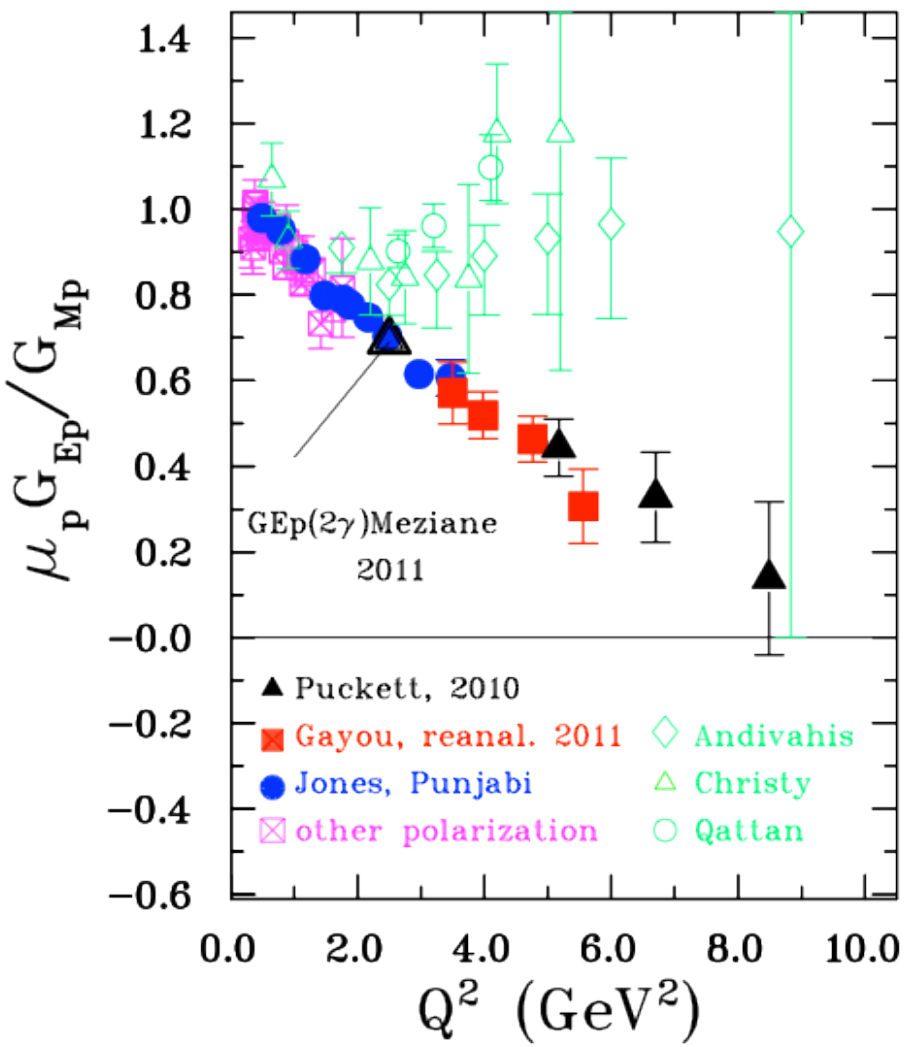
Jefferson Lab
Thomas Jefferson National Accelerator Facility

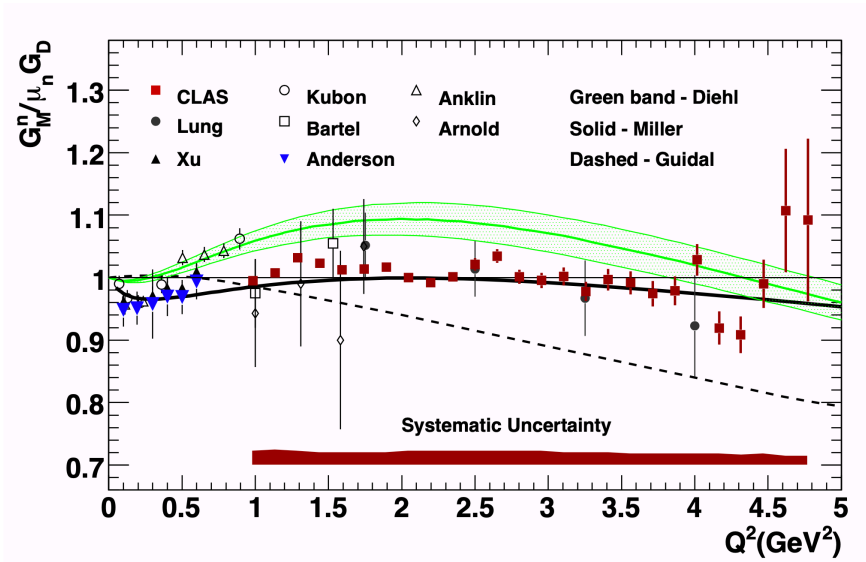
Nucleon Form-Factors at High Momentum Transfer

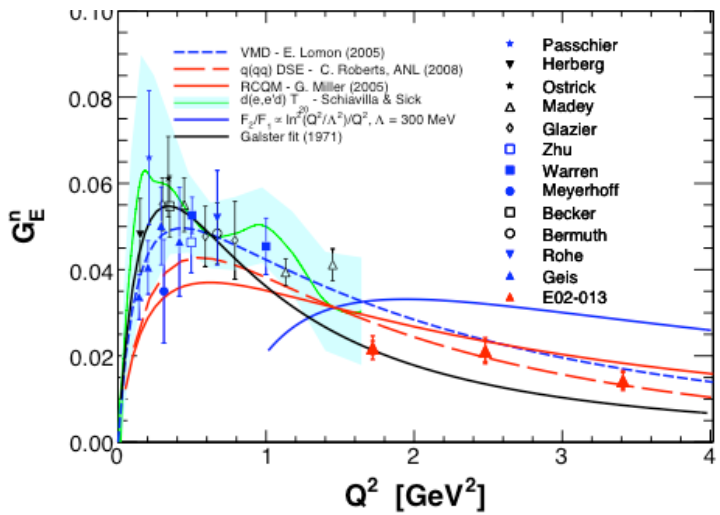
Bogdan Wojtsekhowski, Jefferson Lab

Jefferson Laboratory

The major research highlights include:

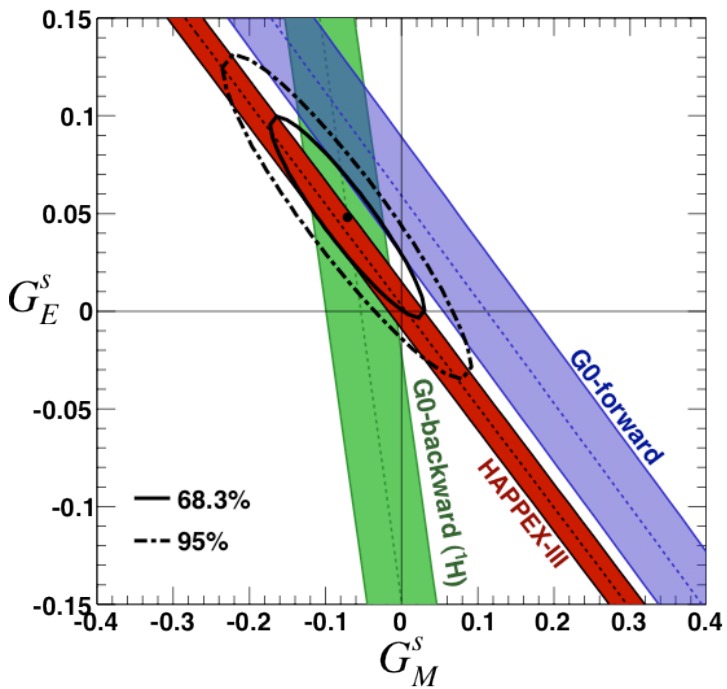


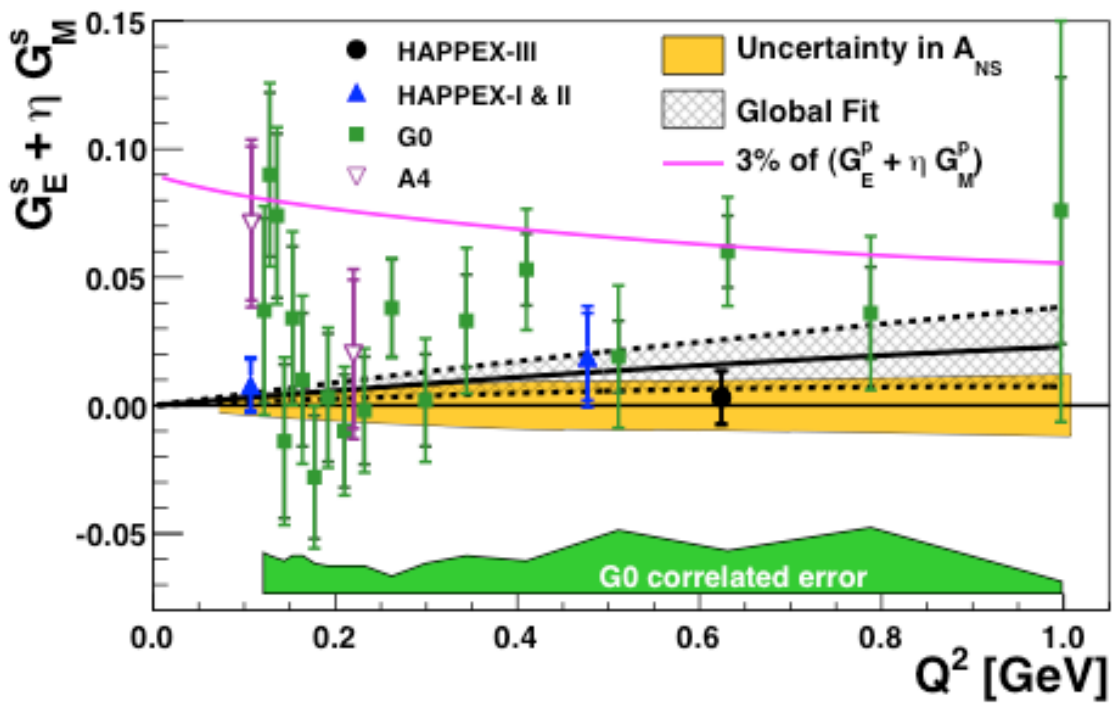




Jefferson Laboratory

Proton strangeness Form Factors via parity non-conserving elastic electron scattering





Composite structure of the nucleon

O.Stern,1937

The magnetic moment of the proton was measured by the method of the magnetic deflection of molecular beams employing H_2 and HD. The result is $\mu P=2.46\mu_0 \pm 3$ *percent.*

E.Fermi,1947

PHYSICAL REVIEW VOLUME 72, NUMBER 12 DECEMBER 15, 1947

On the Interaction Between Neutrons and Electrons*

E. FERMI AND L. MARSHALL
Argonne National Laboratory and Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received September 2, 1947)

The possible existence of a potential interaction between neutron and electron has been investigated by examining the asymmetry of thermal neutron scattering from xenon. It has been found that the scattering in the center-of-gravity system shows exceedingly little asymmetry. By assuming an interaction of a range equal to the classical electron radius, the depth of the potential well has been found to be 300±5000 ev. This result is compared with estimates based on the mesotron theory according to which the depth should be 12000 ev. It is concluded that the interaction is not larger than that expected from the mesotron theory; that, however, no definite contradiction of the mesotron theory can be drawn at present, partly because of the possibility that the experimental error may have been underestimated, and partly because of the indefiniteness of the theories which makes the theoretical estimate uncertain.

