Search for a Nonzero Strange Form Factor of the Proton at 2.5 $(GeV/c)^2$

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Hall C Meeting 1/13/23

Indiana University

Search for a Nonzero Strange Form Factor of the Proton at 2.5 $(GeV/c)^2$

Collaborators

- Bogdan Wojtsekhowski (*spokesperson-contact*)

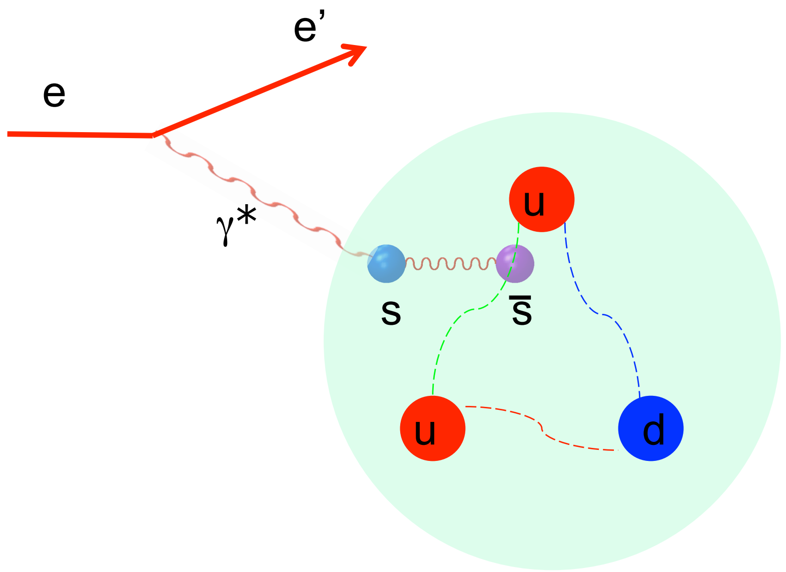
Jefferson Lab

- Rakitha Beminiwattha

LOUISIANA TECH UNIVERSITY

- Kent Paschke

UNIVERSITY of VIRGINIA



Charge symmetry and the nucleon form factors

Charge Symmetry

$$G_E^p = \frac{2}{3}G_E^{u,p} - \frac{1}{3}G_E^{d,p}$$
$$G_E^n = \frac{2}{3}G_E^{u,n} - \frac{1}{3}G_E^{d,n}$$

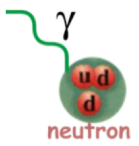
Charge symmetry is assumed for the form factors, $G_E^{u,p} = G_E^{d,n}$, *etc.* and used to find the flavor separated form-factors, measuring $G_{E,M}^{p,n}$ to find $G_{E,M}^{u,d}$

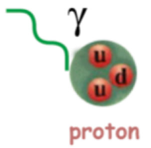
$$G_E^p = \frac{2}{3}G_E^{u,p} - \frac{1}{3}G_E^{d,p} - \frac{1}{3}G_E^s$$
$$G_E^n = \frac{2}{3}G_E^{u,n} - \frac{1}{3}G_E^{d,n} - \frac{1}{3}G_E^s$$

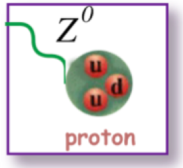
But this can broken! One way is to have a non-zero strange form-factor, which breaks the “2 equations and 2 unknowns” system

The weak form factor provides a third linear combination:

$$G_E^{p,Z} = \left(1 - \frac{8}{3}\sin^2\theta_W\right)G_E^{u,p} + \left(-1 + \frac{4}{3}\sin^2\theta_W\right)G_E^{d,p} + \left(-1 + \frac{4}{3}\sin^2\theta_W\right)G_E^s$$







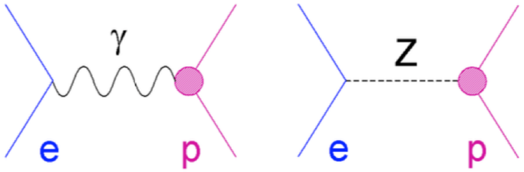
A strange quark form factor would be indistinguishable from a broken charge symmetry in u,d flavors

$$\delta G_E^u \equiv G_E^{u,p} - G_E^{d,n}$$
$$\delta G_E^d \equiv G_E^{d,p} - G_E^{u,n}$$

So, more generally: this experiment tests the assumption of charge symmetry which is crucial to the flavor decomposition of the form factors

Strangeness form factors

Polarized electron beam elastic e-p scattering



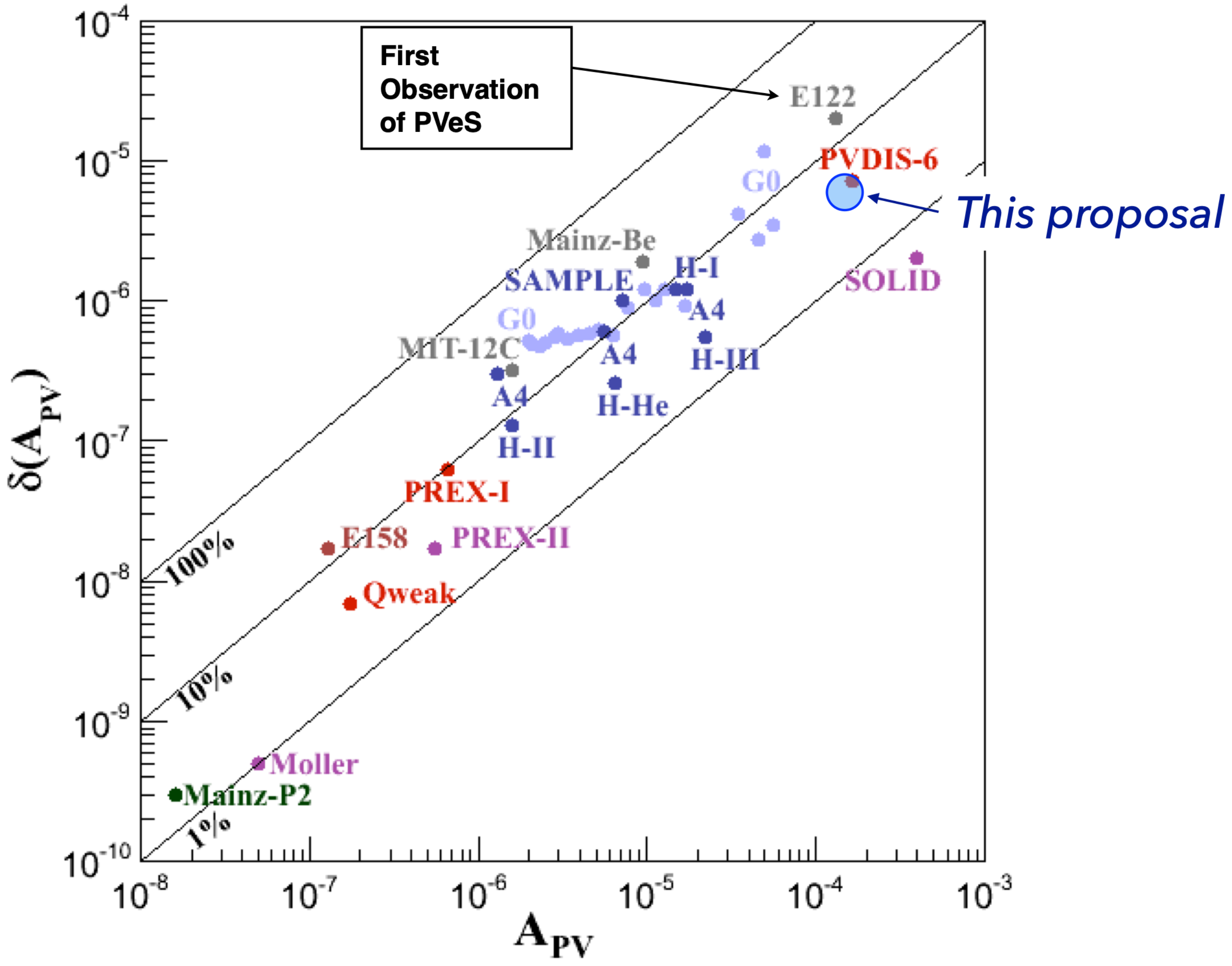
$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \cdot [(1-4\sin^2\theta_W) - \frac{\epsilon G_E^p G_E^n + \tau G_M^p G_M^n}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} - \frac{\epsilon G_E^p G_E^s + \tau G_M^p G_M^s}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}$$
$$+ \epsilon'(1-4\sin^2\theta_W)\frac{G_M^p G_A^{Zp}}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}]$$

