E12-11-009 “C-GEn”

The Neutron Electric Form Factor at Q^2 up to 7 $(GeV/c)^2$ from the Reaction $^2H(e,e'n)^1H$ via Recoil Polarimetry

Spokespeople

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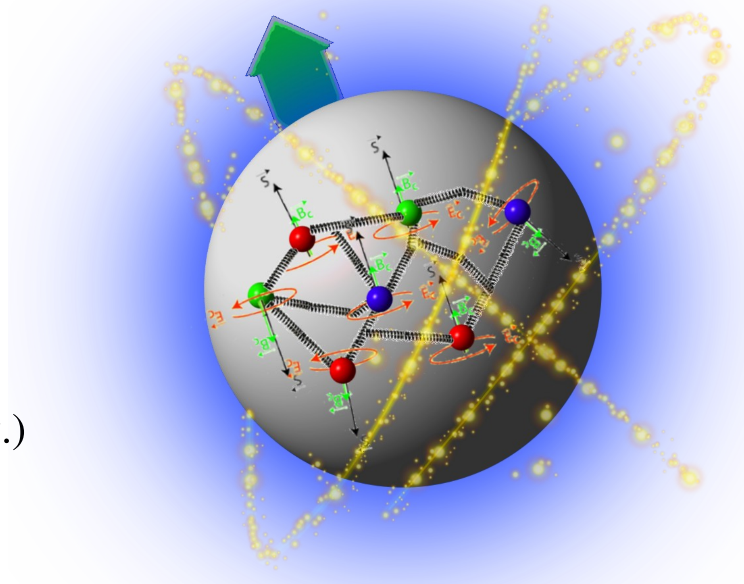

Special thanks: Will Tireman (N. Michigan Univ.)

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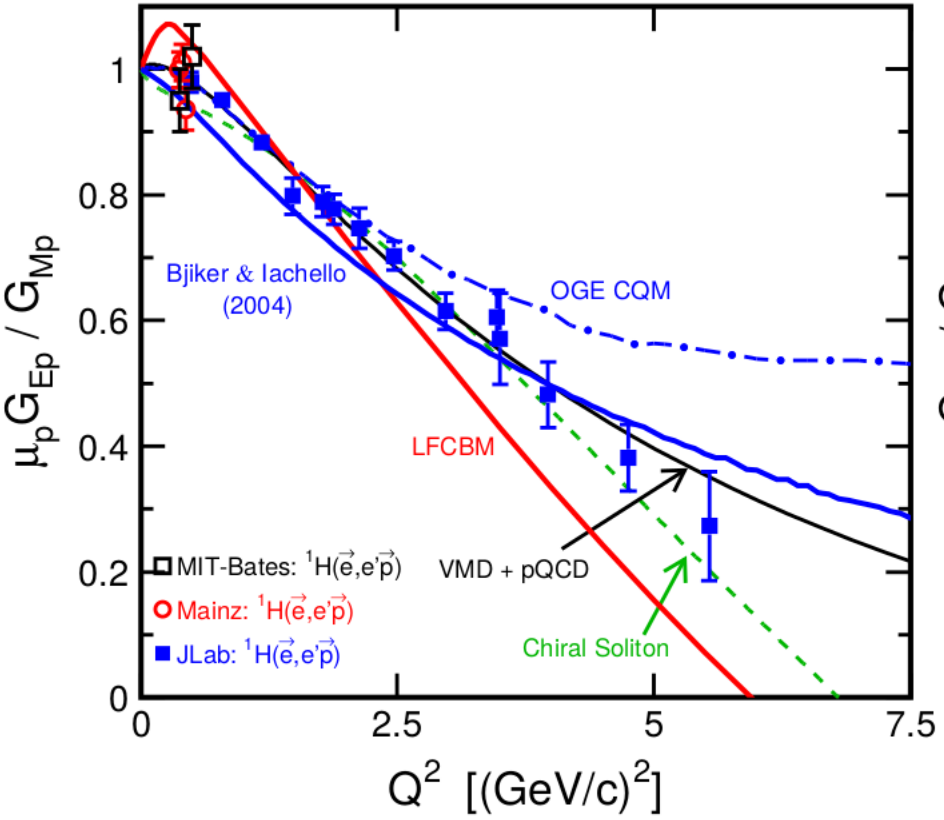
GEn: What can we learn?

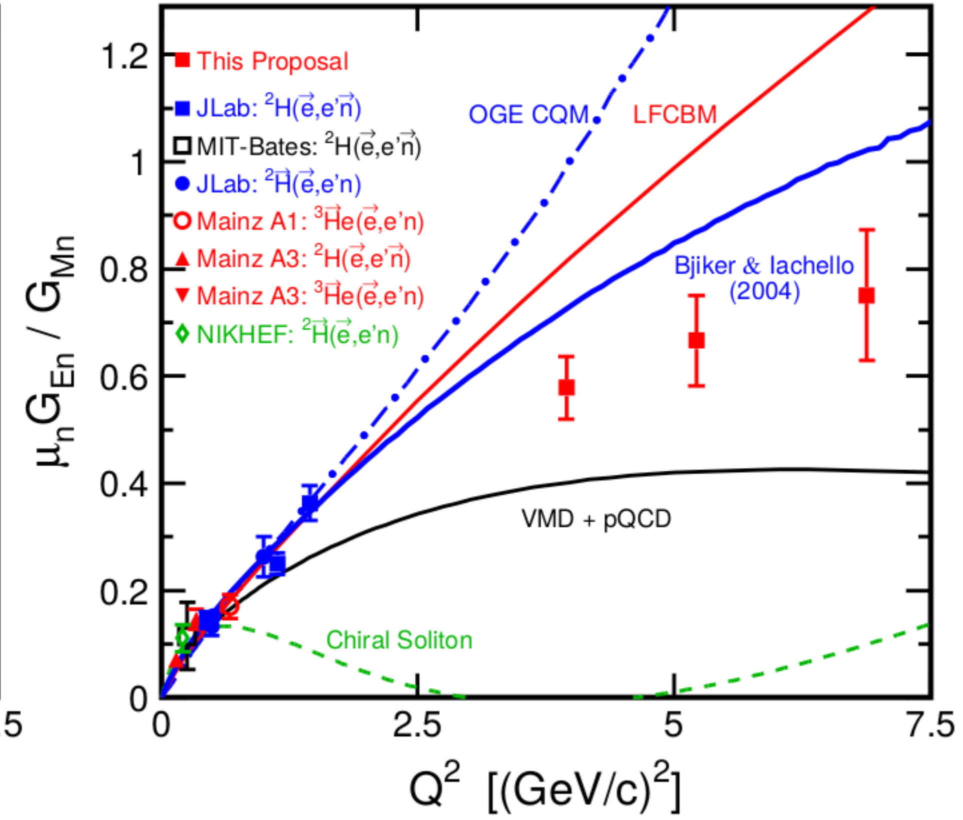
- Measurement of neutron form factors lags that of the proton
  → no free neutron target, lower cross sections
- Measuring GEn at high Q^2 provides insight into:
  - Form Factors in domain with small pion cloud contributions
    - Many available calculations do not include pion cloud contributions
  - Flavor decomposition of *u, d* quark contributions (negl strange quarks) [Cates (2011); Qattan & Arrington et al. (2012)]
  - Sensitive to *u, d* quark distributions in nuclear core
  - Model-independent extraction of neutron infinite-momentum frame transverse charge density [Miller (2007); Venkat et al. (2010)]
  - Test of QCD-based calculations
    - Lattice QCD: isovector form factor (GEp-GEn)
      - IVFF cancels disconnected diagrams that are hard to compute
    - Dyson Schwinger Equation calculations

