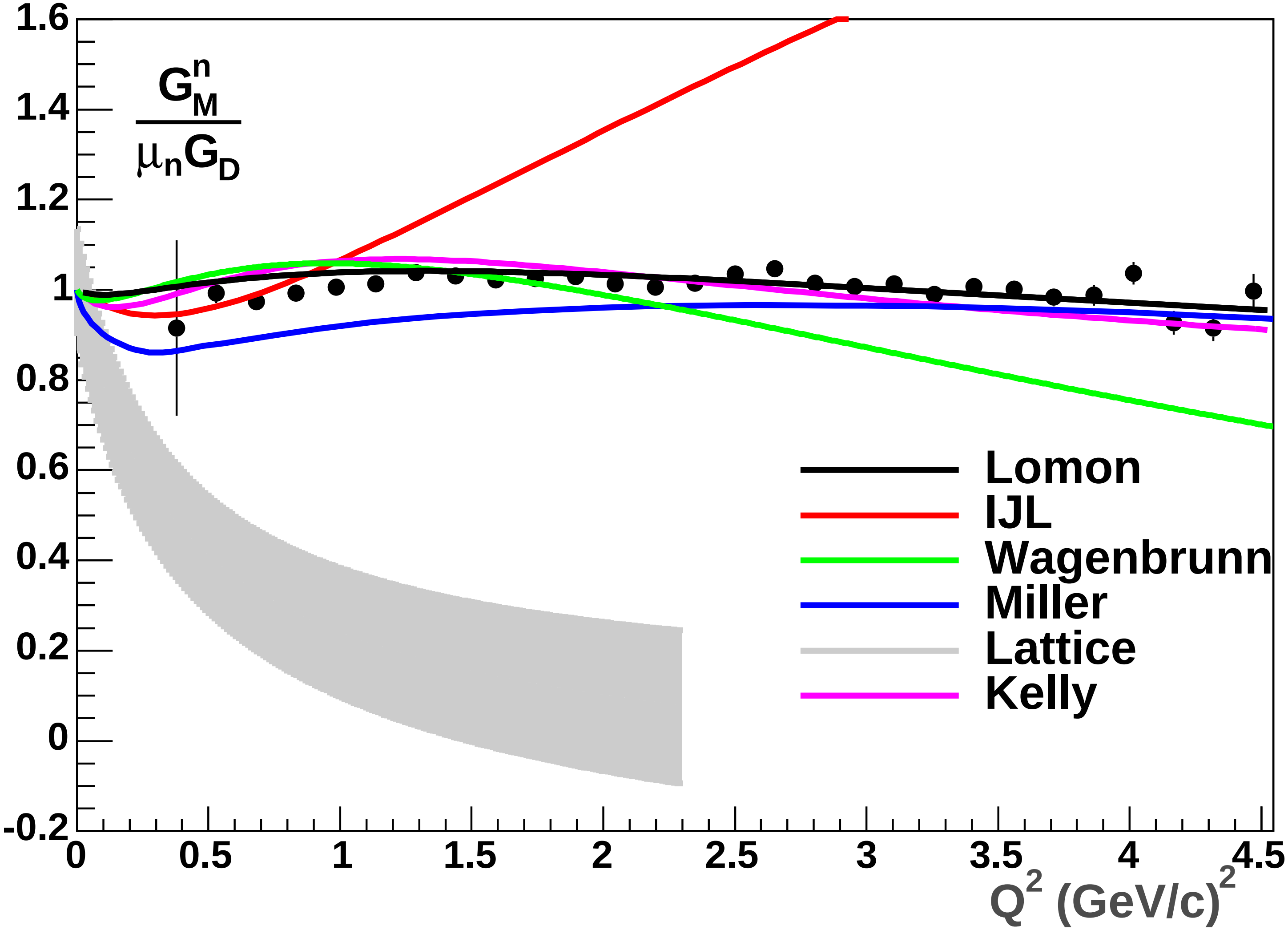
G_M^n results

Selected World Data



G_M^n

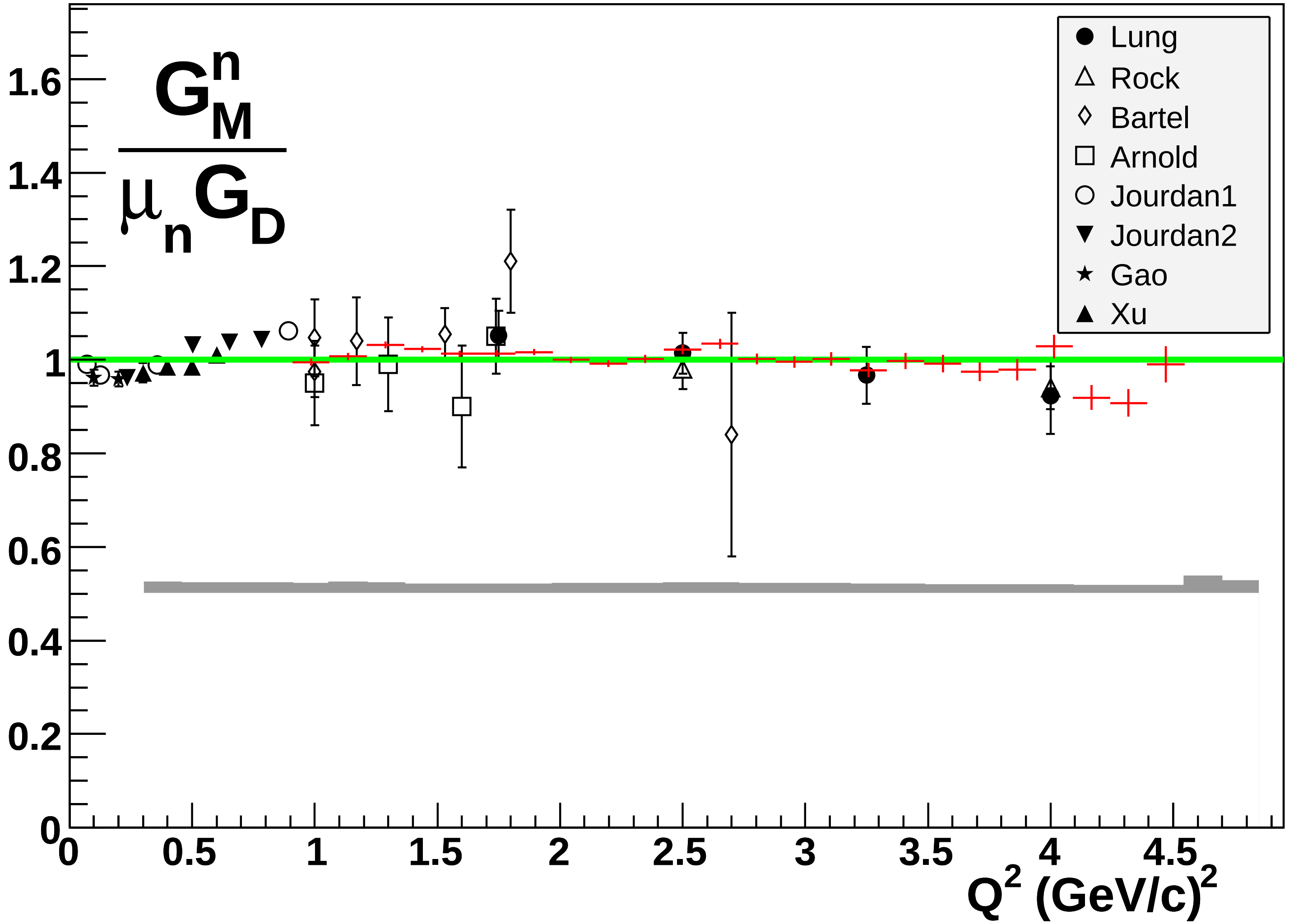
G_M^n results



$\frac{G_M^n}{\mu_n G_D}$
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Q^2 (GeV/c)^2
Lomon
IJL
Wagenbrunn
Miller
Lattice
Kelly

G_M^n results

Selected World Data



Conclusions

- The neutron magnetic form factor has been measured over a wide range of Q^2 at the CLAS detector
- The standard dipole parametrization was found to give a good representation of the data in the region $1.0 < Q^2 < 3.5$ (GeV/c)^2.
- The current measurement disagrees with other recent measurements in the region $Q^2 < 1$ (GeV/c)^2. Resolving this discrepancy provides motivation to complete the analysis of the e5 reversed-field data.
- The data may show G^n_M falling off faster than the dipole for $Q^2 > 3.5$ (GeV/c)^2. A second round of the e5 experiment, using a 6 GeV beam energy would allow the extension of the G^n_M measurement to $Q^2 \approx 7$ (GeV/c)^2. This would allow a resolution of this ambiguity at high Q^2, and allow us to extend the CLAS measurement into a region where no reliable data exisit.
- Theoretical models that are not tightly constrained by fits to previous data are unable to reproduce the results of this mesurement over the full Q^2 range.

Conclusions

- An analysis note is being reviewed by a committee from the CLAS Deep Processes working group, and a draft PRL note is being prepared. Once all the needed approvals are obtained, the $Q^2 > 1$ (GeV/c)^2 data will be submitted for publication.