A_{PV} = 150 ppm at θ = 15.5°, Q^2 = 2.5 GeV^2 (for sFF = 0)

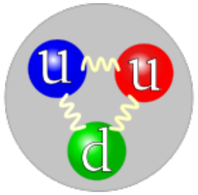
A_{PV} = (-226 ppm) *[0.075 + 0.542 – 6.43*($G_M^s + 0.32\, G_E^s$) + 0.038]

Q_w EMFF axial

strange form-factors


First Observation of PVeS
E122
PVDIS-6
This proposal
G0
Mainz-Be
SAMPLE
H-I
A4
SOLID
G0
MIT-12C
A4
H-III
A4
H-He
H-II
PREX-I
E158
PREX-II
Qweak
100%
10%
1%
Moller
Mainz-P2
$\delta(A_{PV})$
A_{PV}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}

Breakdown of U/D scaling at larger Q^2



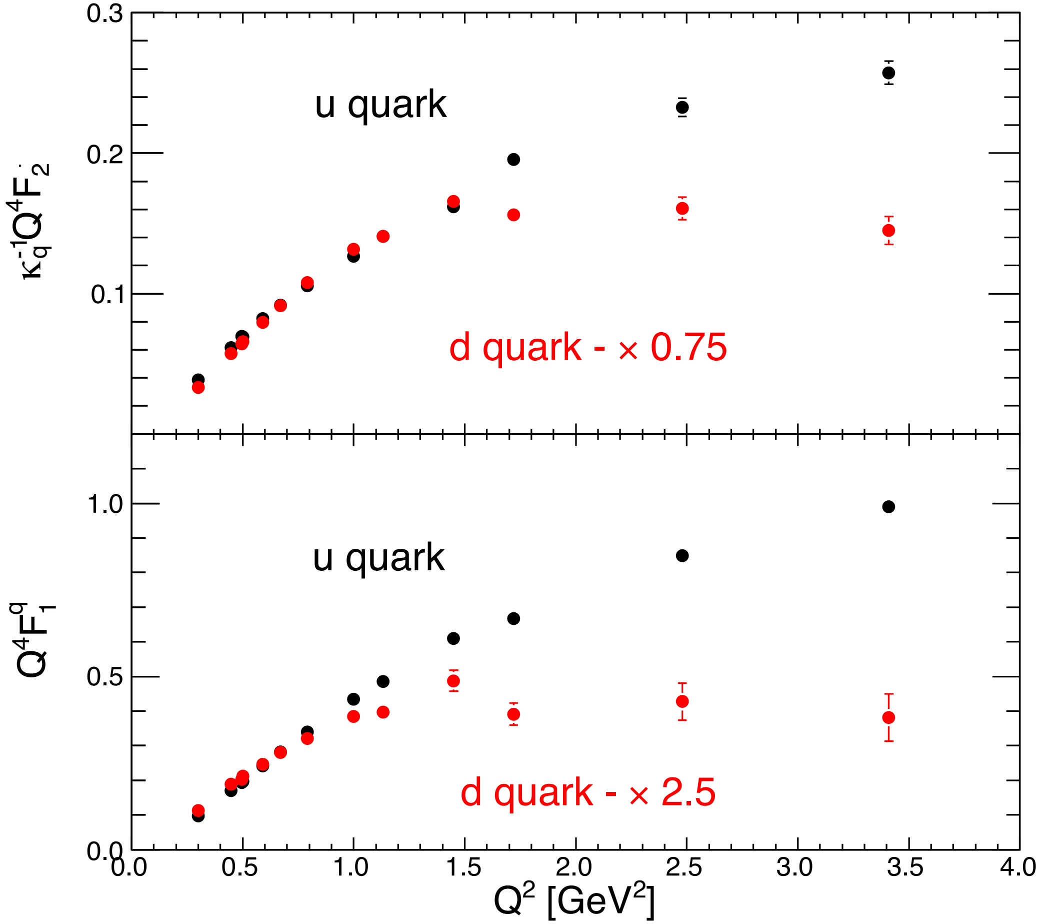


FIG. 3: The Q^2-dependence for the u- and d-contributions to the proton form factors (multiplied by Q^4). The data points are explained in the text.

Flavor decomposition of the elastic nucleon electromagnetic form factors

G.D. Cates,[1] C.W. de Jager,[2] S. Riordan,[3] and B. Wojtsekhowski[2,*]

[1] *University of Virginia, Charlottesville, VA 22903*
[2] *Thomas Jefferson National Accelerator Facility, Newport News, VA 23606*
[3] *University of Massachusetts, Amherst, MA 01003*
(Dated: March 6, 2011)

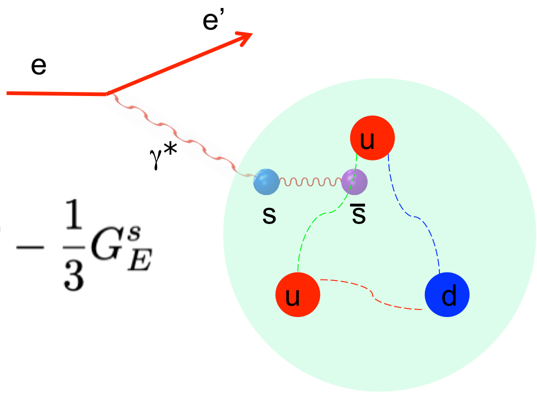
The u- and d-quark contributions to the elastic nucleon electromagnetic form factors have been determined using experimental data on G_E^n, G_M^n, G_E^p, and G_M^p. Such a flavor separation of the form factors became possible up to 3.4 GeV^2 with recent data on G_E^n from Hall A at JLab. At a negative four-momentum transfer squared Q^2 above 1 GeV^2, for both the u- and d-quark components, the ratio of the Pauli form factor to the Dirac form factor, F_2/F_1, was found to be almost constant, and for each of F_2 and F_1 individually, the d-quark component drops continuously with increasing Q^2.

- Why is there a breakdown of U/D scaling at > 1 GeV^2
- Diquark?
  - "In the framework of Dyson-Schwinger equation calculations, the reduction of the ratios F_1^d/F_1^u and F_2^d/F_2^u at high Q^2 is related to diquark degrees of freedom"
- Unless there's something strange going on….

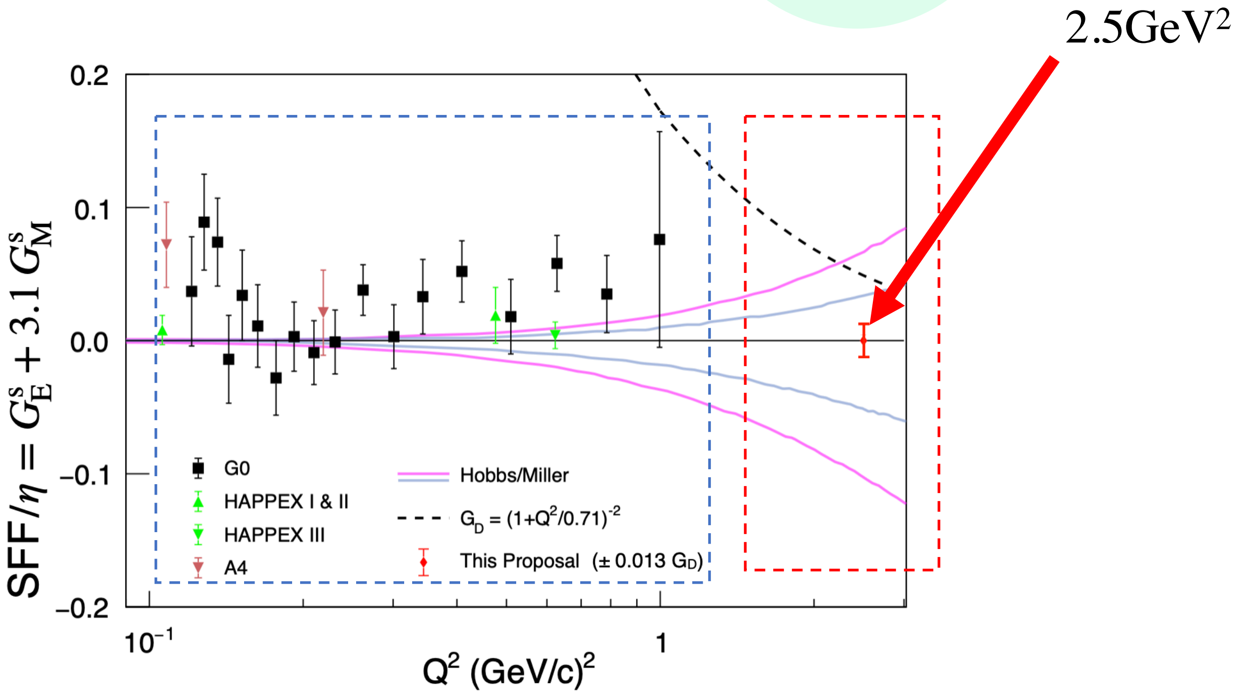
$$F_1 = \frac{G_E + \tau G_M}{1+\tau} \quad F_2 = -\frac{G_E - G_M}{1+\tau}$$