Predictions for GEn

Proton



Neutron



Predictions for GEn

Proton **Neutron**

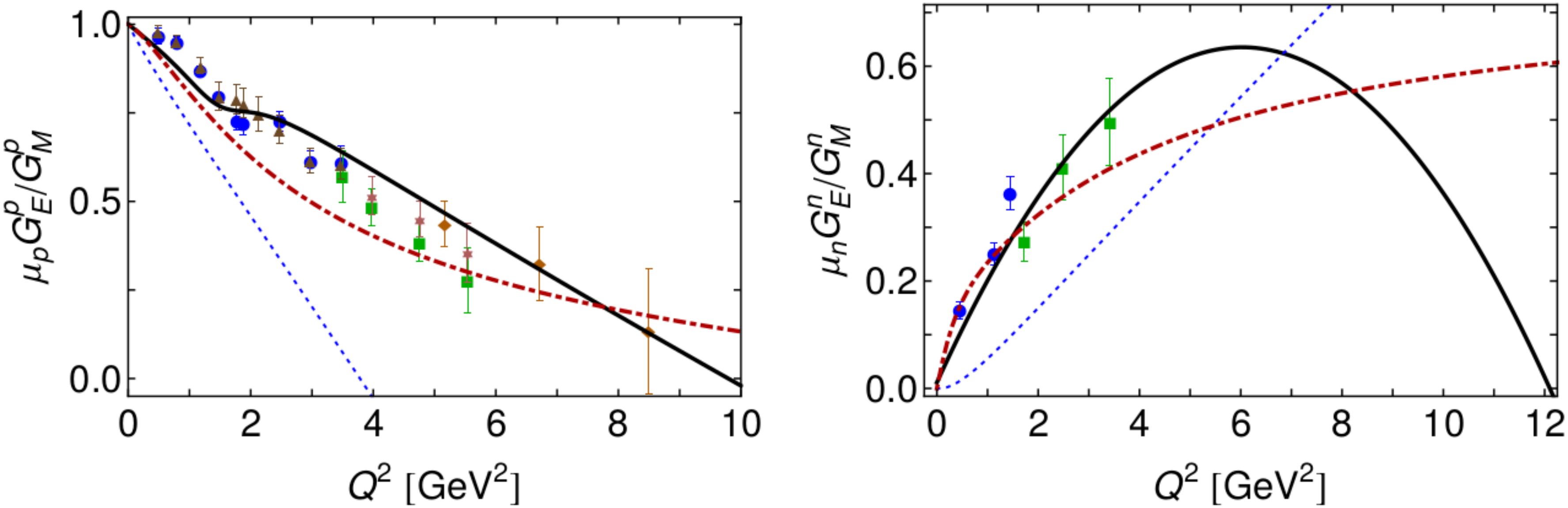
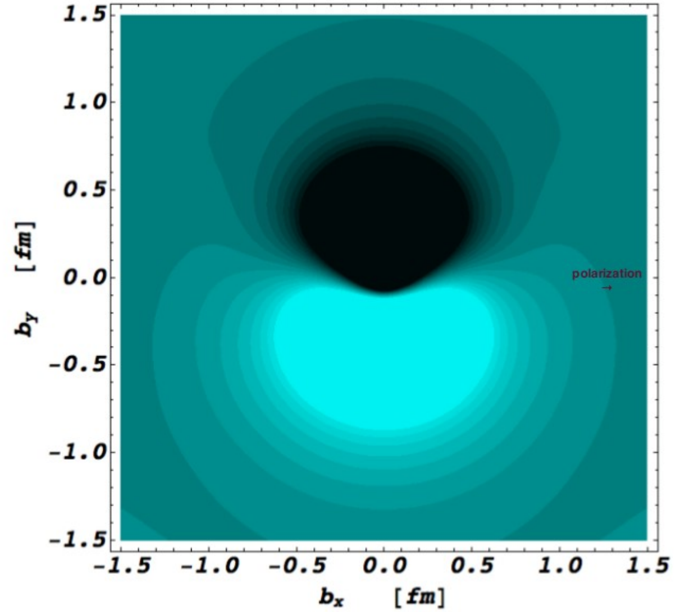


Fig. 3 *Left panel*: normalised ratio of proton electric and magnetic form factors. Curves: *solid, black* – result obtained herein, using our QCD-kindred framework; *Dashed, blue* – CI result [18]; and *dot-dashed, red* – ratio inferred from 2004 parametrisation of experimental data [65]. Data: blue circles [68]; green squares [69]; brown triangles [70]; purple asterisk [71]; and orange diamonds [72]. *Right panel*: normalised ratio of neutron electric and magnetic form factors. Curves: same as in left panel. Data: blue circles [73]; and green squares [74].

Segovia, Cloet, Roberts, Schmidt: arXiv:1408.2919 (2014)

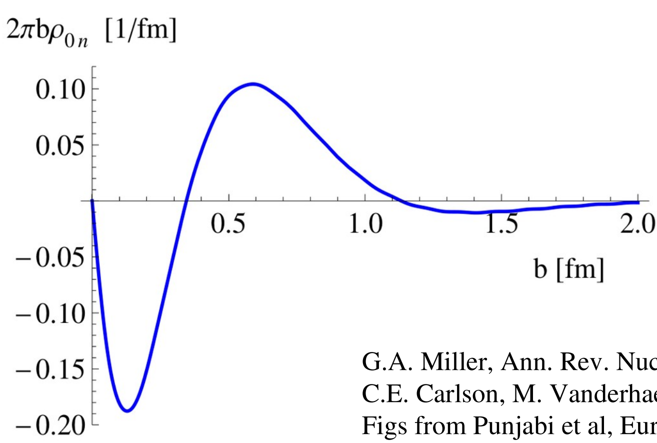
Transverse Charge Density

- Transverse charge density of Neutron
  - positive charge density in 'middle' sandwiched by negative densities

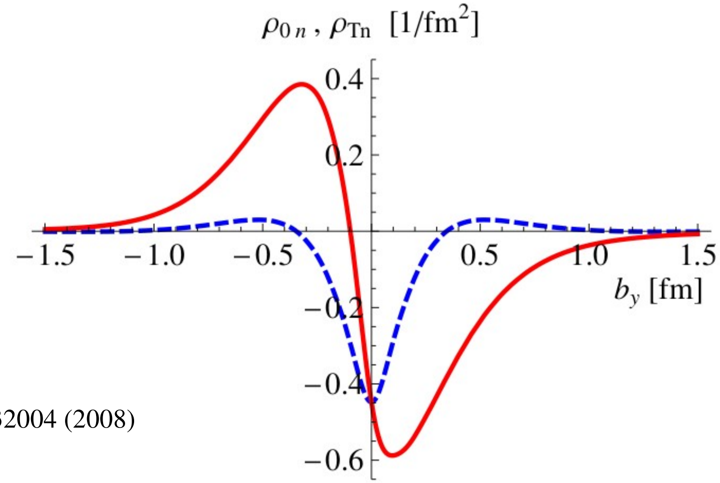


$$\rho(b)=\int_0^\infty \frac{dQ\,Q}{2\pi} J_0(Qb)\frac{G_E(Q^2)+\tau G_M(Q^2)}{1+\tau}$$