INTRODUCTION

THE purpose of this paper is to investigate an interaction between neutrons and electrons due to the possible existence of a short range potential between the two particles. If such a short range force should exist, one would expect some evidence of it in the scattering of neutrons by atoms. The scattering of neutrons by an atom is mostly due to an interaction of the of nuclear forces. According to these theories, proton and neutron are basically two states of the same particle, the nucleon. A neutron can transform into a proton according to the reaction:

$$N=P+\bar{\mu}. \qquad (1)$$

(N=neutron, P=proton, $\bar{\mu}$=negative mesotron)

Actually, a neutron will spend a fraction of its time as neutron proper (left-hand side of Eq. (1))

Electro-Magnetic Form Factors

Rosenbluth (1950)

One-photon approximation, α_{em} = 1/137, hadron current

$$\mathcal{J}^{\mu}_{hadronic} = ie\overline{N}(p')\left[\gamma^{\mu}F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2M}F_2(Q^2)\right]N(p)$$

Akhiezer (1958)

At large Q^2, study of G_E requires use of polarization observables - FFs at JLab

Arnold, Carlson and Gross (1981)

$1\gamma+2\gamma$ expression for M has three complex functions, F_1, F_2, F_3

$$\mathcal{M} = \frac{4\pi\alpha}{Q^2}\bar{u}'\gamma_\mu u \cdot \bar{N}'\left(\tilde{F}_1\gamma^\mu - \tilde{F}_2[\gamma^\mu,\gamma^\nu]\frac{q_\nu}{4M} + \tilde{F}_3 K_\nu\gamma^\nu\frac{P^\mu}{M^2}\right)N$$

Guichon & Vanderhaeghen

$$\tilde{G}_M = \tilde{F}_1 + \tilde{F}_2 \qquad \tilde{G}_E = \tilde{F}_1 - \tau\tilde{F}_2$$

$\tilde{F}_i$ are functions of $(s-u)$ and t

$$d\sigma = d\sigma_{NS}\left\{\varepsilon(\tilde{G}_E + \frac{s-u}{4M^2}\tilde{F}_3)^2 + \tau(\tilde{G}_M + \varepsilon\frac{s-u}{4M^2}\tilde{F}_3)^2\right\}$$

$$\sigma_R = \varepsilon G_E^2 + \tau G_M^2 +$$
$$+2\tau G_M \mathcal{R}e\left(\delta\tilde{G}_M + \varepsilon\frac{s-u}{M^2}\tilde{F}_3\right) + 2\varepsilon G_E\,\mathcal{R}e\left(\delta\tilde{G}_E + \frac{s-u}{M^2}\tilde{F}_3\right)$$

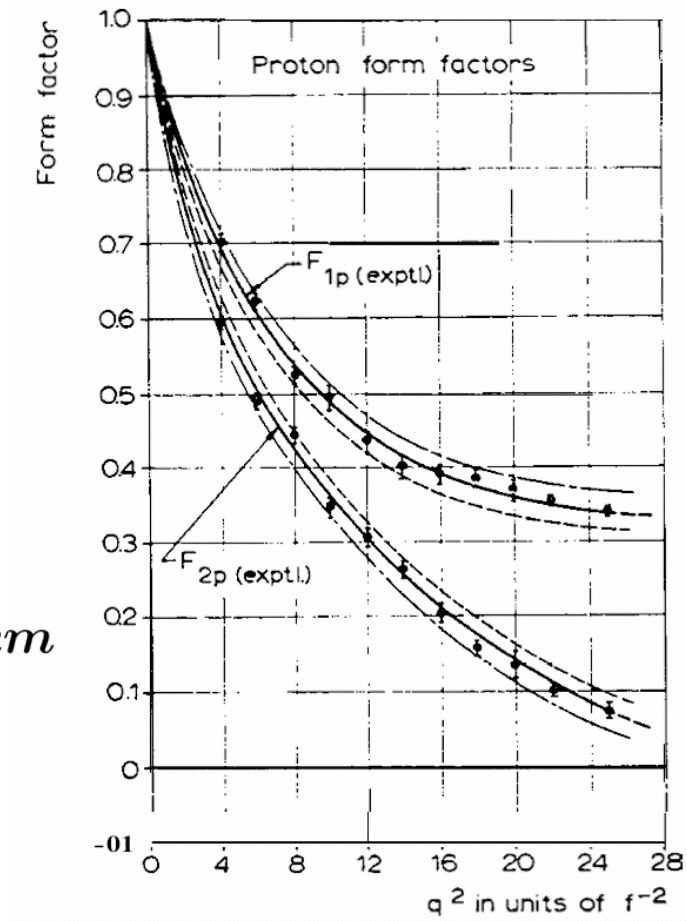
The first measurement of the Form Factors

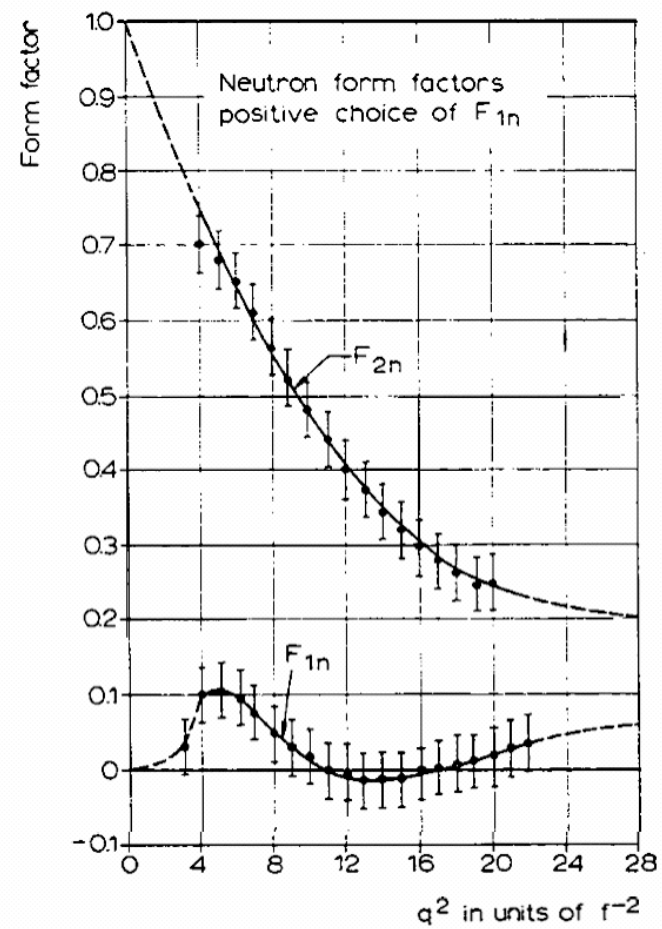
R.Hofstadter, 1956

$$r_e = r_m = 0.8 \times 10^{-13}\, cm$$

$$\rho = \rho_0 \times e^{-\sqrt{12}\, r/r_{e,m}}$$

$$F(q) = \frac{1}{[1+(q\,r)^2/12]^2}$$





SLAC results for the proton Form Factors

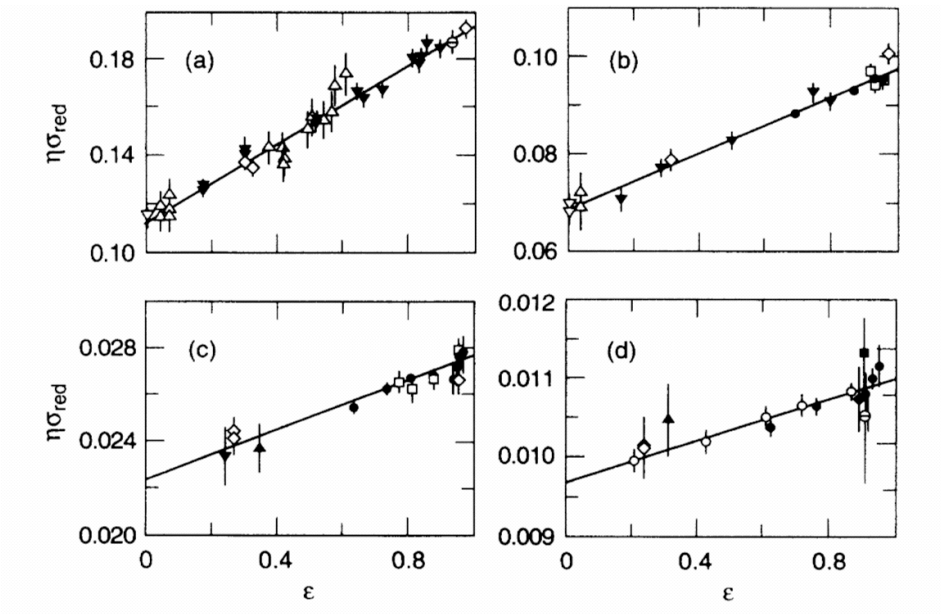
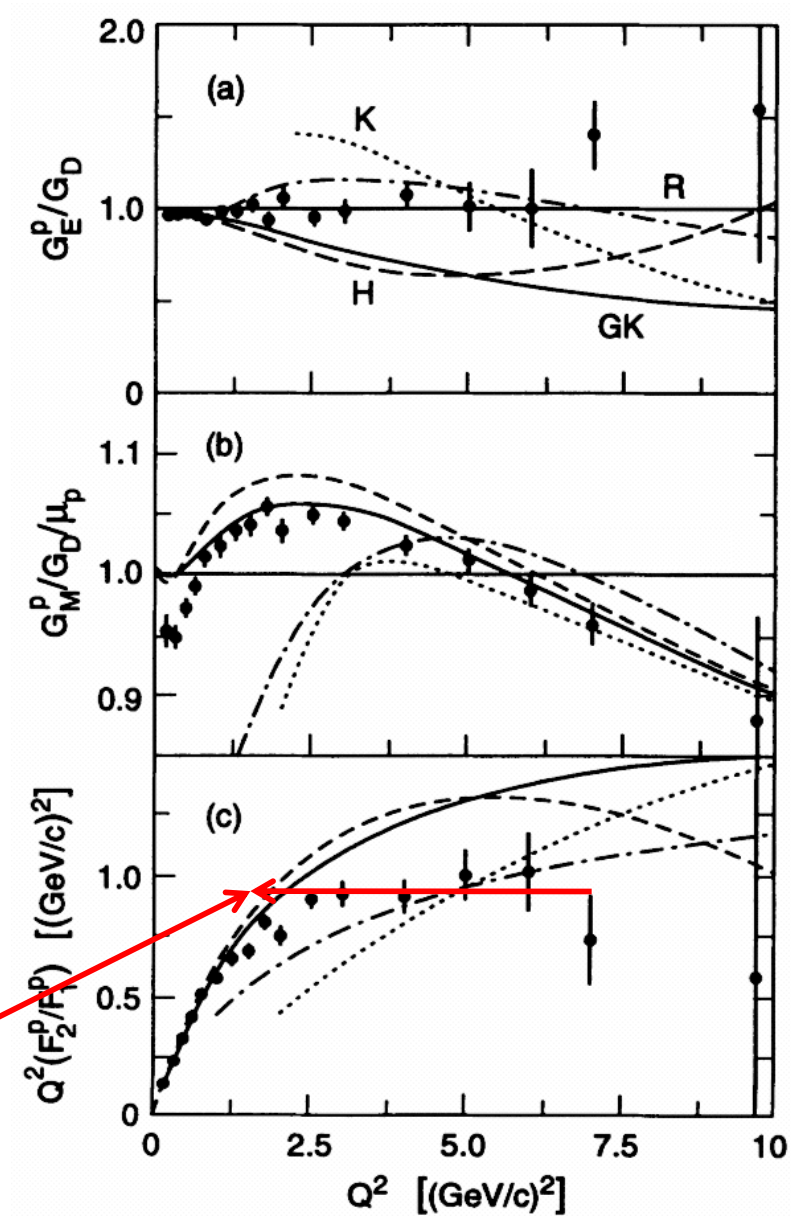