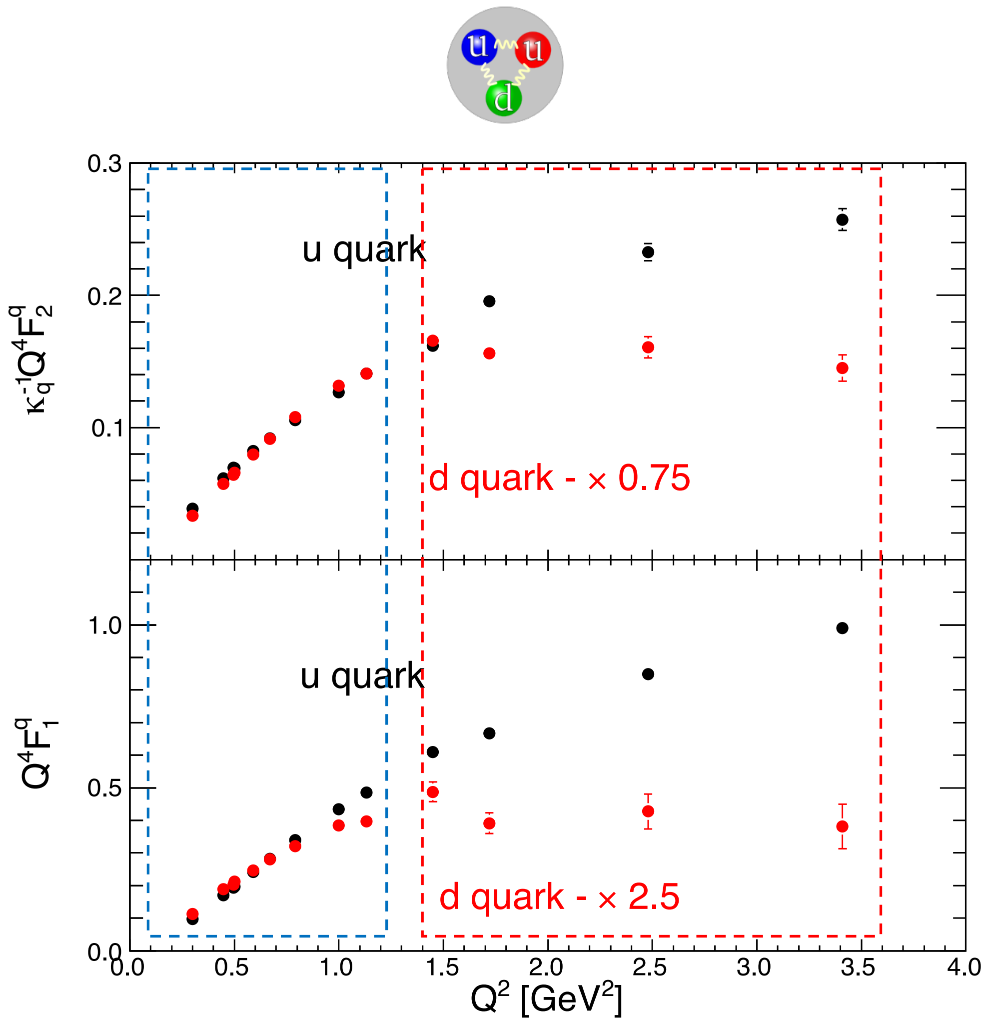
$$\tau = Q^2/4M^2$$

Strange FF zero at high Q²?



$$G_E^p = \frac{2}{3}G_E^{u,p} - \frac{1}{3}G_E^{d,p} - \frac{1}{3}G_E^s$$

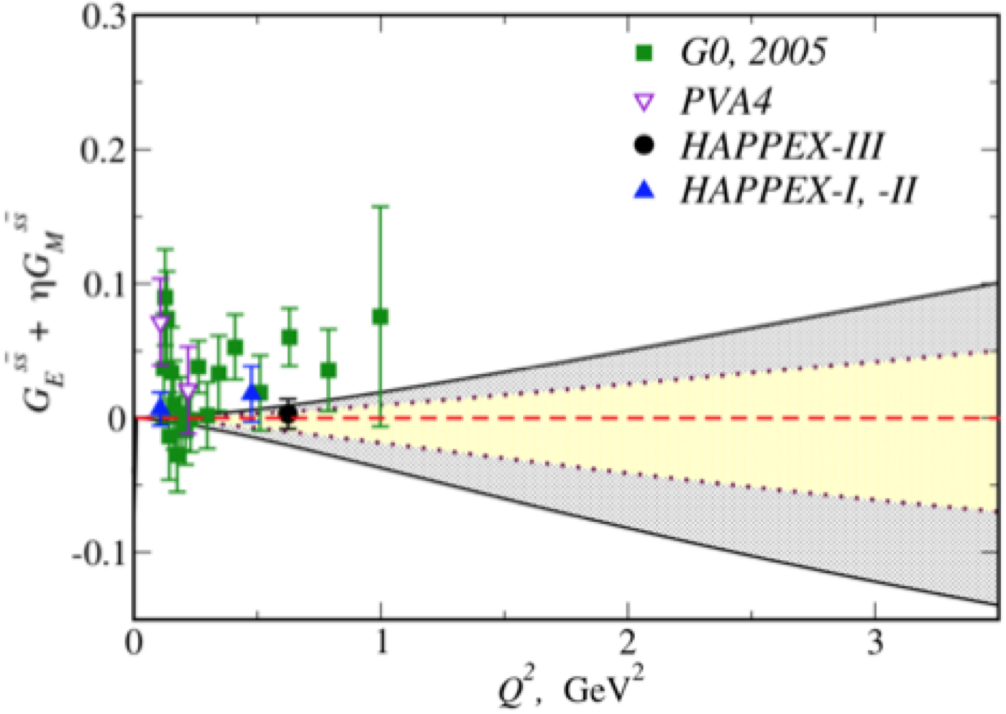




- How will SFF impact flavor decomposition of the nucleon FF at higher Q²?