Unpolarized Charge Density



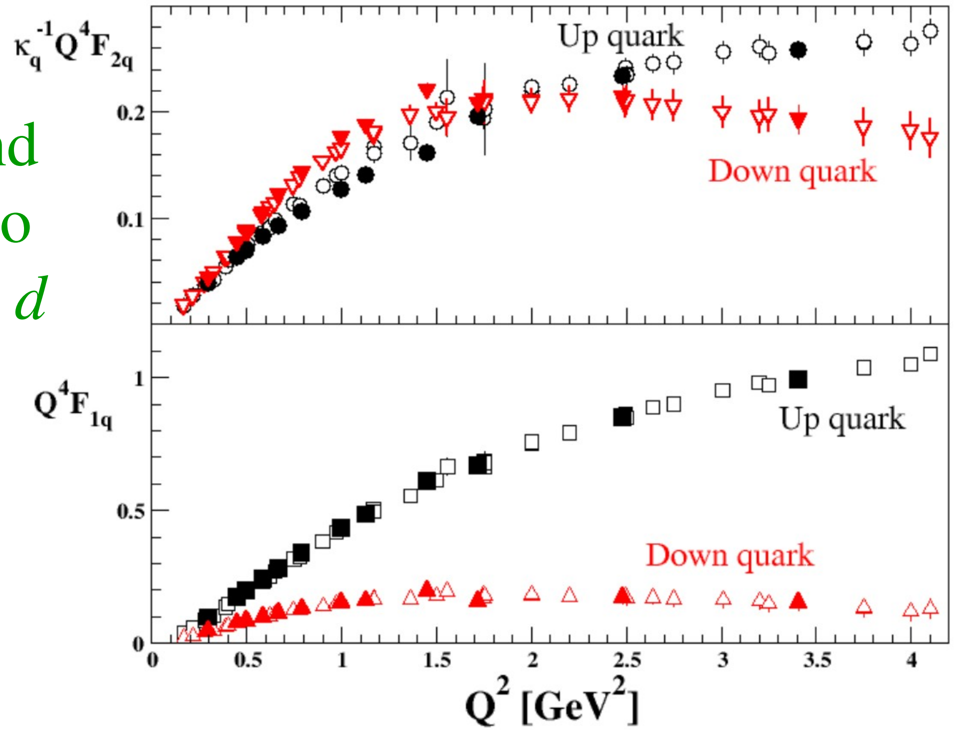
Polarized Charge Density



G.A. Miller, Ann. Rev. Nucl. Part. Sci. 60, 1 (2010)
C.E. Carlson, M. Vanderhaeghen, Phys. Rev. Lett. 100, 032004 (2008)
Figs from Punjabi et al, Eur.Phys.J. A51 (2015) 79

Flavor Decomposition

- Flavor decomposition
  - assume charge symmetry and combine FF data from *n, p* to extract information about *u, d* quark contributions
  - Precision data required to constrain input parametrizations of FFs
- Reduction of *d* vs *u* related to diquark correlations in *q(qq)* DSE approach

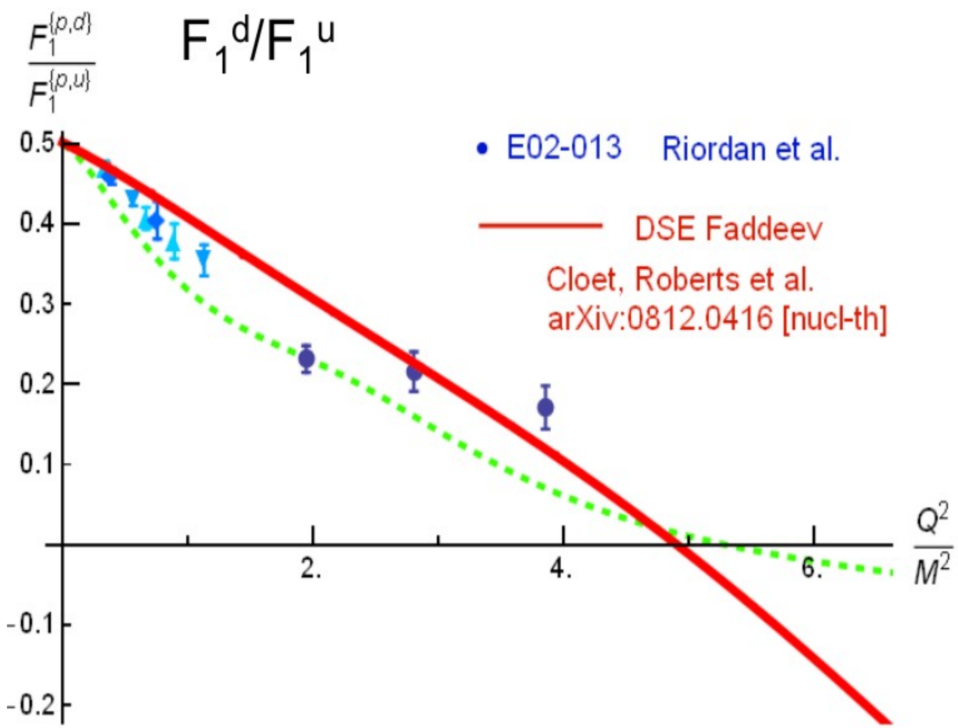


$$F_{(1,2)u} = 2F_{(1,2)p} + F_{(1,2)n}$$
$$F_{(1,2)d} = F_{(1,2)p} + 2F_{(1,2)n}$$

G. Cates et al., PRL106 (2011) 252003
I.A. Qattan & J. Arrington, PRC86 (2012) 065210

Flavor Decomposition and Scaling

- Separate *u, d* in comprehensive analysis of nucleon form factors
  - Study non point-like scalar, axial-vector diquark correlations
- Singly-represented *d*-quark is most likely to be struck in association with 1^+ diquark & these FF contributions are soft
- *u*-quark is predominantly linked with 0^+ diquark contributions

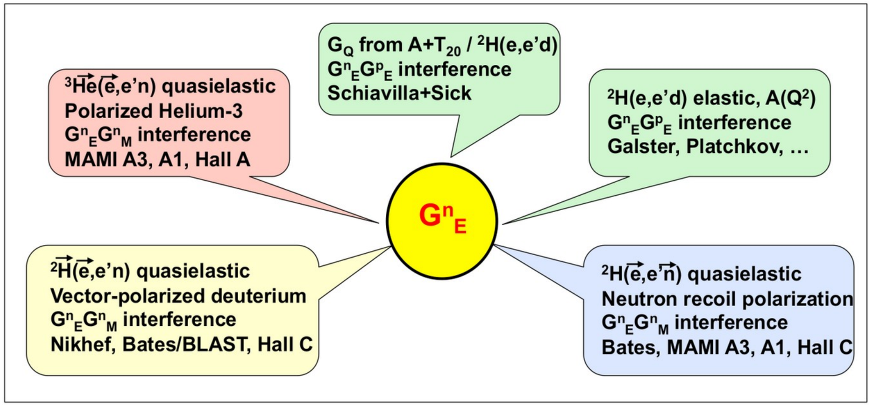


- Follows that
  - *d*-quark Dirac FF is softer than that of *u*-quark
  - F_1^d/F_1^u passes through zero
  - Location of zero depends on relative probability of $1^+/0^+$ diquarks in proton