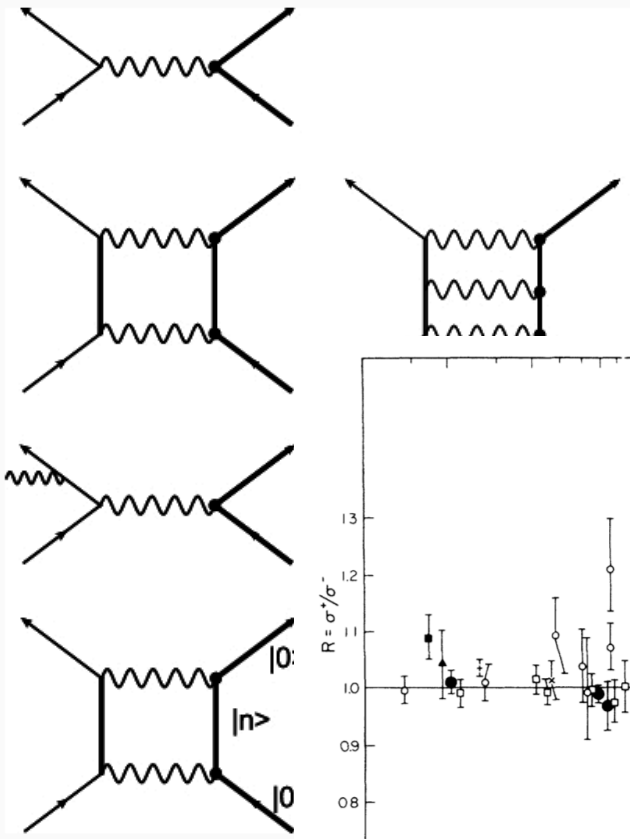
FIG. 9. Four typical Rosenbluth fits for the form factor extraction from the global data set at (a) $Q^2 = 0.6$, (b) $Q^2 = 1.0$, (c) $Q^2 = 2.0$, and (d) $Q^2 = 3.0$ $(\mathrm{GeV}/c)^2$.

Walker et al,1993



The onset of the pQCD scaling?

Higher order diagrams



PHYSICAL REVIEW VOLUME 106, NUMBER 3 MAY 1, 1957

Proton Polarizability Correction to Electron-Proton Scattering*

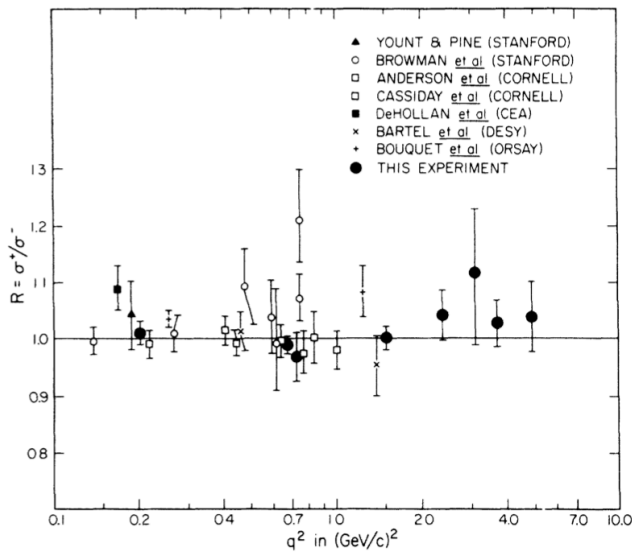
S. D. DRELL, *Stanford University, Stanford, California*

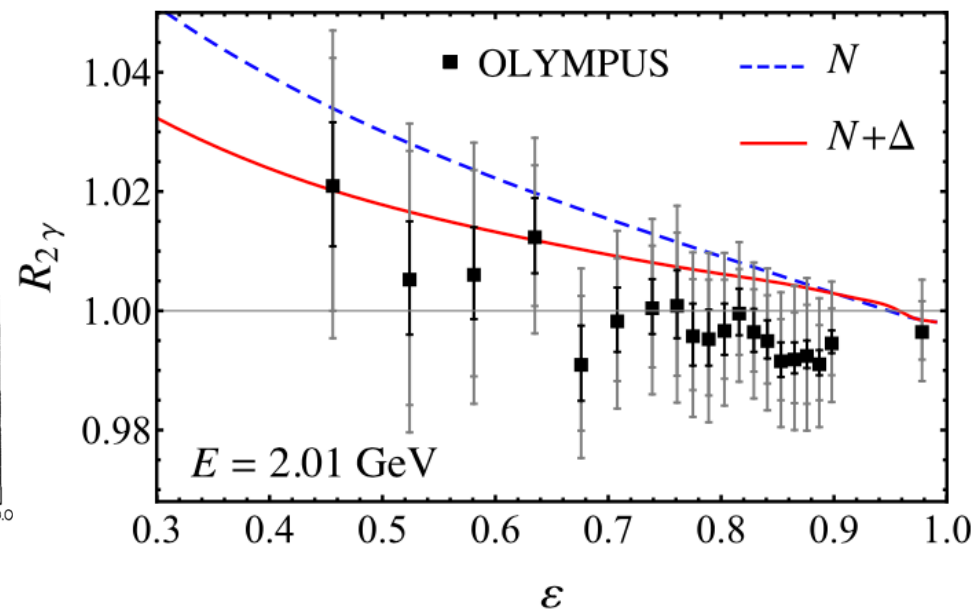
AND

M. A. RUDERMAN, *University of California, Berkeley, California*

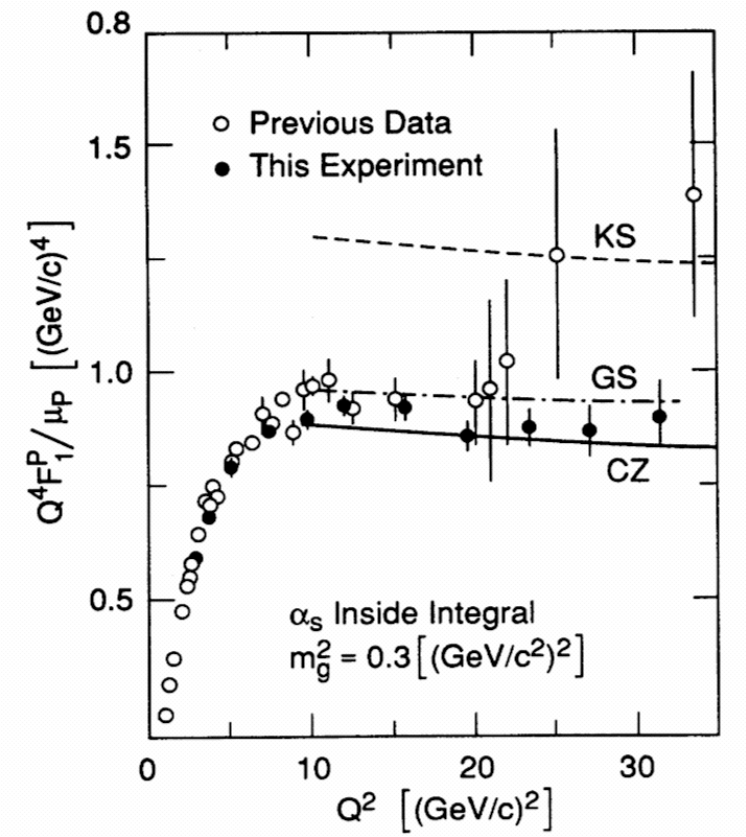
(Received January 23, 1957)

The contribution to observed electron-proton scattering cross sections of the electron-induced polarization of the proton is estimated and found to be small for electron energies <500 Mev.