Strange form-factor predictions

T.Hobbs & J.Miller, 2018



Follows work from *Phys.Rev.C* 91 (2015) 3, 035205
(LFWF to tie DIS and elastic measurements in a simple model)

Conclusion: sFF small (but non-zero) at low Q^2, but quite reasonable to think they may grow relatively large at large Q^2

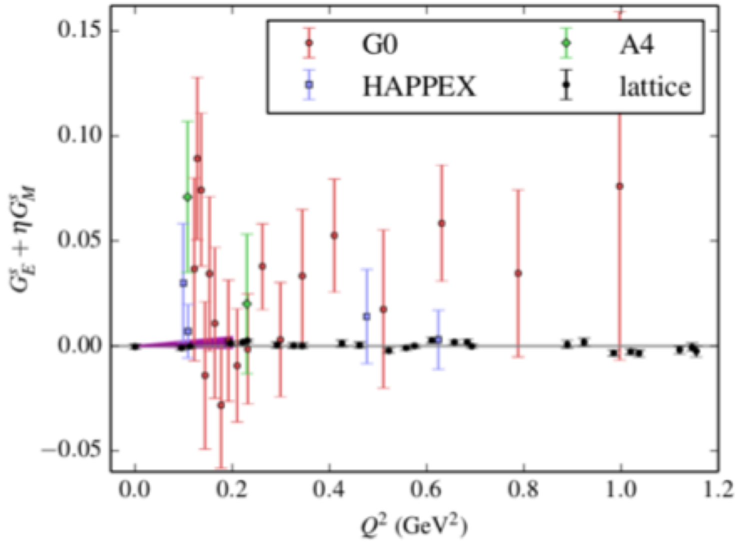
G_D = 0.0477 at 2.5 GeV^2
uncertainty here ranges from (0.036,-0.051)

G_s/G_D ~ 1 is not excluded

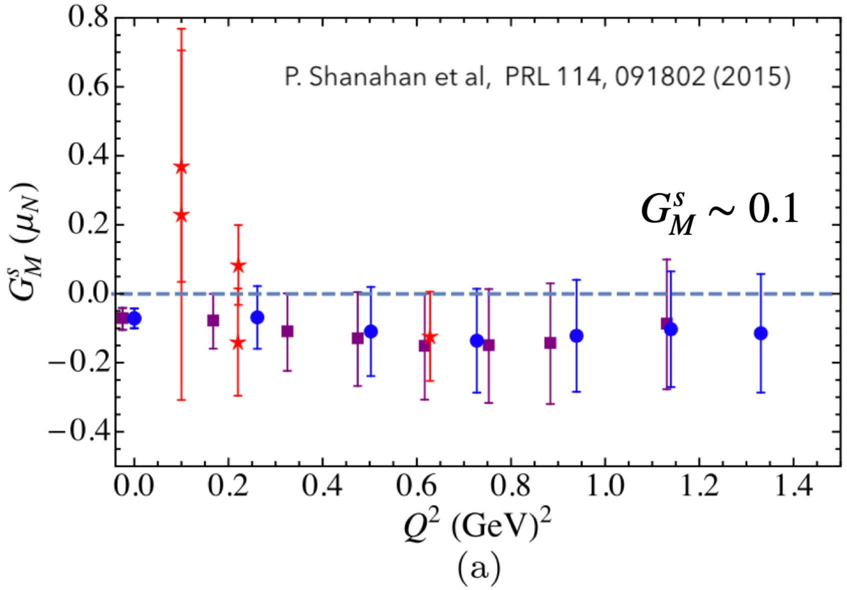
Tim Hobbs and Jerry Miller have both joined the collaboration

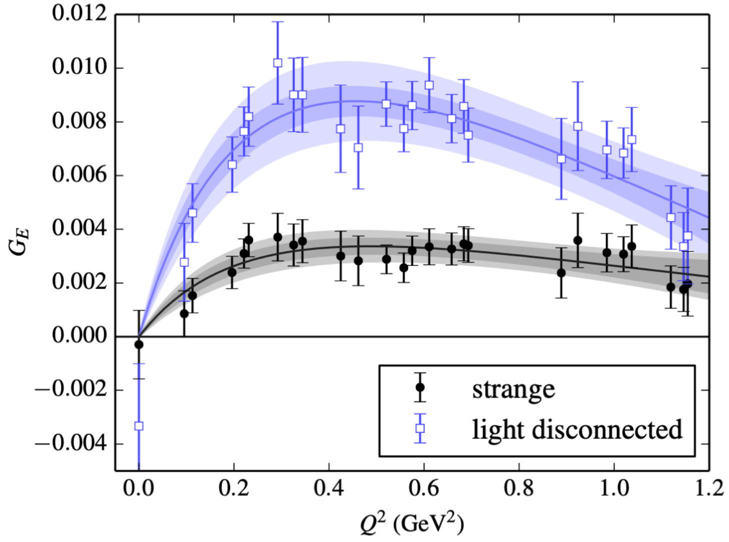
Strange form-factors on the lattice

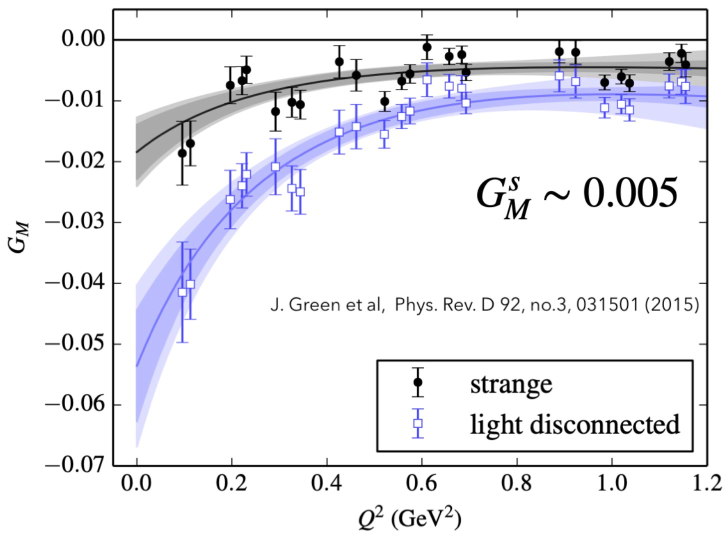
J.Green etal, 2015

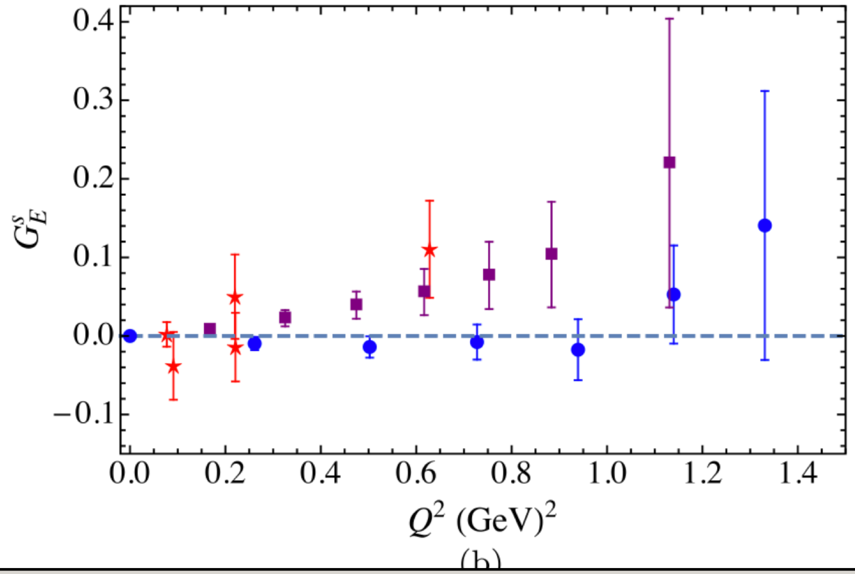


Some lattice calculations predict non-zero central values that would be visible with the proposed precision