Segovia, Cloet, Roberts, Schmidt
arXiv:1408.2919 [nucl-th]

Neutron Electric Form Factor: GEn

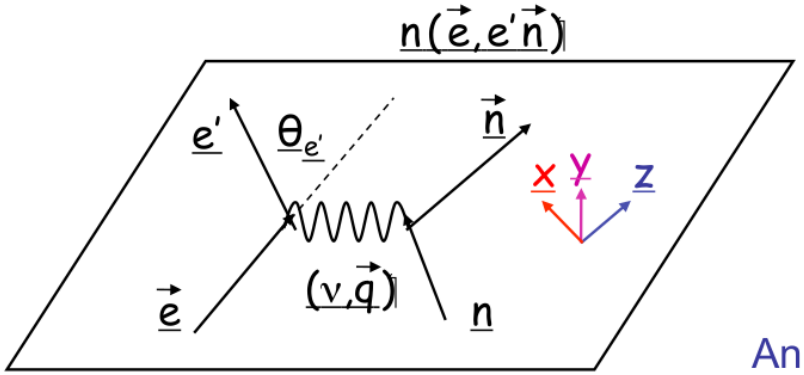
- Challenges moving to high Q^2
  - No free neutron target
    - rely on Elastic or QE scattering and extract the neutron contribution later
  - GEn is small
    - L-T separation is not practical
    - Polarized ^{2}H target → luminosity limited
  - Minimize effect of nuclear corrections (FSI, MEC, …)



- Solution: *High Luminosity Double Polarization Methods*
  - Polarized ^{3}He target → high FOM, high Q^2 reach (*ie.* E12-09-016)
    - somewhat more complicated systematics, nuclear corrections
  - Measure polarization transfer with an unpolarized ^{2}H target
    - good systematic controls, "middle range" Q^2 reach

C-GEn

Recoil polarization technique



electron scattering plane

Recoil polarization

$$P_x = -P_e K_t G_{En} G_{Mn}$$

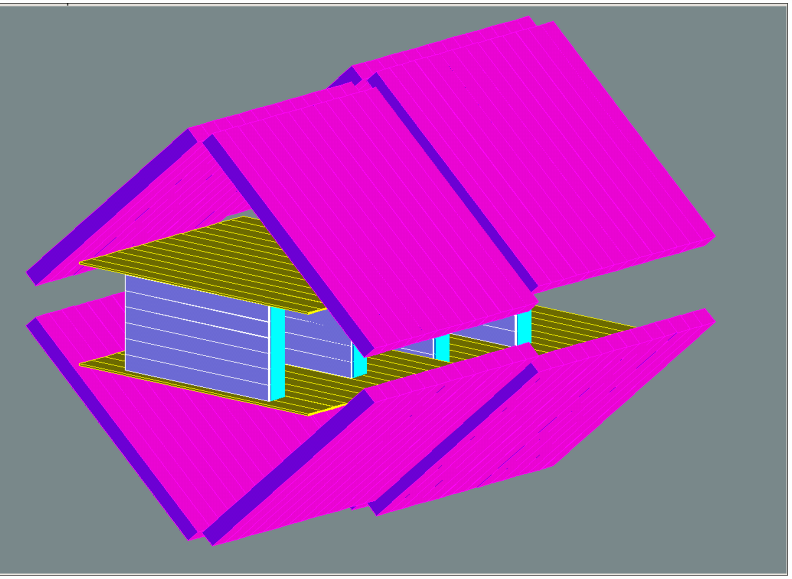
$$P_z = P_e K_\ell G^2_{Mn}$$

Analyzed by second scattering in polarimeter with analyzing power A_Y

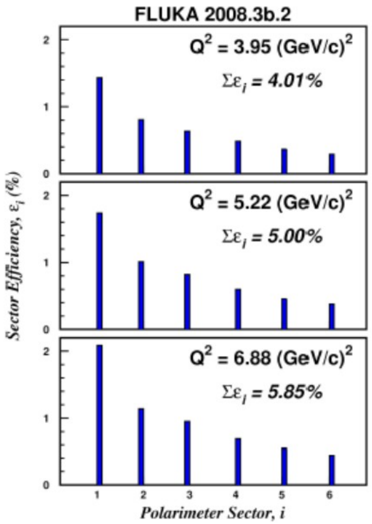
Ratio Technique: Measure P_x and P_z → $\frac{P_x}{P_z} = -\frac{K_t}{K_\ell}\frac{G_{En}}{G_{Mn}}$ → small systematics $A_Y(q)$ and P_e cancel

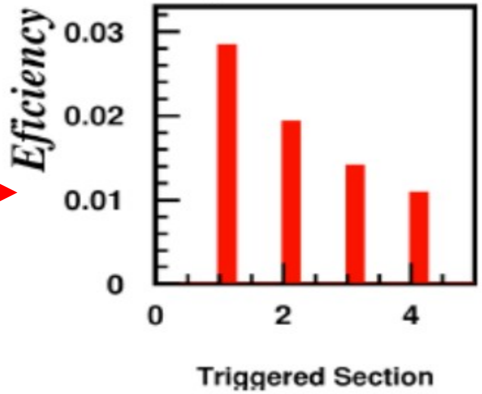
- Electrons detected in Hall C SHMS ← High Precision Spectrometer
- Neutron spin precessed in dipole magnet
- Neutron detected, polarization analyzed in NPOL via *up-down* asym ξ
  - Two linear combinations of P_x and P_z (2 *precession angles*, χ)
    - » $\xi(\chi) = A_y\,[\,P_x \cos\chi \;+\; P_z \sin\chi\,]$
- Cross Ratio technique → beam charge asym and NPOL geom. asym cancel
- Minimal sensitivity to FSI, MEC, IC, choice of NN potential for ^2H wavefunction

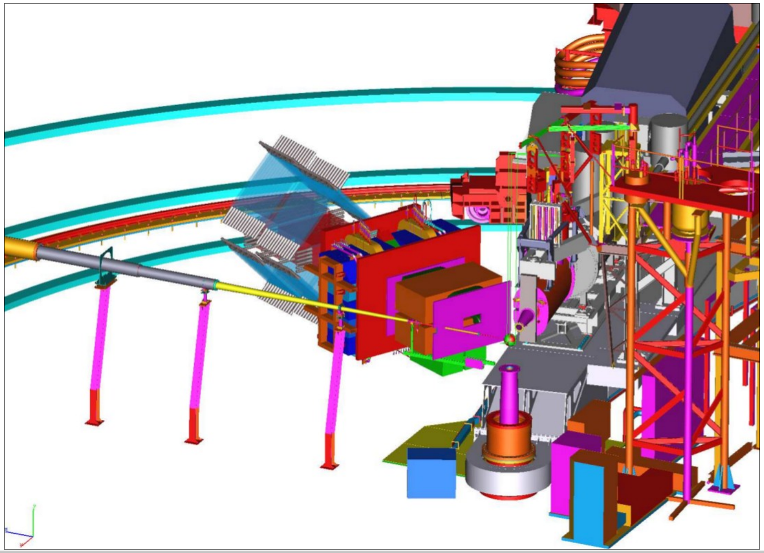
Updated Neutron Polarimeter (NPOL)