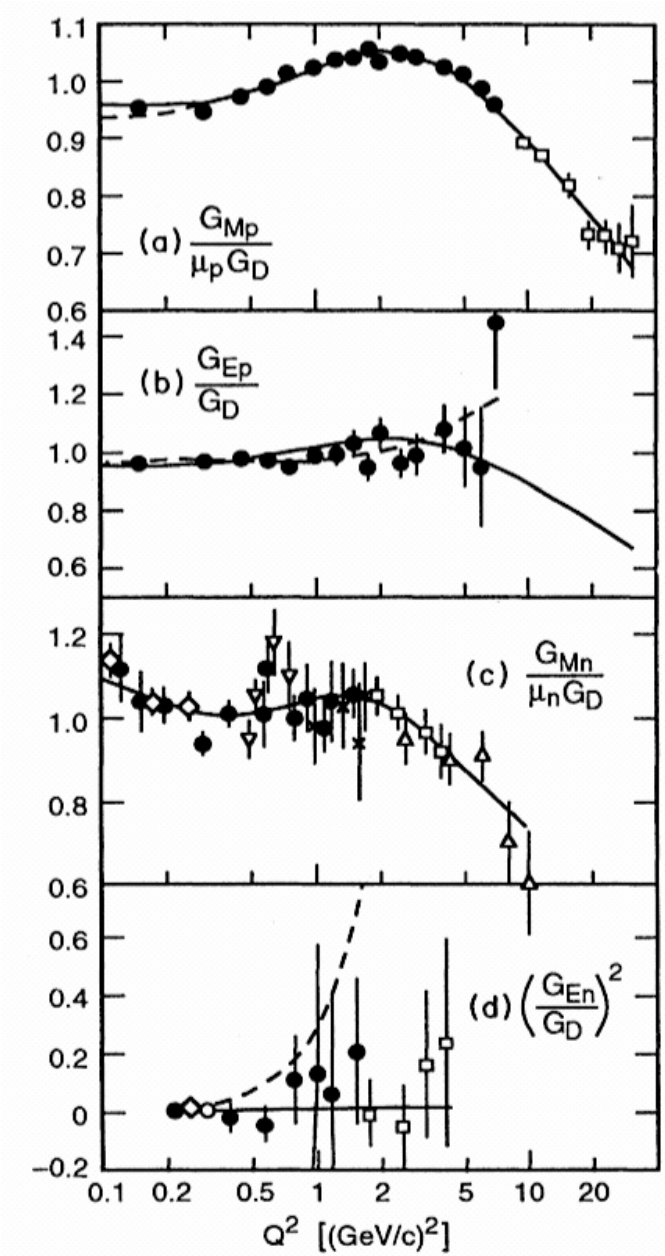


SLAC results for the Form Factors

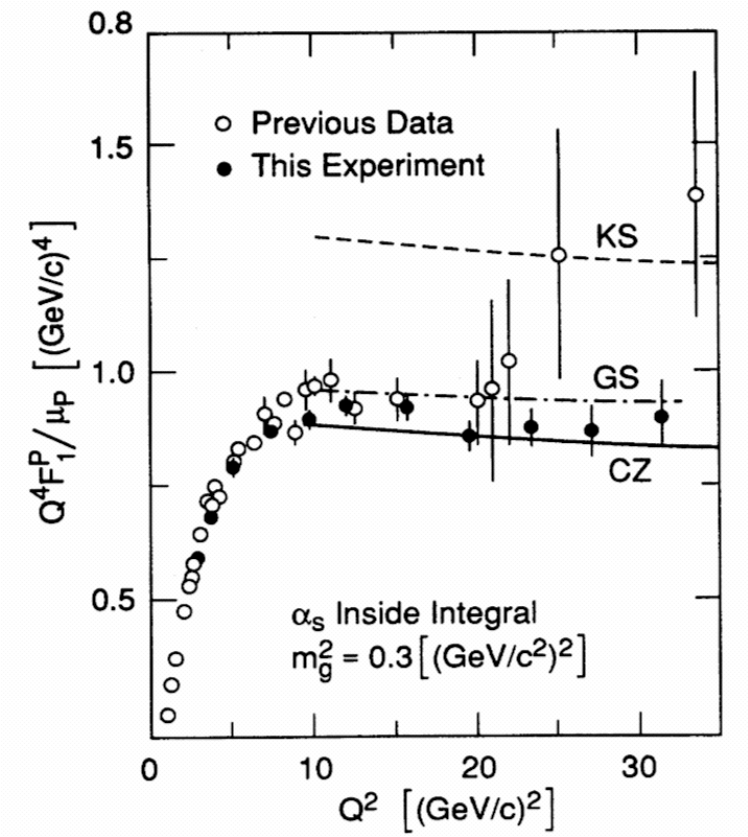


Sill et al,1993

Bosted,1995

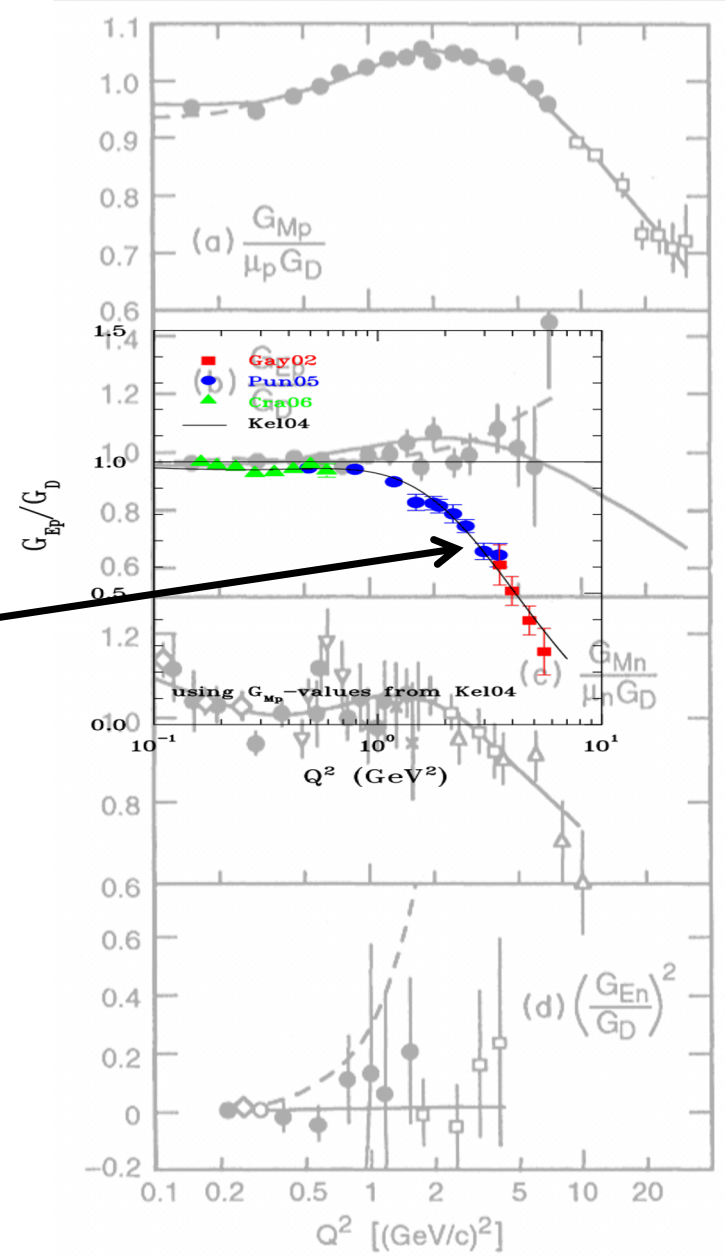


Results for the Form Factors



Sill et al,1993

Perdrisat, 2001

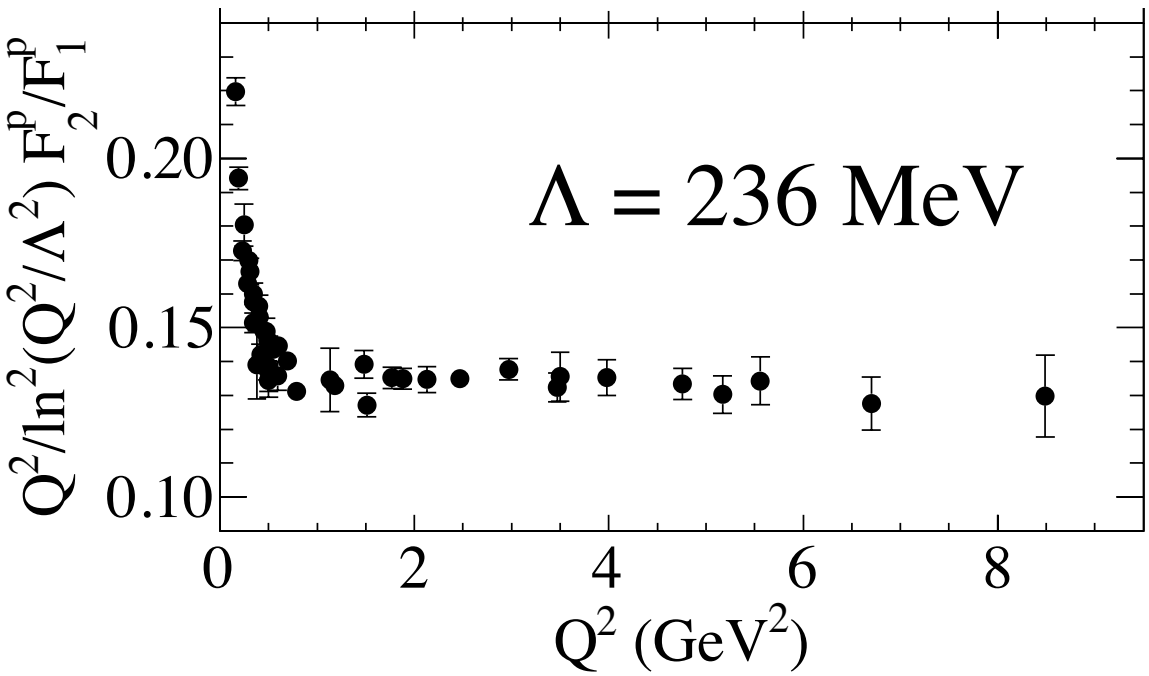


Nucleon form factors scaling

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

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

Analysis was motivated by pQCD: Q^2F_2/F_1 = const

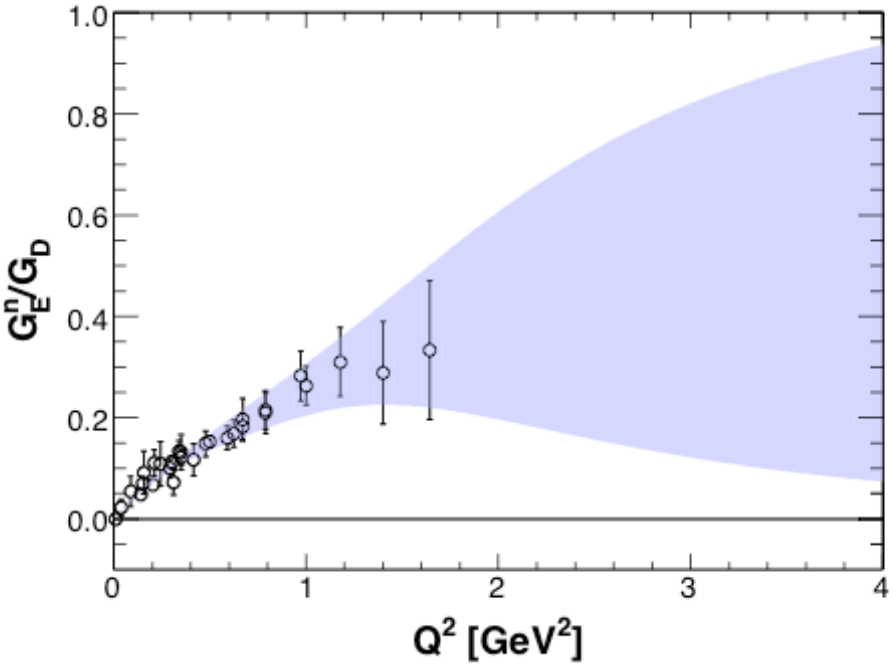


Balitsky-Ji-Yuan:
Modified logarithmic scaling works from surprisingly low Q^2

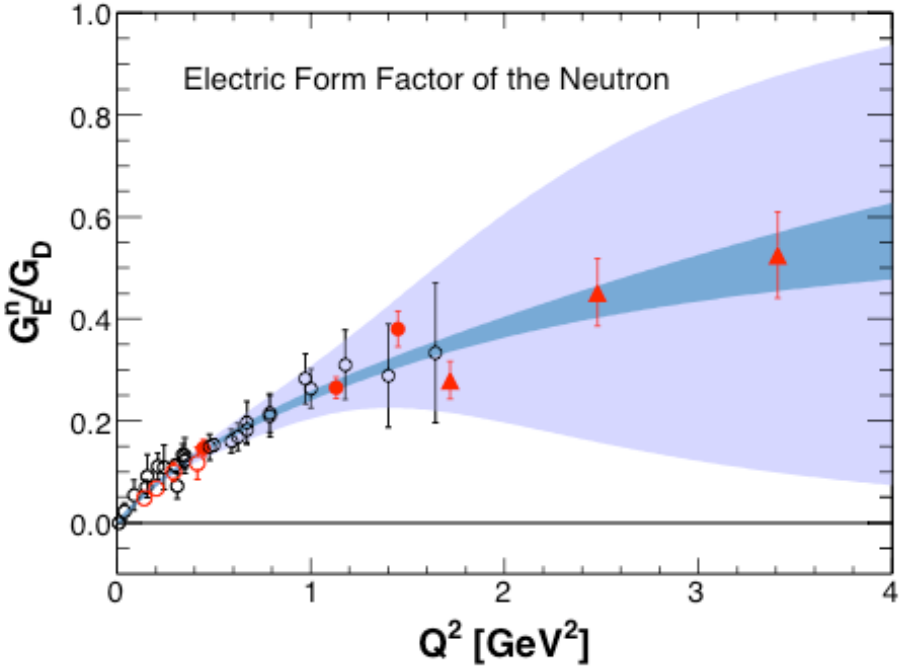
courtesy of A. Puckett

The JLab G_E^n experiments

without JLab GEn experiments



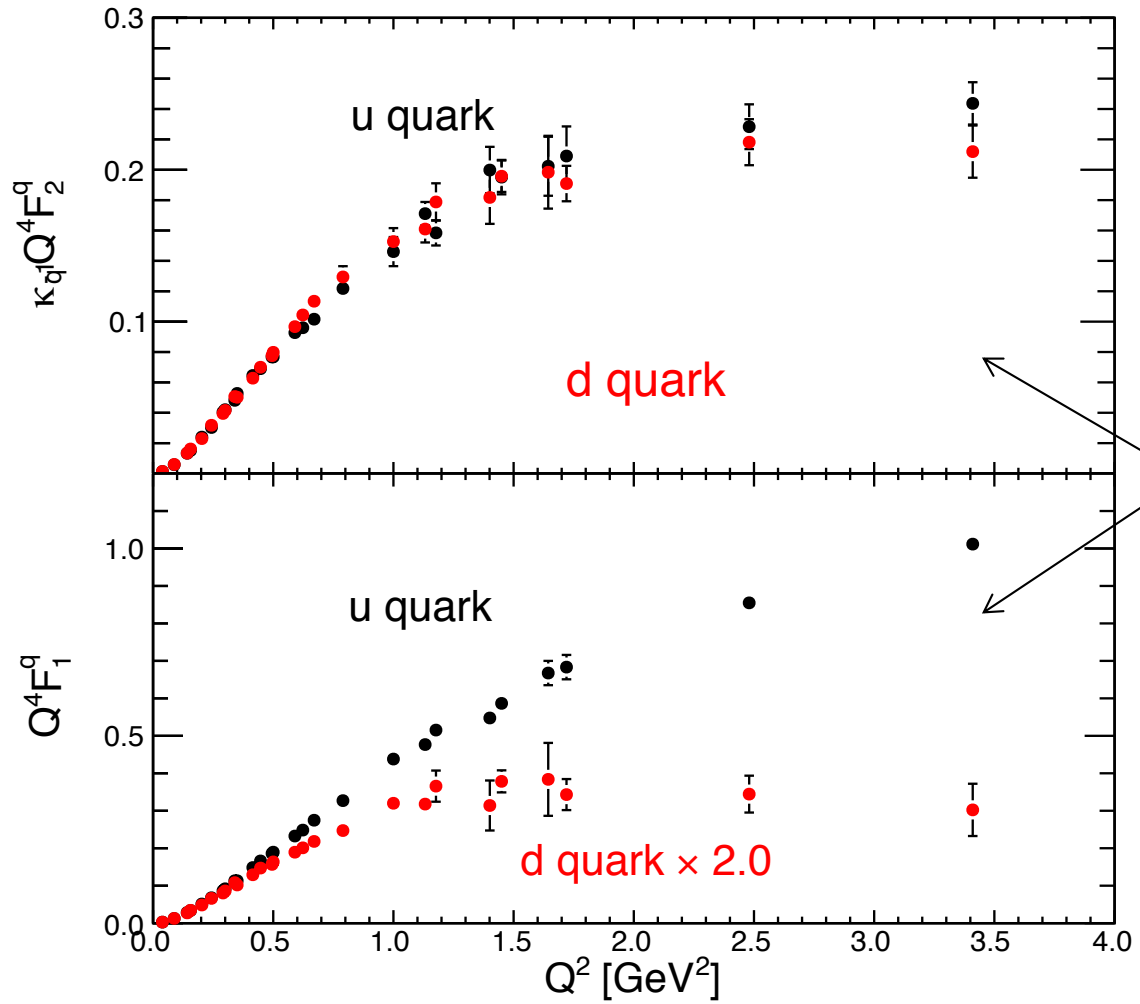
significantly better accuracy for high Q^2



F. Gross, 1987
CEBAF
Physics program

(iv) *Measurement of the charge structure of the neutron and deuteron*. Coincidence techniques must be used to measure these basic quantities, and hence the capabilities of CEBAF will be needed to obtain accurate measurements at high Q^2. These important quantities are sensitive to quark distributions.

Four contributions to the nucleon FFs



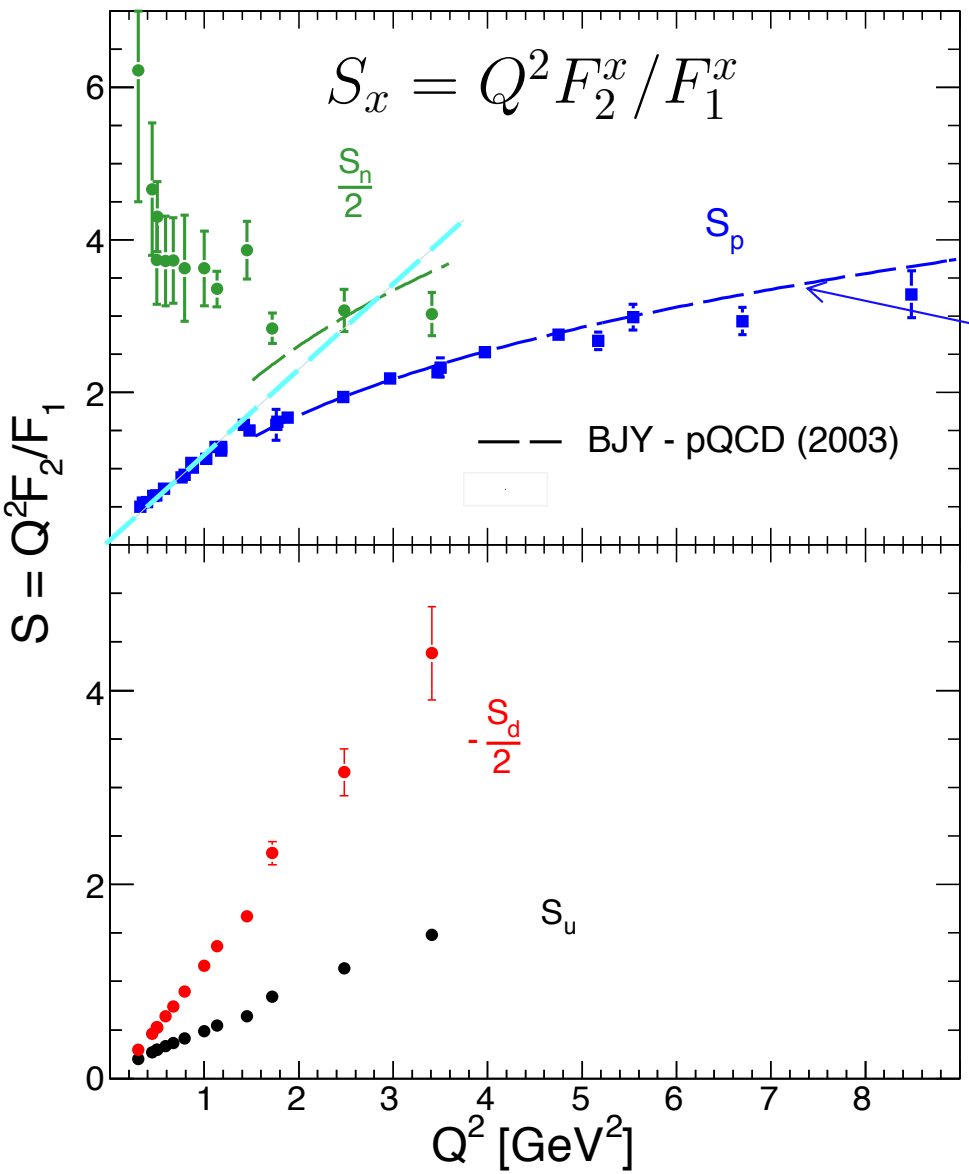
CJRW (u/d with new GEn data)
Phys. Rev. Lett. 106 (2011)

M.Diehl and P.Kroll (GPDs)
Eur.Phys.J. C73 (2013) 2397

Using the D&K table of F^u, F^d