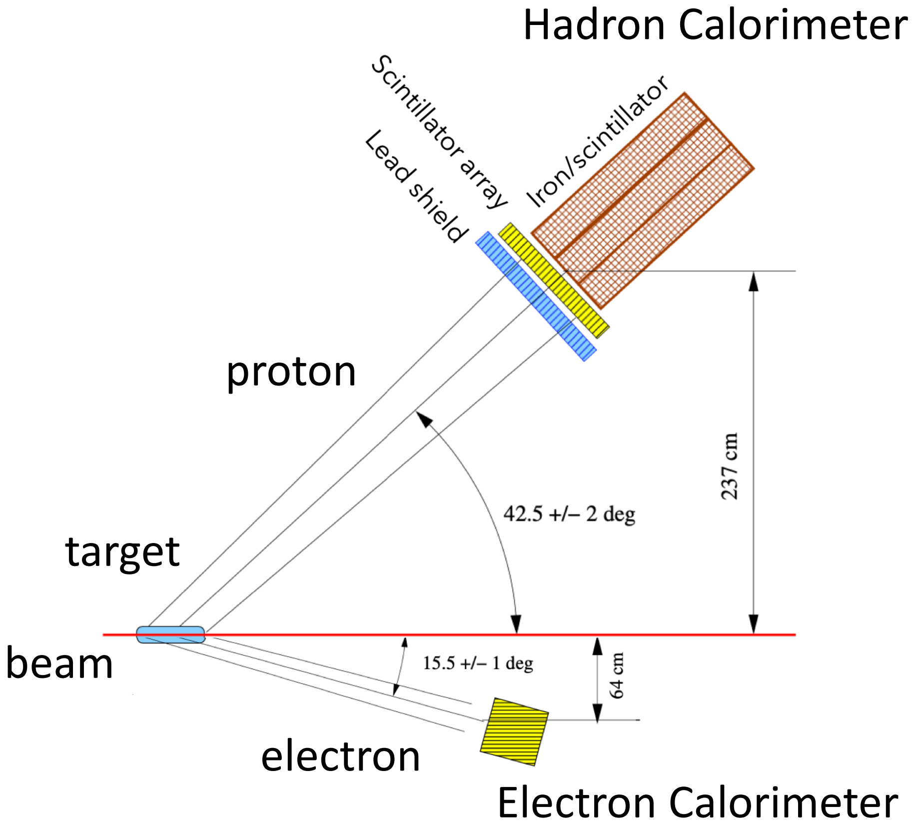


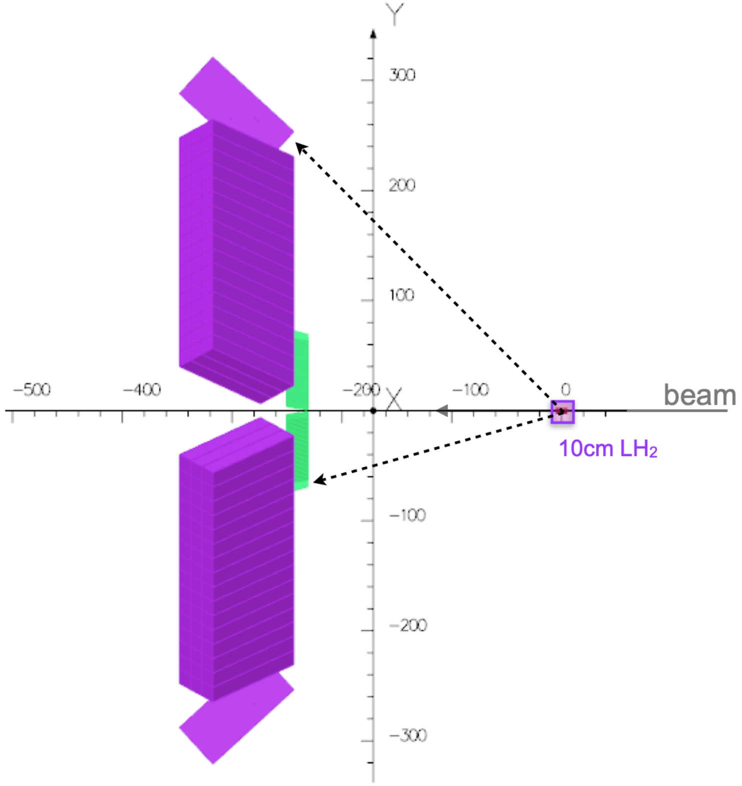


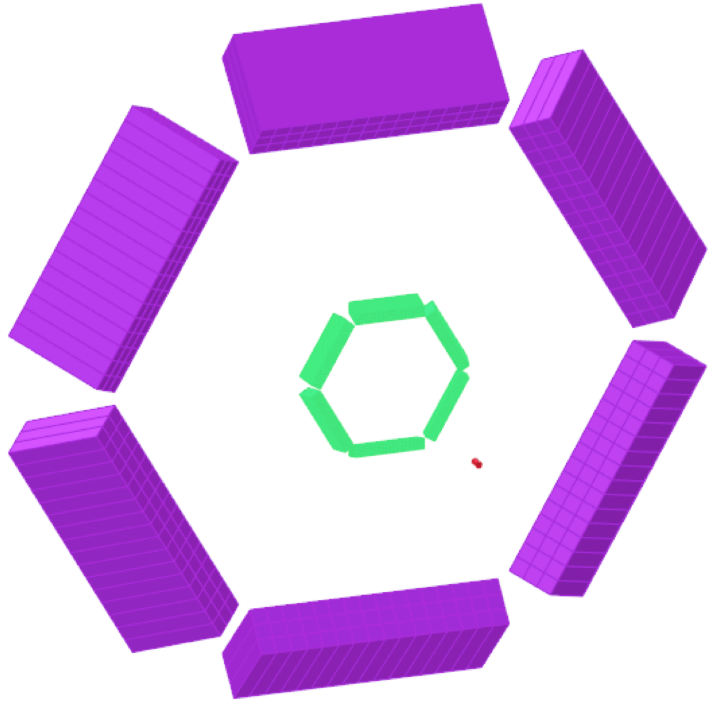
Experimental concept

- Elastic kinematics between electron and proton
- Full azimuthal coverage, ~42 msr
- High resolution calorimeter for electron arm
- Angular correlation e-p

- 6.6 GeV beam
- Scattered electron at 15.5 degrees
- Scattered proton at 42.4 degrees
- 10 cm LH_2 target, 60 μA, $\mathcal{L}$ =1.6 x 10^{38} cm^{-2}/s







Detector System

HCAL - hadron calorimeter

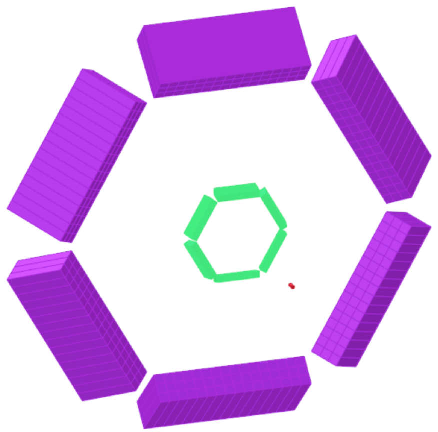
- Reassembled from detector elements from the SBS HCAL
- 288 blocks, each 15.5 x 15.5 x 100 cm^3
- iron/scintillator sandwich with wavelength shifting fiber readout

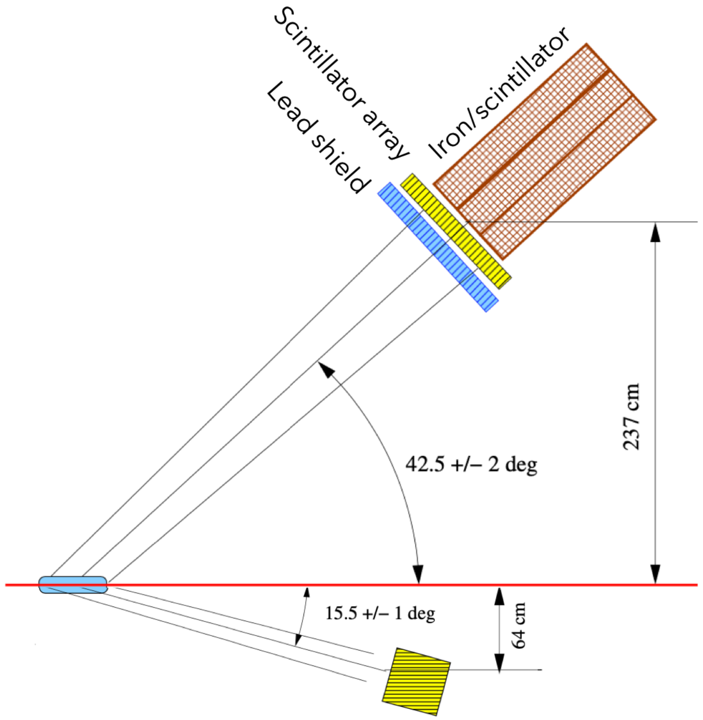
ECAL - electron calorimeter

- Reassembled from detector elements from the NPS calorimeter
- 1000 blocks, each 2 x 2 x 20 cm^3
- $PbWO_4$ scintillator

Scintillator array

- Used for improved position resolution in front of HCAL
- Not used to form trigger
- 7200 blocks, each 3 x 3 x 10 cm^3
- Lead shield in front (thickness to be optimized) to reduce photon load