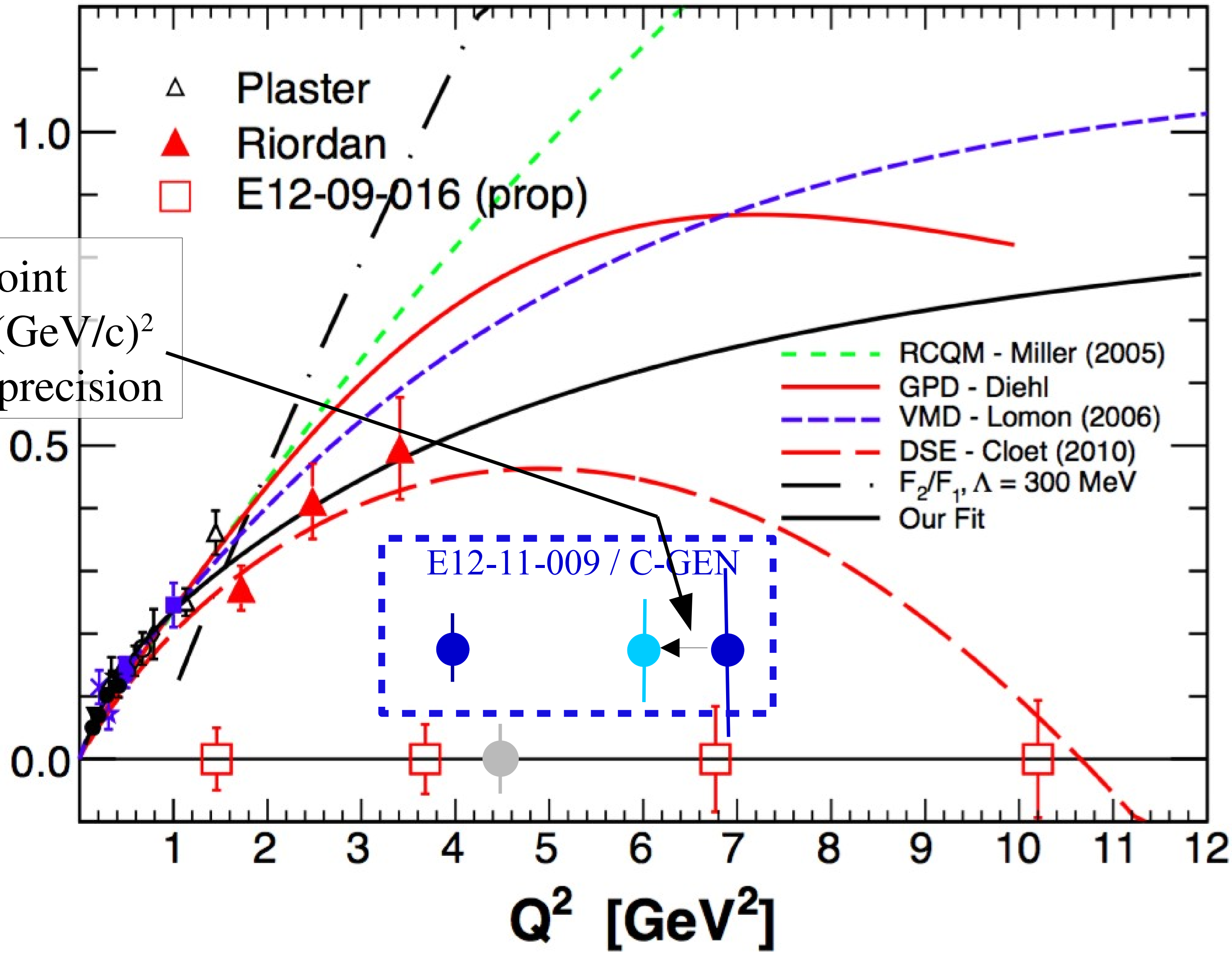
- Updated since PAC37 and refined again after PAC41 to improve FoM
  - Fluka 2011.2.9 + MCEEP-generated *n* flux
  - New G4 based simulation developed to cross check rates and validate older simulations
- Overall Polarimeter efficiency improved from 4–5.8% → ~7%
  - Roughly uniform response vs. Q^2







Predictions for C-GEn



May shift point
6.88 → 6.0 $(GeV/c)^2$
to improve precision

Progress Since PAC37

- Regular C-GEn group and Collaboration meetings since 2011 (until pause in 2016)
- Collaboration restructured in 2014/2015
  - Updated Spokespeople:
    - J. Arrington, M. Kohl, B. Sawatzky, A. Semenov
  - Developed and ratified a Charter for the Collaboration
  - Refreshed Collaborator list and redistributed responsibilities
  - Significant refinement of C-GEn neutron polarimeter design (NPOL)
    - Prototype bars with updated geometry constructed and tested to confirm mean-timing requirements were met
  - Began outlining MRIs necessary to support outstanding detector purchases, etc.
  - Engaged Lab management, JLab engineers for mechanical engineering support
  - Initiated talks with BNL on procurement of BNL 48D48 magnet (to pair with Charybdis)
  - JLab target group engaged for LH2 and LD2 cell requirements

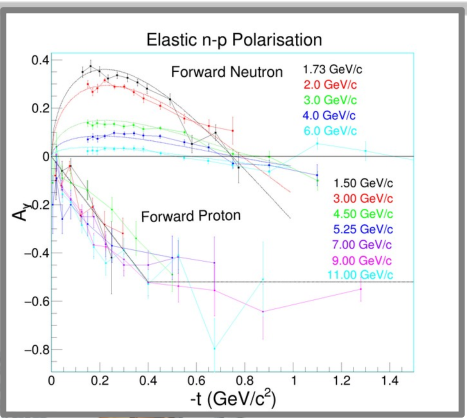
- Goal at that time was to be ready for formal Beam Request and (possible) scheduling on 2019/20 timescale (following completion of Hall C's Commissioning experiments)

- Charge-Exchange technique proposal by Annand et. al submitted as LOI12-15-003 to PAC43 (2015)
  - Ultimately resulted in a large shift in focus for majority of C-GEn group to RP-GEn

- RP-GEn proposal jointly developed and approved for PAC45 (2017)
  - Spokespeople: J.R.M. Annand*, V. Bellini, M. Kohl, N. Piskunov, B. Sawatzky, B. Wojtsekhowski
  - "Proof-of-Principle" measurement to validate Charge-Exchange method and provide quantitative information on large-angle *np* scattering at moderate Q^2
    - More on RP-GEn in a moment...