The down quark contribution to the F_1 proton form factor is strongly suppressed at high Q^2

The goal is understanding of the nucleon



pQCD prediction for large Q^2:

$$S \to Q^2 F_2/F_1$$

pQCD updated prediction:

$$S \to \left[Q^2/\ln^2(Q^2/\Lambda^2)\right] F_2/F_1$$

Flavor separated contribution: The log scaling for the proton Form Factor ratio at few GeV^2 is "accidental".

F_1 is lower than expected!

The lines for individual flavors are straight!

Cates, Jager, Riordan, BW
Physical Review Letters, 106, 252003 (2011)

JLab high-Q^2 data on Form Factors change our notion of the nucleon

- The notion that all FFs are like a Dipole fit is gone!

  JLab discovered that the proton GE/GM varies with Q^2.
  JLab observed a factor of three drop in $F1_d$ relative to $F1_u$.

- The nucleon is not an SU3 symmetric object.
  The role of quark orbital angular momentum needs clarity.

  The u-d correlations are at the center of investigation.
  The DSE solution of QCD suggests that these correlations are responsible for the 3-quark bound state.

Study of nucleon structure requires IMF GPDs in the impact parameter representation

$$F_1(t) = \sum_q e_q \int dx H_q(x,t)$$

Muller, Ji, Radyushkin

$$q(x,\mathrm{b}) = \int \frac{d^2q}{(2\pi)^2} e^{i\,\mathrm{q}\cdot\mathrm{b}} H_q(x, t = -\mathrm{q}^2)$$

M.Burkardt

P.Kroll: u/d segregation

$$\rho(b) \equiv \sum_q e_q \int dx\, q(x,\mathrm{b}) = \int d^2q F_1(\mathrm{q}^2) e^{i\,\mathrm{q}\cdot\mathrm{b}}$$