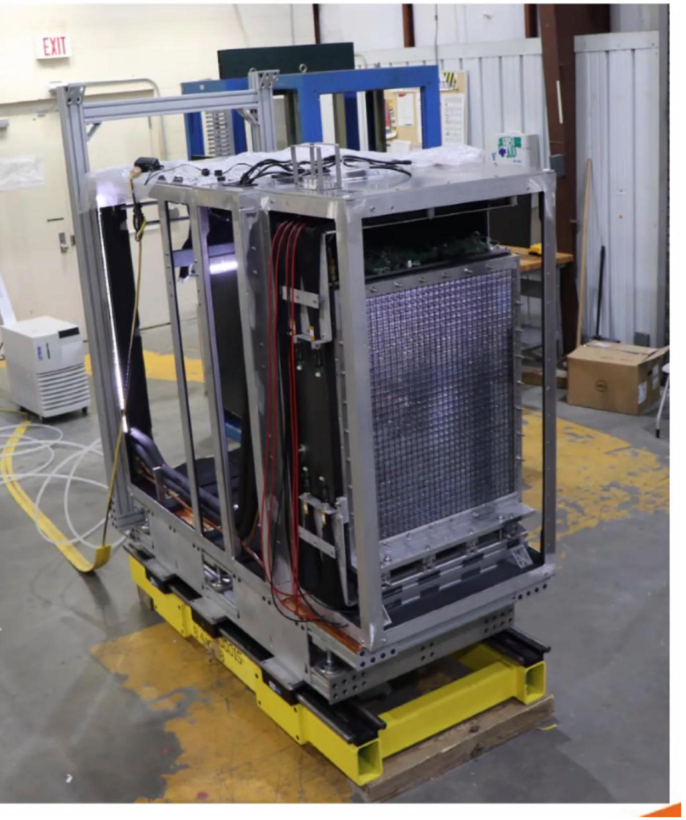




Calorimeters reusing components

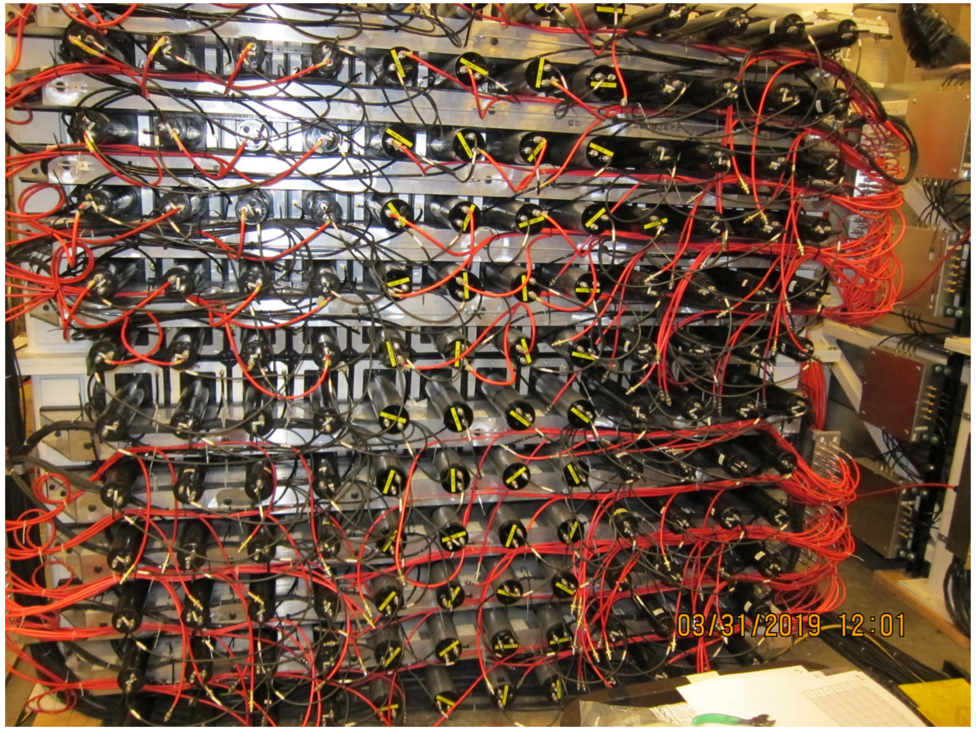
NPS electromagnetic calorimeter

- 1080 $PBWO_4$ scintillators, PMTs + bases
- will run in future NPS experiment

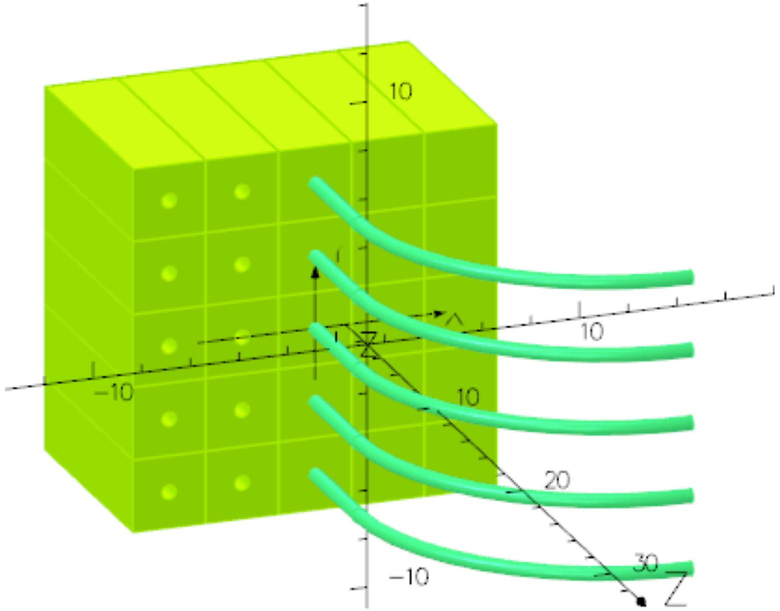


SBS hadronic calorimeter

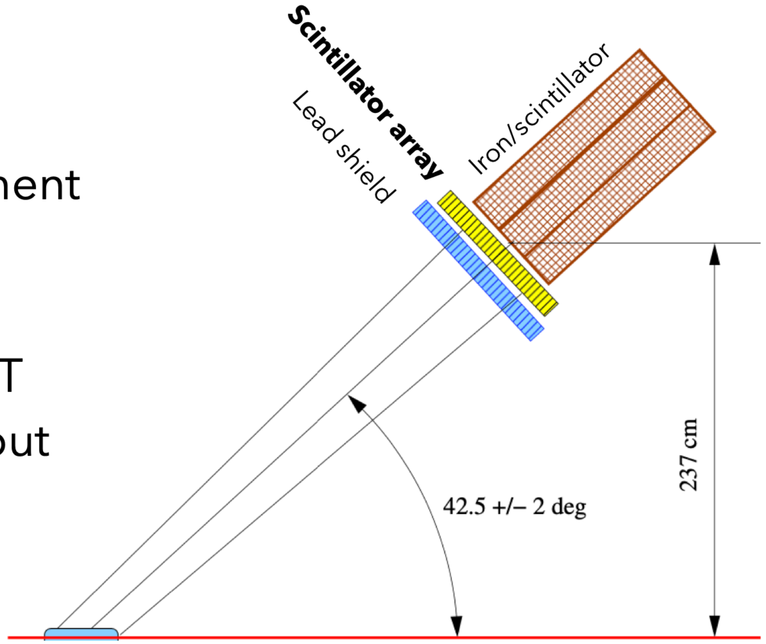
- 288 iron/scintillator detectors, PMTs + bases
- Already in use with SBS