RP-GEn: Optimizing the Path to GEn

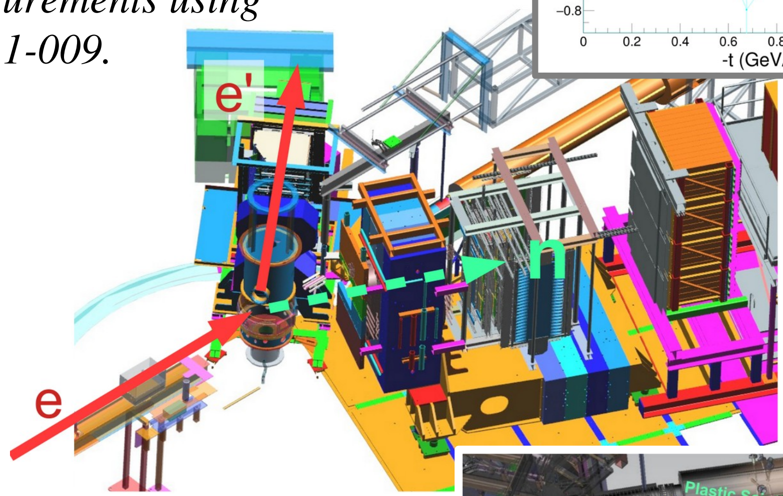
- Following PAC43 (2015) response to LOI12-15-003: a Charge-Exchange focused recoil polarimetry approach:
  - *Recommendation: The proponents are encouraged to work with the lab management and the E12-11-009 collaboration to improve the FOM of the recoil neutron polarimeter in order to optimize the measurements using the already approved beam time of E12-11-009.*



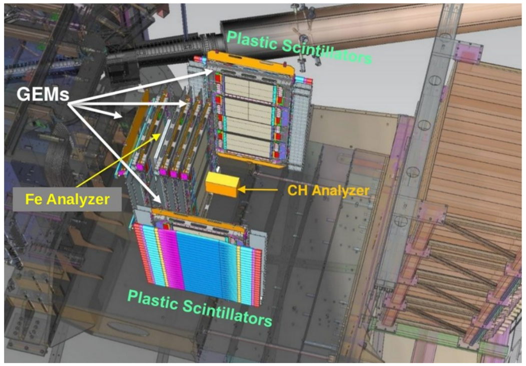
- A joint collaboration between Hall A&C recoil polarimetry proponents was developed and approved at PAC47: RP-GEn (E12-17-004)

  Spokespeople: Annand*, Bellini, Kohl, Piskunov, Sawatzky, Wojtsekhowski

  - Integrated into the upcoming Hall A SBS GMn program (to run Fall 2021)



- RP-GEn: "Proof of Principle" Measurement
  - Short (5 PAC days); One moderate $Q^2 = 4.4$ (GeV/c)^2
  - Simultaneously measure GEn/GMn using *both* the Charge Exchange channel and the Large-Angle Recoil channel
  - Outcome will guide the best approach to measuring GEn via recoil polarimetry



Summary / Outlook

- E12-11-009 / C-GEN allocated 50 days in Hall C (*Earliest* possible run slot would be 2023+)
  - One Low Q^2 point at 4 $(\mathrm{GeV/c})^2$ (~10% stat. err)
    - overlap with E02-013 ^{3}He data
  - One High Q^2 point at either:
    - 6.88 $(\mathrm{GeV/c})^2$ (~14% stat. err)

      ~ OR ~
    - 6.0 $(\mathrm{GeV/c})^2$ (~10% stat. err)
- Extends Q^2 coverage for GEn into region that discriminates between several models
- Provides a critical cross check against the upcoming SBS-based pol. ^{3}He measurement
  - Different target, different systematics, different extraction technique
- ***C-GEN is an extrapolation of proven recoil polarimetry technique using toolkit refined from earlier measurements at JLab. At present, this is a well developed, proven method of accessing the physics.***

We encourage the PAC to reaffirm the importance of an RP-based GEn measurement, and maintain the 50 PAC days until the RP-GEn program bears fruit.

Optimal Path is still To Be Determined

- RP-GEn run in Fall 2021 as part of upcoming SBS rungroup in Hall A will provide critical information on best approach to accessing GEn with recoil polarimetry technique
  - Charge-Exchange channel is a potential game changer
  - If the RP-GEn "proof-of-principle" experiment validates ChEx, then the best path forward would be a new proposal for either Hall A or C guided by what is learned.
    - E12-11-009 would likely be withdrawn in favor of a more optimal approach.

Misc. Backup

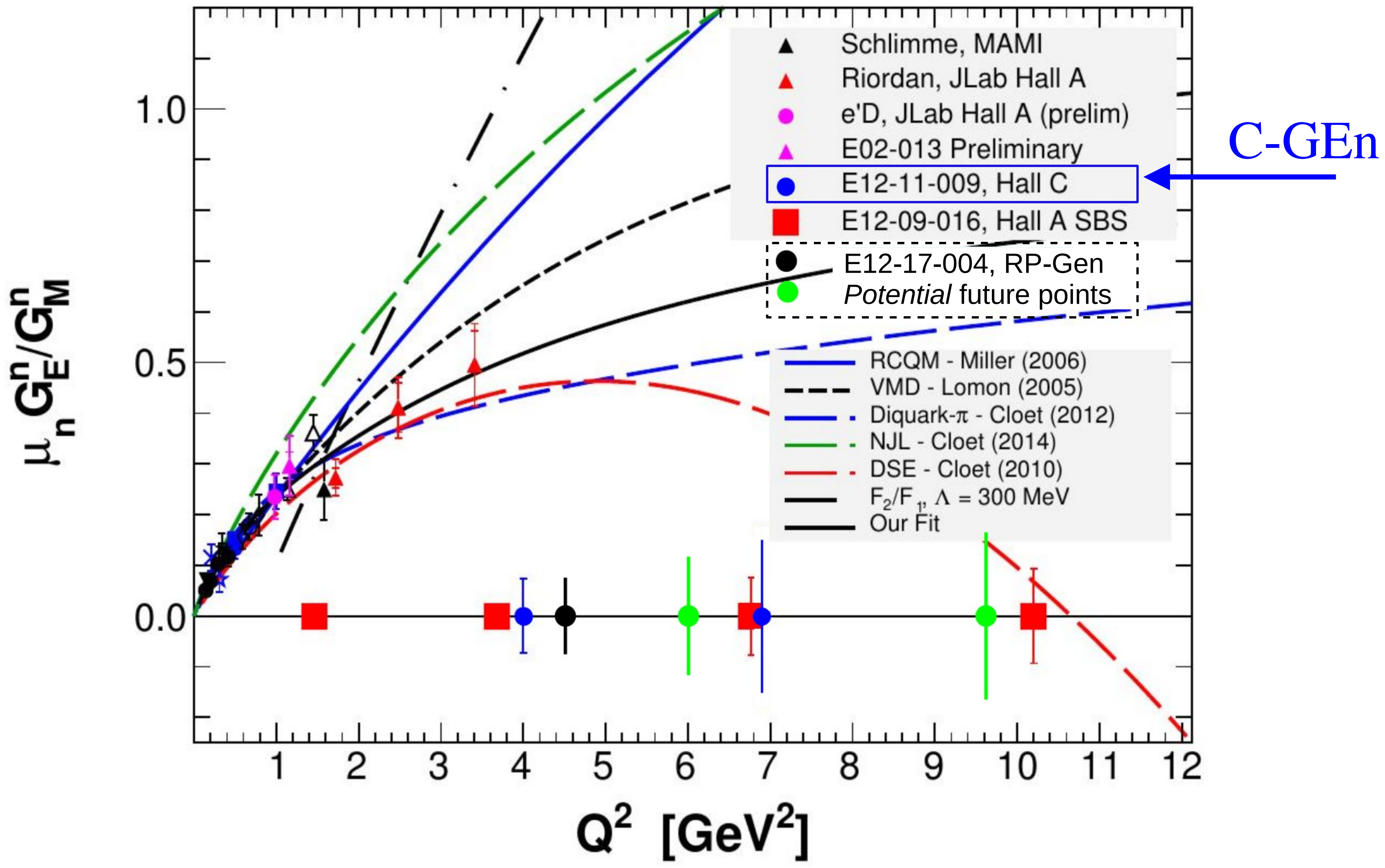
C-GEn Approved Time (PAC41)