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

G.Miller

center of momentum $\boldsymbol{R}_\perp = \sum_i x_i \cdot r_{\perp,i}$

$\boldsymbol{b}$ is defined relative to $\boldsymbol{R}_\perp$

Transverse center of the quarks longitudinal momentum fractions

Sachs Form Factors before 12-GeV

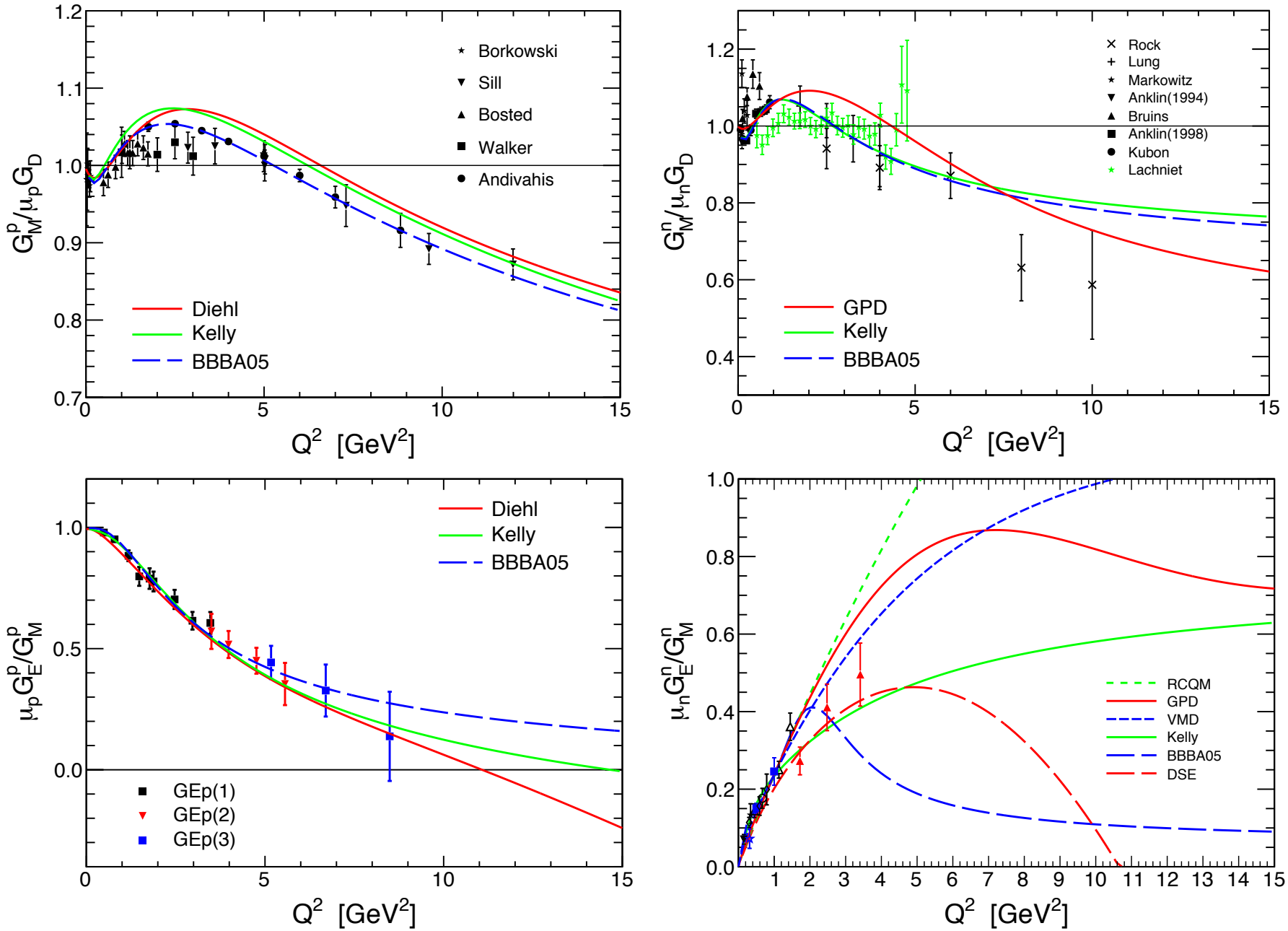


Figure-of-Merit for O&TA experiments

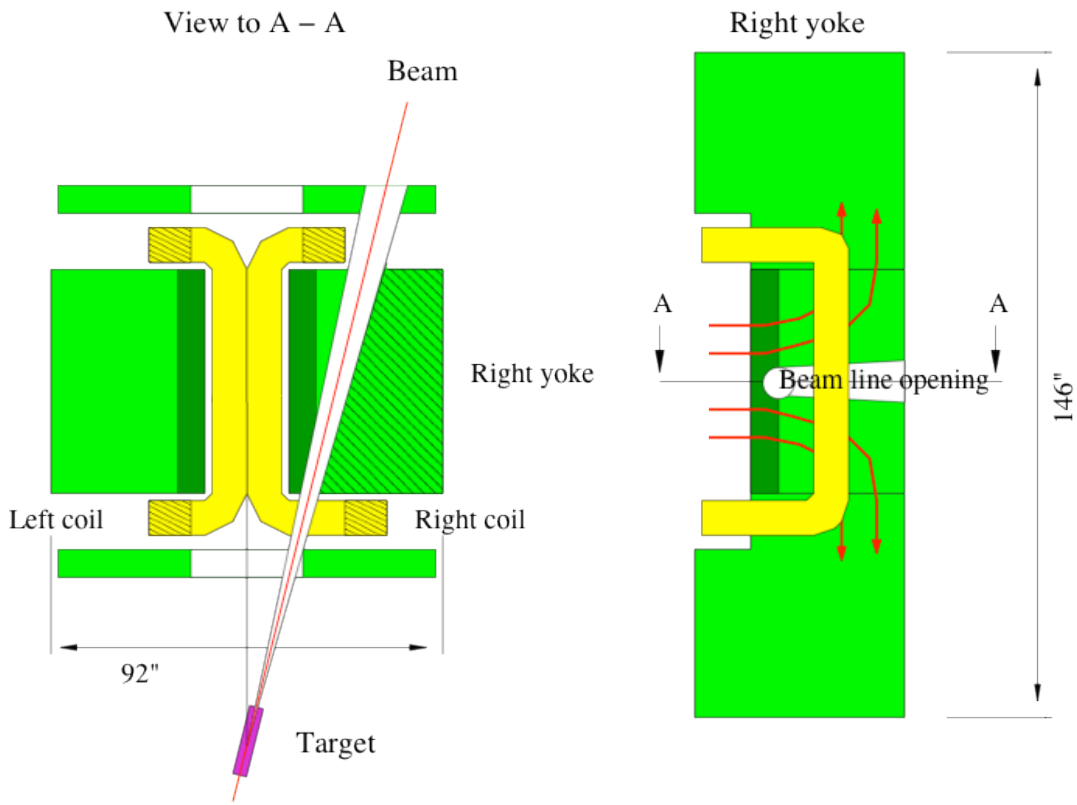
One-arm experiments: high $\mathcal{L}$ and large Ω ($\Delta Q^2/Q^2 \sim 0.1$) :
The Super Bigbite Spectrometer is the best choice due to large solid angle $\Omega = 70$ msr and detector rate capability

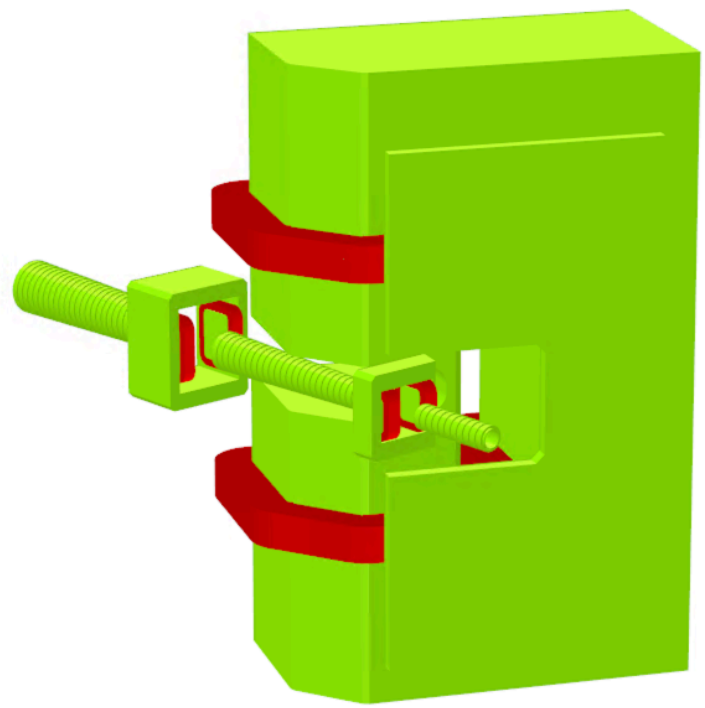
Two-arm experiments deal with elastic or quasi-elastic
$p_m \sim 0.2$ GeV/c for the nuclei; ~ 0.5-1 GeV/c for the nucleon
The high $Q^2/t/\nu$ experiment N(e,e'h) means $p_h \sim 2$-8 GeV/c;
70 msr of SBS acceptance: the detector captures efficiently events up to
$p_m \sim p_h/5$ => one setting could be a whole experiment

$$FOM = \mathcal{L} \times \Omega_{electron} = \boxed{10^{38}} \cdot 0.07 = 7 \times 10^{36}$$