Scintillator Array

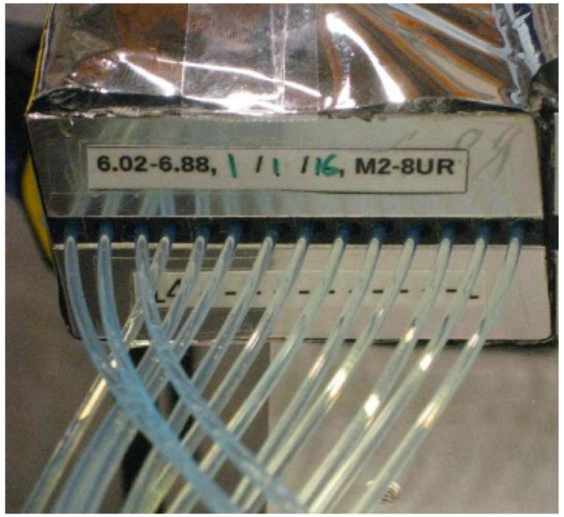


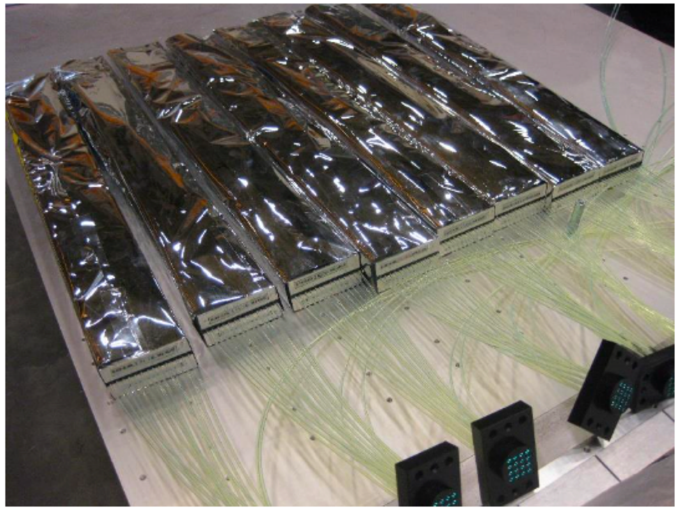
- New detector, must be built for this experiment
- Extruded plastic scintillator block
- Readout with wavelength-shifting fiber
- Each fiber read by pixel on multi-anode PMT
- Originally proposed for 2x2 cross-section, but 3x3 provides sufficient resolution
- 7200 blocks, each 3 x 3 x 10 cm^3



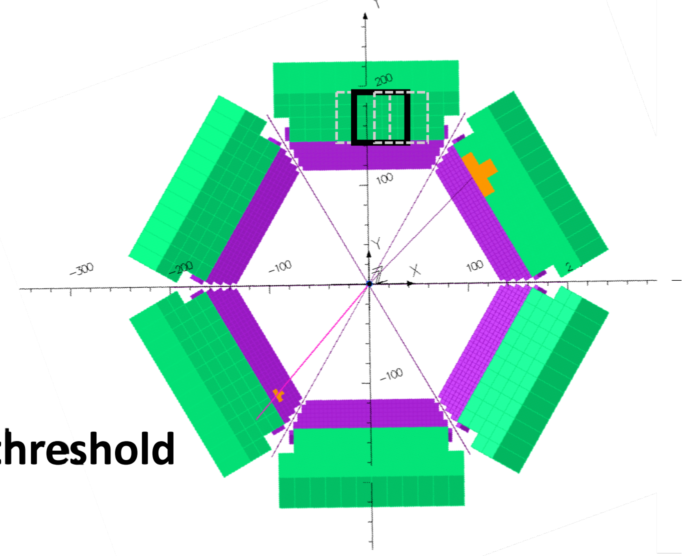
Design matches scintillator array built for GEP

- 2400 elements, 0.5 x 4 x 50 cm^3
- Already built, will run soon





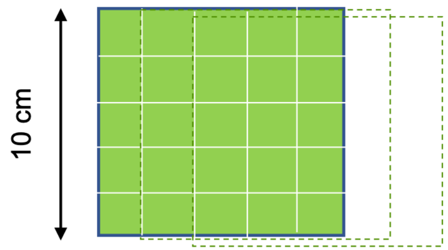
Triggering and Analysis



Grouping into "subsystems" for energy threshold and coincidence triggering

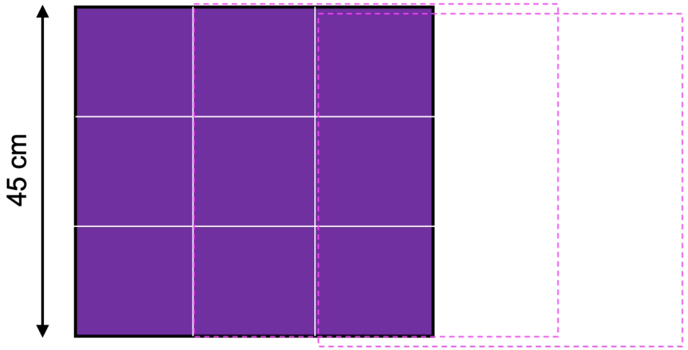
- each polar column of detectors, overlapping with neighbors
- sum amplitude with conservative coincidence timing window
- compare to conservative energy threshold
- trigger when complementary (ECAL and HCAL) subsystems are both above **threshold**

Electron subsystems

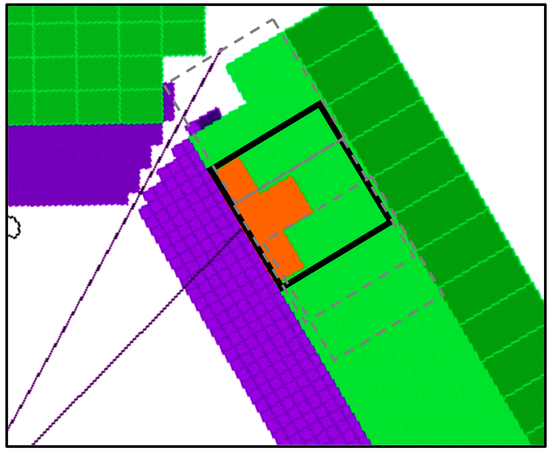


- 1000 $PbWO_4$ crystals
- 2x2x20 cm^3
- 5x5 grouping for subsystem
- 200 overlapping subsystems

Proton subsystems



- 288 iron/scintillators
- 15.5x15.5x100 cm^3
- 3x3 grouping for subsystem
- 96 overlapping subsystems



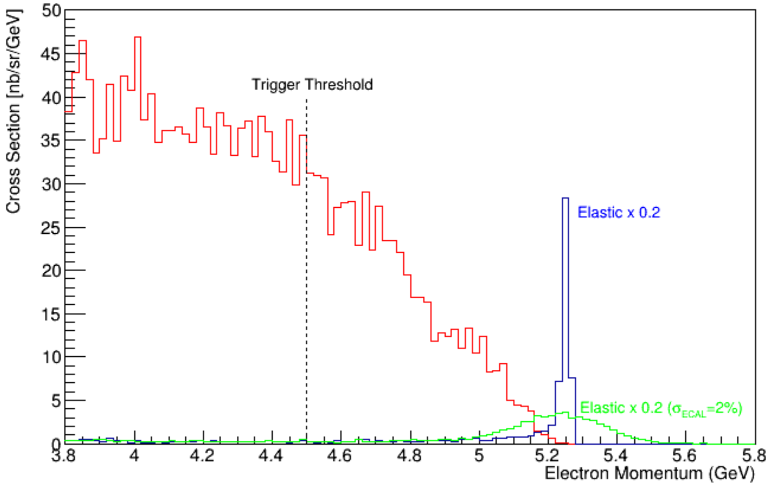
Subsystems adjacent crystals

Rates and Precision

Beam and target: 60 uA on 10 cm LH_2 => luminosity is 1.6×10^{38} cm^{-2}/s

Trigger (online)

- Elastic 37 kHz signal in full detector
- Inelastic (pion production) coincidence trigger rate ~10 kHz
- Accidental coincidence rate < 0.2 kHz
  - ~60 kHz total singles rate in ECAL > 5 GeV energy threshold
  - ~1.2MHz total singles rate in HCAL > 50 MeV energy threshold
- Temporal coincidence cut 40ns
- ~50 kHz total coincidence trigger rate



Offline analysis

- clustering, scintillator array to improve geometric cuts, tighter acceptance and ECAL cut, 4ns timing
- Accepted elastic signal reduced to 14 kHz - production statistics
- Inelastic (pion production) <0.5%, accidentals $<1\times10^{-5}$ due to higher E cut, angular precision

Beam polarization 85%

30 days runtime ⟶ Raw asymmetry statistical precision $\delta(A_{raw})$ ~ 5 ppm

⟶ A_{PV} = -150 +/- 6.2 ppm

Error budget

Apv expected to be -150 ppm (without Strange FF)

quantity	value	contributed uncertainty
Beam polarization	85% ± 1.5%	1.8%
Beam energy	6.6 +/− 0.003 GeV	0.1%
Scattering angle	15.5° ± 0.03°	0.4%
Beam asymmetries	<100 nm,<10 ppm	0.2%
Backgrounds	< 0.5%	0.5%
G_E^n/G_{Dipole}	0.41 ± 0.04	0.6%
G_E^p/G_{Dipole}	0.75 ± 0.02	0.5%
G_{Mn}/G_{Dipole}	1.01 ± 0.02	1.7%
G_M^p/G_{Dipole}	1.08 ± 0.01	0.9%
$G_A^{Zp}/G_{\text{Dipole}}$	-0.15 ± 0.02	0.9%
Total systematic uncertainty:		3.0%