80 μA beam, 80% polarization, 40-cm LD_2 target

Four-Momentum Transfer, Q^2 $(\mathrm{GeV}/c)^2$	3.95	5.22	6.88
Beam Energy, E_0 (GeV)	4.4	6.6	11.0
Electron Scattering Angle, θ_e (deg)	36.53	26.31	16.79
Scattered Electron Momentum, P'_e (GeV/c)	2.288	3.815	7.330
Neutron Scattering Angle, θ_n (deg)	28.0	28.0	28.0
Neutron Momentum, P_n (GeV/c)	2.901	3.602	4.511

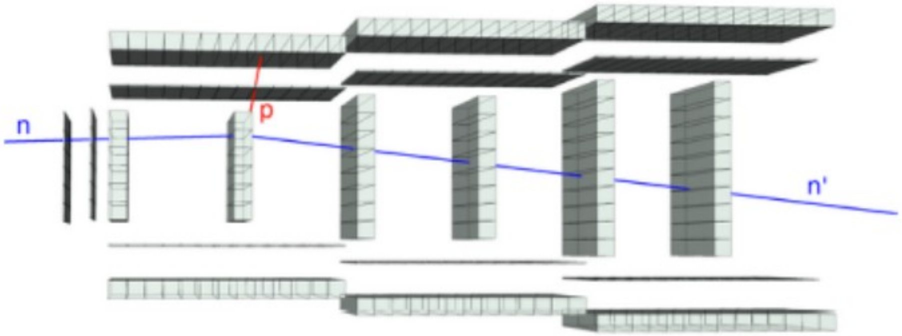
- PAC41 Approved: 50 days, only two settings
- Stat. uncertainty: 10.1% ~~12.7%~~ <14%
- Syst. uncertainty 2.5–3% for all settings
- Beam Time on LD2 [days] 10 ~~15~~ 36
  Beam Time (LH2, etc) [days] 1 ~~1.5~~ 2.5
  50d production + 7d checkout w/beam: 57 total PAC days
- Two Q^2 values: One overlap with 6 GeV data,
  2nd as high as possible with optimal statistics

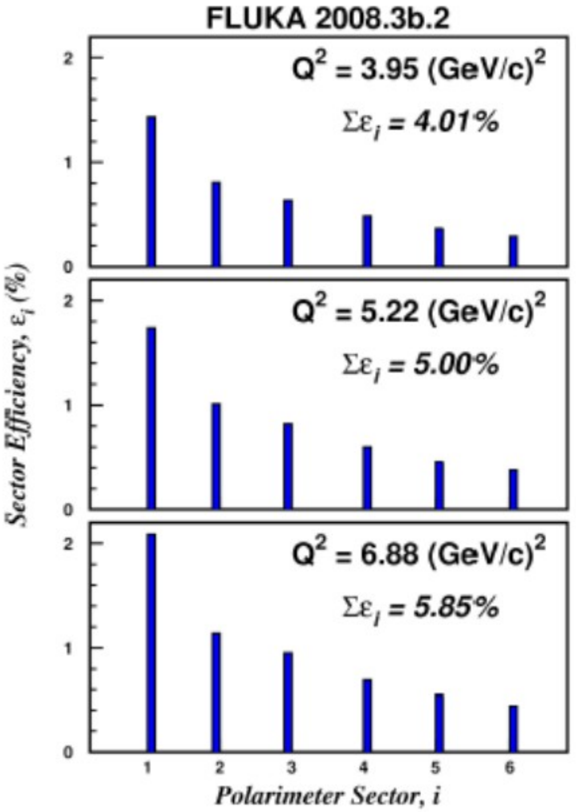
Predictions for GEn (Present and Future)



PAC37 Polarimeter Layout (Old)

PAC37 : Detection of Recoil Protons Instead of Scattered Neutrons





* Easy detection of 300-500 MeV protons via TOF and dE-E techniques

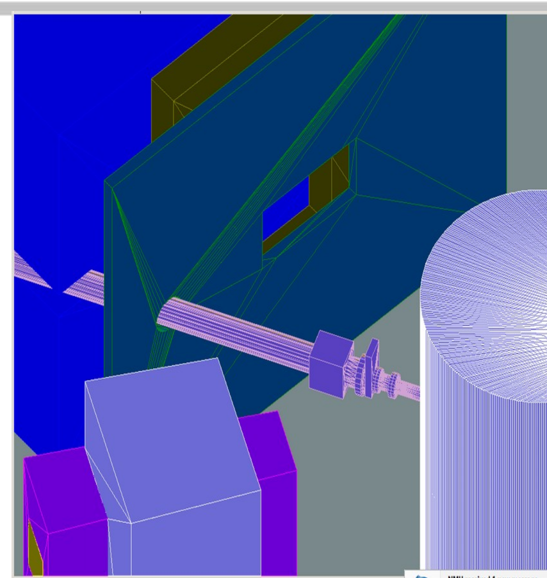
* Comfortable access to the small scattering angles of neutrons

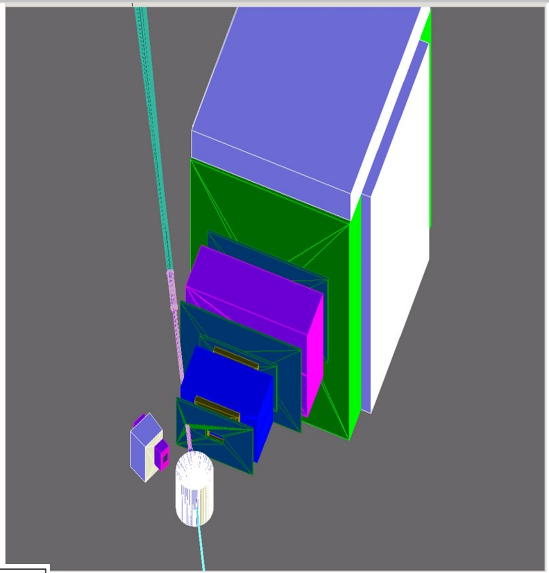
* Segmented and distributed analyzer (easy escape of protons and control on double-scattered neutrons)