$$electron/s \times nucleon/cm^2 \times sr$$

Super Bigbite Spectrometer



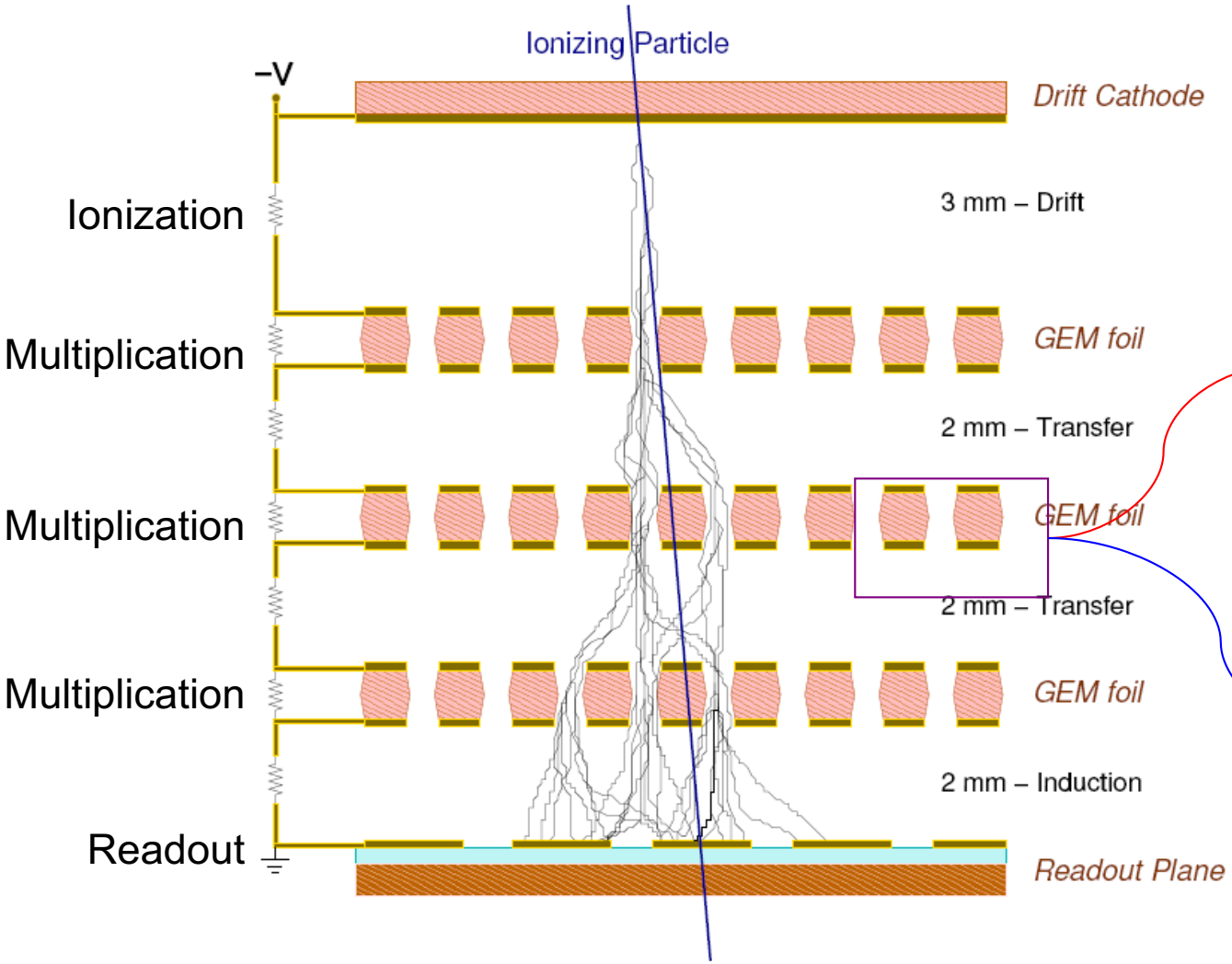


48D48 – 46x155 cm^2 aperture and 2.5 Tesla*m

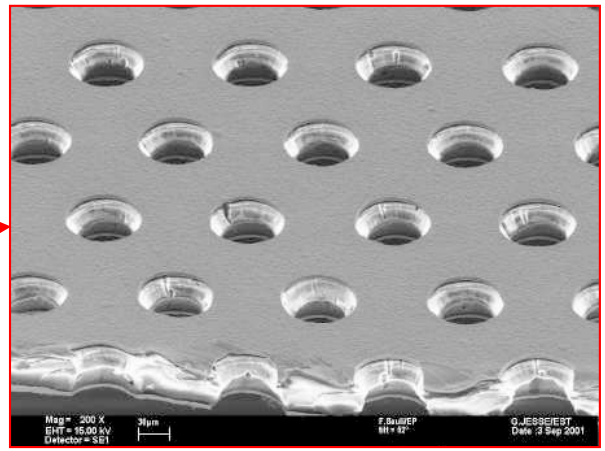
GEM chambers with 70 μm resolution

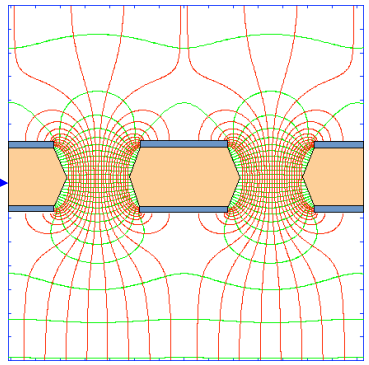
- momentum resolution is 0.5% for 5 GeV/c
- solid angle is 70 msr at angle 15°
- angular resolution is 0.3 mr

Novel coordinate detector



GEM foil: 50 μm Kapton + few μm copper on both sides with 70 μm holes, 140 μm pitch

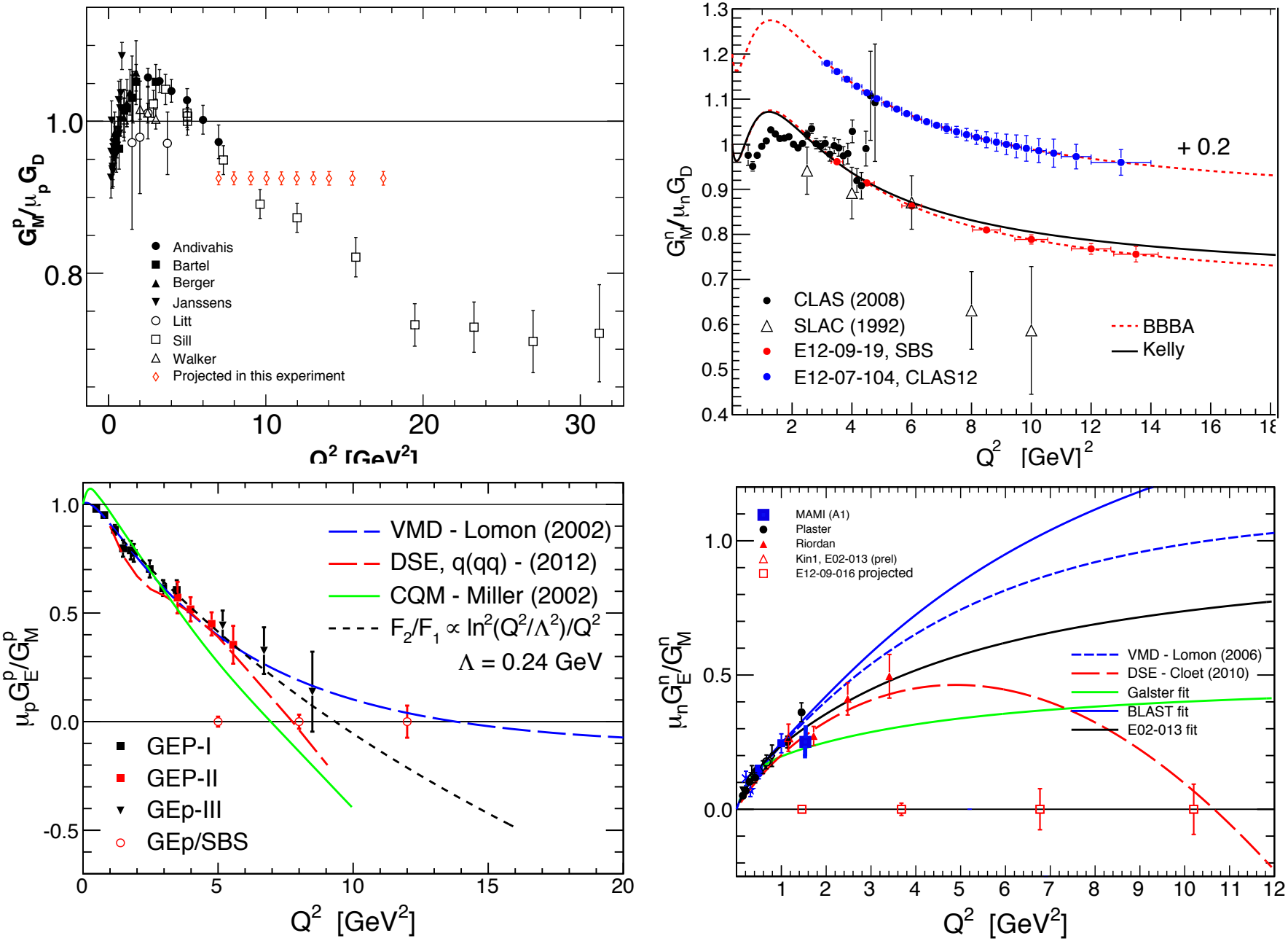




Strong electrostatic field in the GEM holes

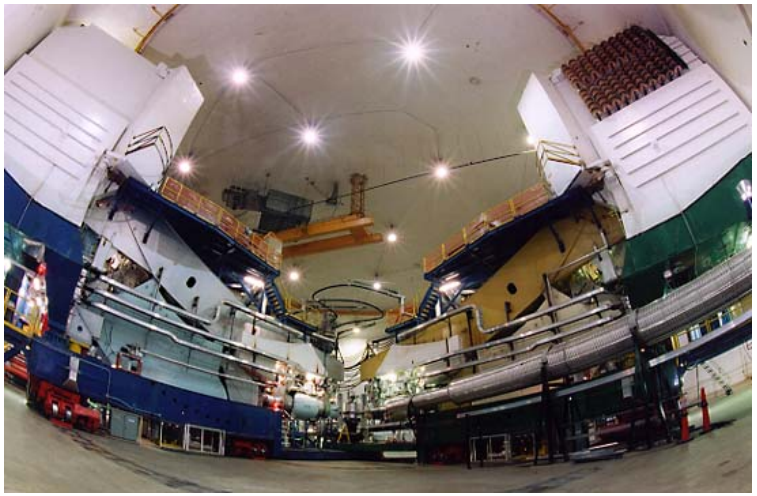
F. Sauli, Nucl. Instrum. Methods A386(1997)531

The nucleon FFs by 2014

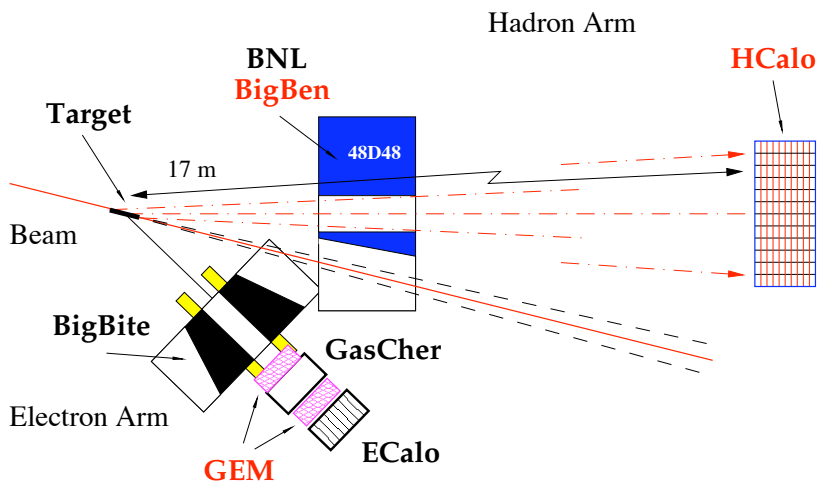


Hall A form factor experiments

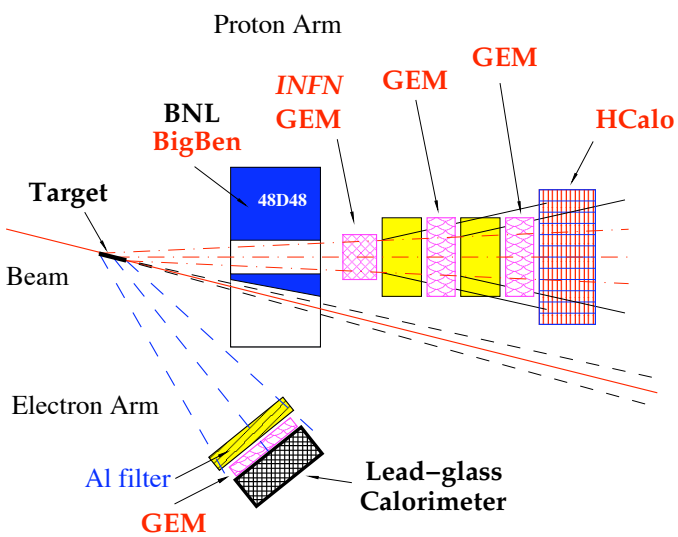
Proton magnetic form factor: E12-07-108



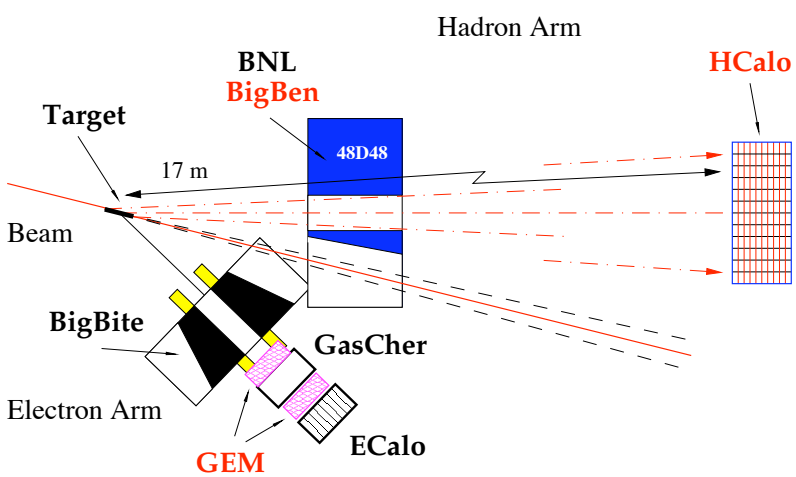
Neutron/proton form factors ratio: E12-09-019