(Polarimetry precision better than 1% has been achieved for multiple experiments)

or 4.5 ppm

Statistical precision for A_{PV}: 6.2 ppm (4.1%)

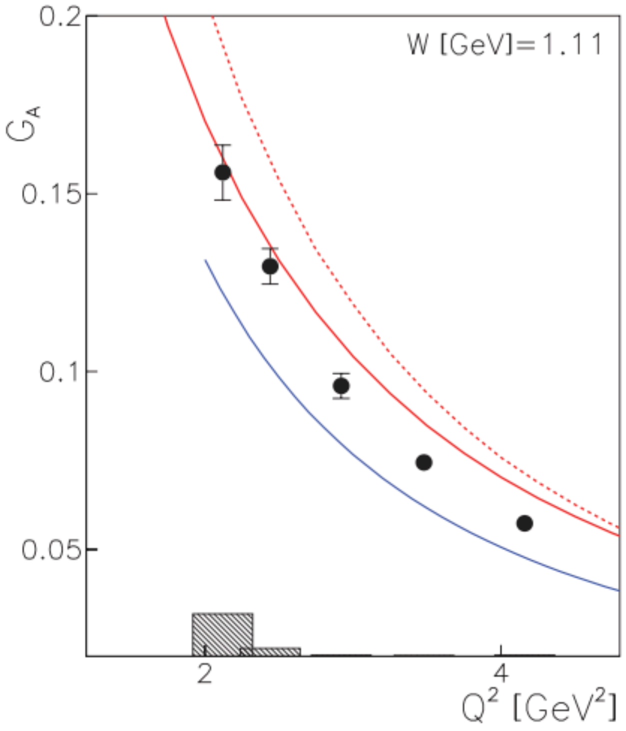
- With 30 days of production running

There is also an uncertainty from radiative correction, is small except for a dominant “anapole” piece.

If the anapole uncertainty is not improved, this would contribute at additional 4.1 ppm (2.7%) uncertainty

Axial FF Contributions

$$A_A = (1 - 4\sin^2\theta_W)\epsilon' G_M^p \tilde{G}_A$$



K. Park *et al*. [CLAS Collaboration], Phys. Rev. C **85**, 035208 (2012).

- Axial form factor parameterization $G_A{}^p = 0.15$ at $Q^2 = 2.5$ GeV^2

  C. Chen, C. S. Fischer, C. D. Roberts, and J. Segovia, Form factors of the nucleon axial current, Physics Letters B 815, 136150 (2021)

- Confirmed with pion photoproduction measurements

  K. Park *et al*. [CLAS Collaboration], Phys. Rev. C **85**, 035208 (2012).

  - (~15% interpretation uncertainty)

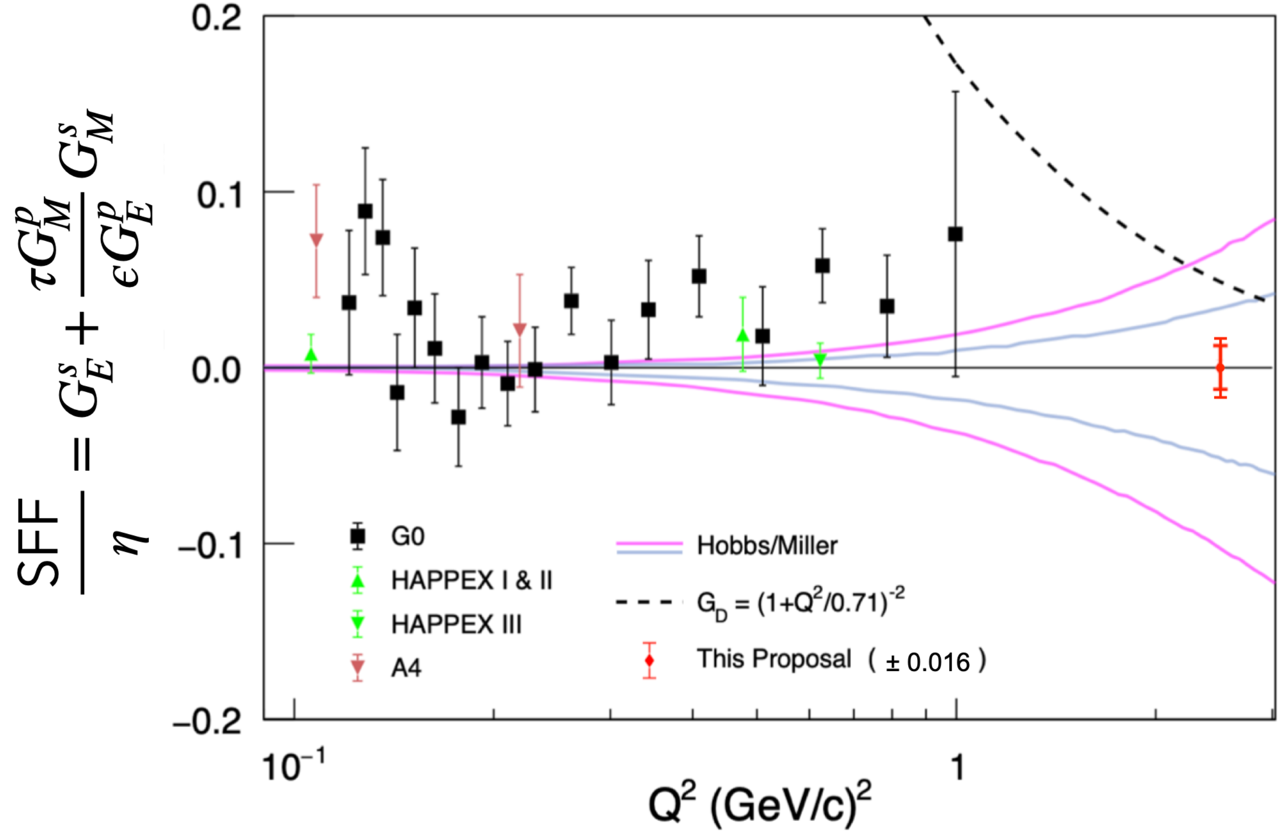
  I.V. Anikin, V.M. Braun, and N. Offen, Phys.Rev.D 94 (2016) 3, 034011.

- How uncertain is this measurement because of it?
  - **Axial term ~6% of A_{PV}**
  - ~15% uncertainty, so estimate **1% relative uncertainty** on the 4% statistical measurement

Projected result

$\delta A_{PV} = \pm 6.2$ (stat) ± 4.5 (syst)

$\delta\left(G_E^s + 3.1G_M^s\right) = \pm 0.013$ (stat) $\pm$ 0.010 (syst) $= 0.016$ (total)



If $G_M^s = 0$, $\delta G_E^s \sim 0.016$, (about 34% of G_D)

If $G_E^s = 0$, $\delta G_M^s \sim 0.0052$, (about 11% of G_D)

The proposed measurement is especially sensitive to G_M^s

The proposed error bar reaches the range of lattice predictions, and the empirically unknown range is much larger.

Summary

Search for a Nonzero Strange Form Factor of the Proton at 2.5 (GeV/c)^2

- 10+ years after the last sFF searches were performed, a new experiment is proposed for much higher Q2, motivated by interest in flavor decomposition of electromagnetic form factors
- Measurement of A_{pv} in e-p scattering at high $Q^2 = 2.5$ GeV^2 with projected accuracy of 11% of the dipole value
- The proposed error bar is in the range possibly suggested by lattice predictions, and significantly inside the range from the simple extrapolation from previous data
- Coincidence-Parity measurement with highly segmented calorimeters
- Goal: Confirm whether Strange Form Factor is zero or non-zero in this kinematic region
- Result informs the breakdown of U/D scaling
- These results will be crucial to support the interpretation of the nucleon form-factors as constraints on GPDs
- Allows for flavor decomposition at high Q^2