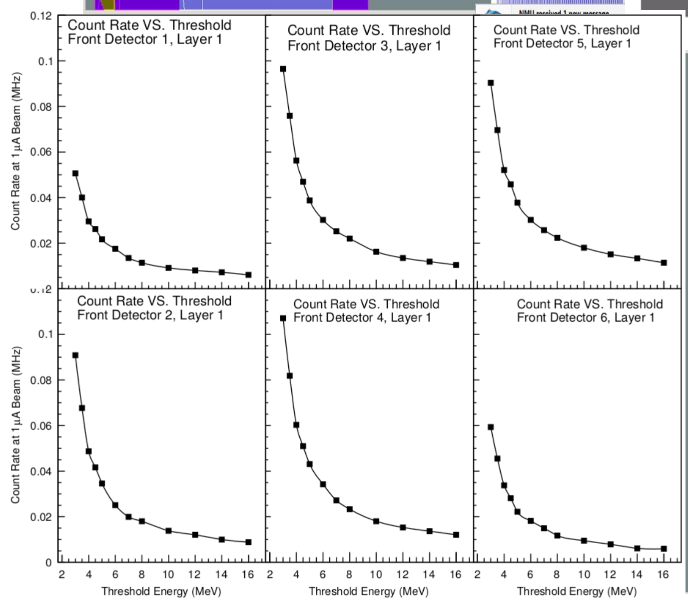
* Issues:
  - No full coverage of top/bottom acceptance
  - 5th and 6th Sections (too small efficiency with too many detectors)

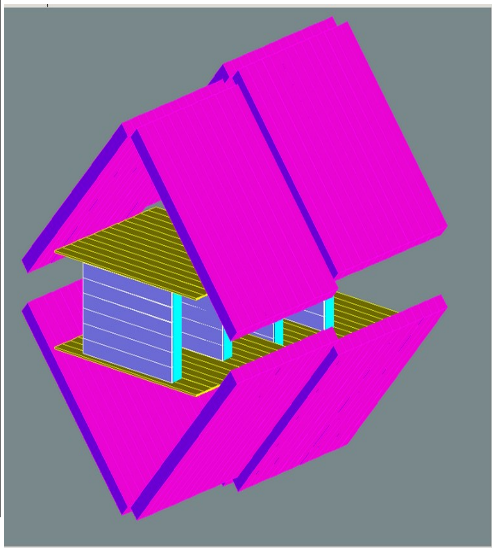
GEANT4 Simulation in Development

- Will Tireman (N. Michigan Univ.) & student
- Reimplementation of experiment “from scratch”
  - Includes full beamline, dump, Experimental Hall, portions of SHMS, complete NPOL w/ shield hut
- Fully integrated simulation (vs. MCEEP + FLUKA + external codes)
- Allows cross checks of historical simulation, plus more rapid prototyping of new ideas (ie. CX channel)









Cross Ratio Method

Both recoil polarization components $P_t \propto -G_E^n G_M^n$ and $P_\ell \propto {G_M^n}^2$ are accessed via a secondary analyzing reaction in our neutron polarimeter configured to measure an up-down scattering asymmetry. Transport through a vertical magnetic dipole field located ahead of the polarimeter results in a precession of the recoil polarization vector through some angles χ, leading to a scattering asymmetry $\xi(\chi)$ which is sensitive to a mixing of P_t and P_ℓ. With another measurement of the scattering asymmetry ξ_- for a precession through an angle $-\chi$, the ratio of G_E and G_M is given by

$$g \equiv \left(\frac{G_E}{G_M}\right) = K_R \, tan(\chi) \, \frac{(\eta+1)}{(\eta-1)} \tag{8}$$

where the asymmetry ratio

$$\eta \equiv \frac{\xi_-}{\xi_+} = \frac{P_-^x}{P_+^x} \tag{9}$$

and K_R is a kinematic function that is determined by the electron scattering angle θ_e and four-momentum transfer Q^2 in the d($\vec{e}$,e'$\vec{n}$)p reaction.

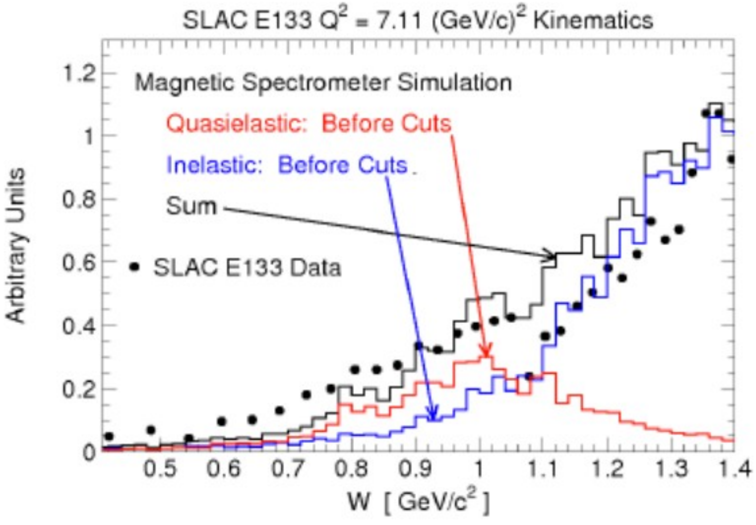
A significant advantage of this technique for measuring the ratio of the two scattering asymmetries is that the scale and systematic uncertainties are minimal because the relative uncertainty in the analyzing power of the polarimeter does not enter in the ratio. The same is true for the beam polarization P_L because, as demonstrated in E93-038, P_L does not change much during sequential measurements of ξ_+ and ξ_-.

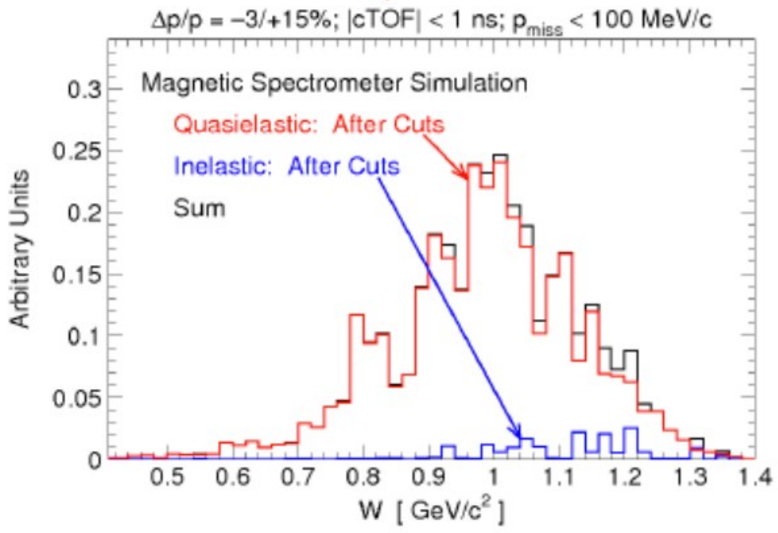
Good timing for clean QE event selection

Time Resolution of Analyzer: Selection of Quasielastic *en*

Cut on the SHMS-NPOL Analyzer time difference is an important part of selection of e-n quasielatic scattering events in the target.

High mean-time resolution (as better as possible, but definitely better than 1 ns) is desired for neutron bars in the polarimeter analyzer.





A. Semenov