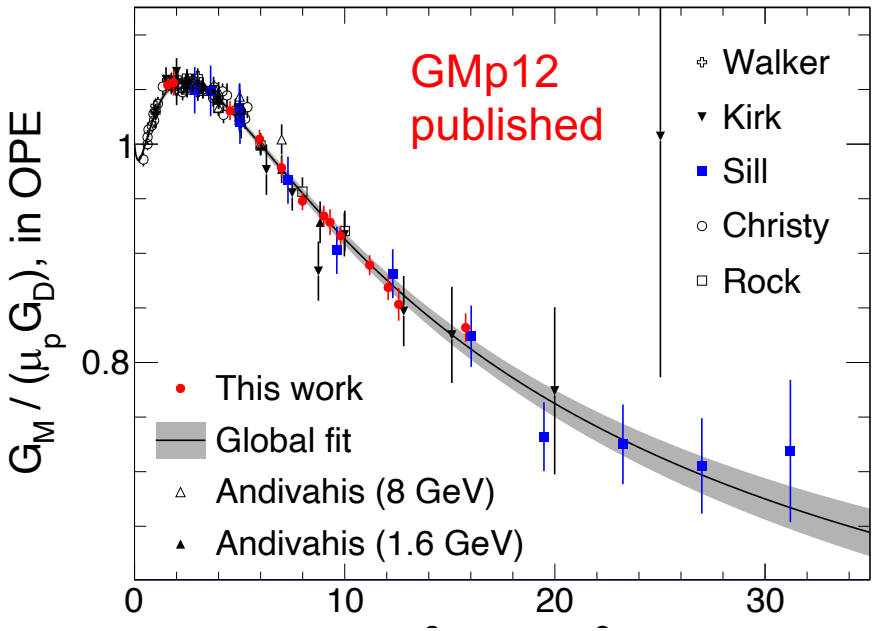
Proton form factors ratio, GEp(5): E12–07–109

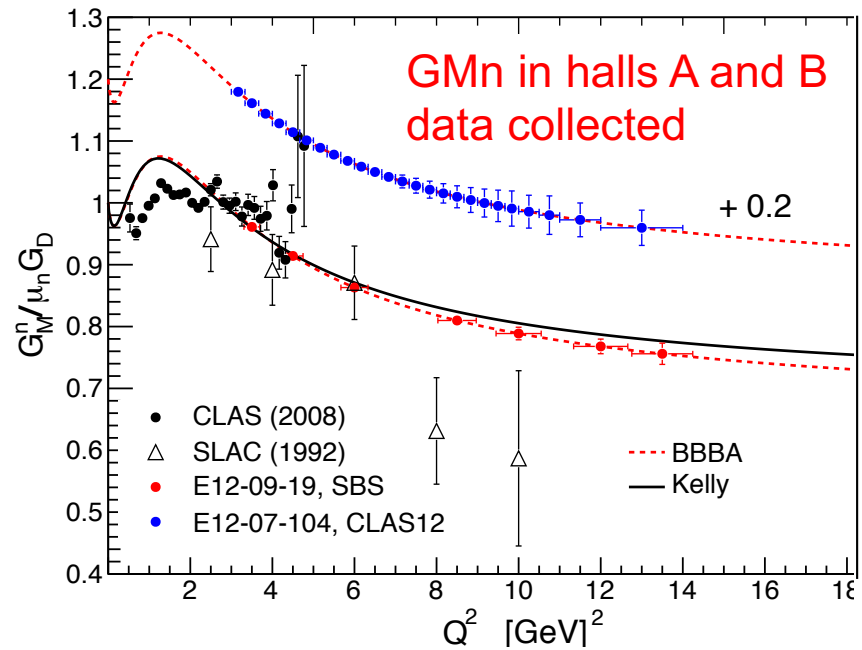


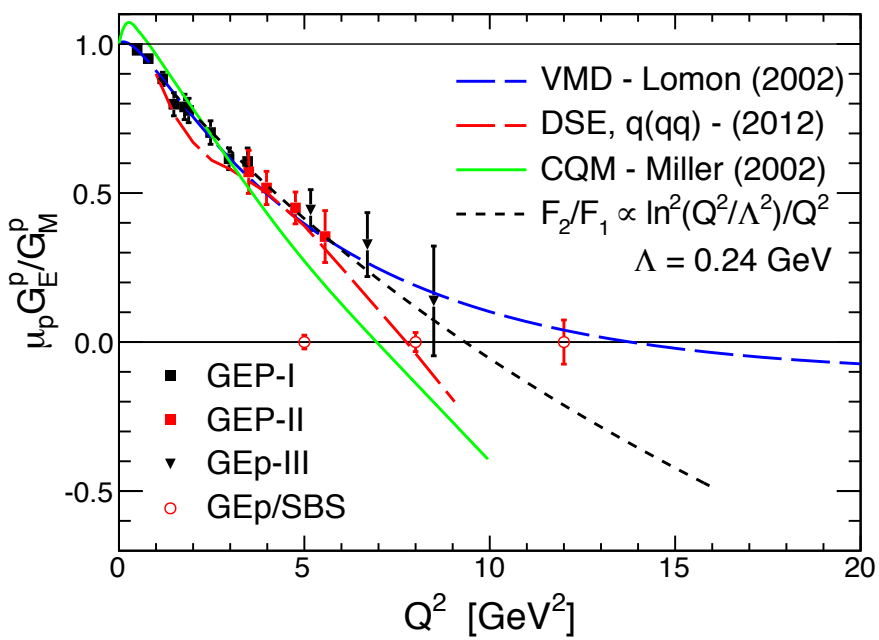
Neutron form factors ratio, GEn(2):E12-09-016

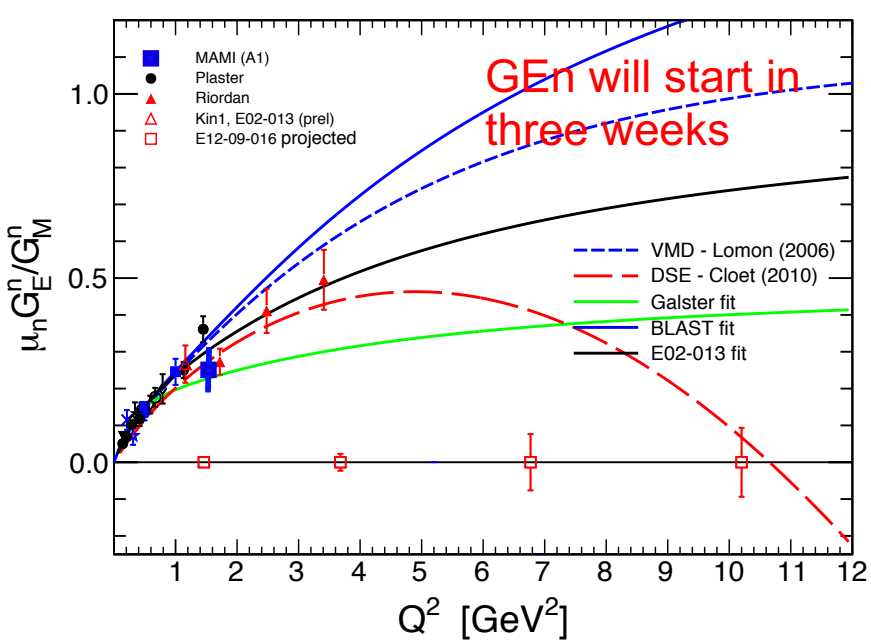


Sachs Form Factors today



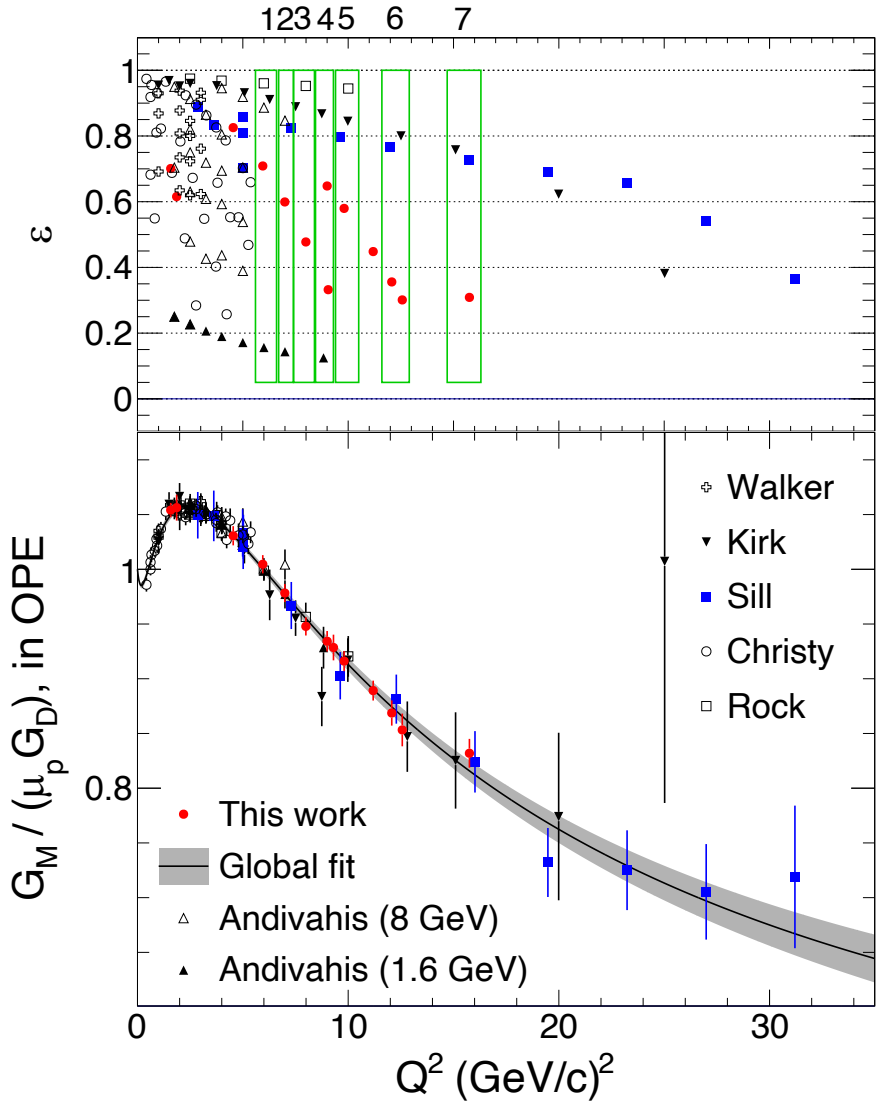


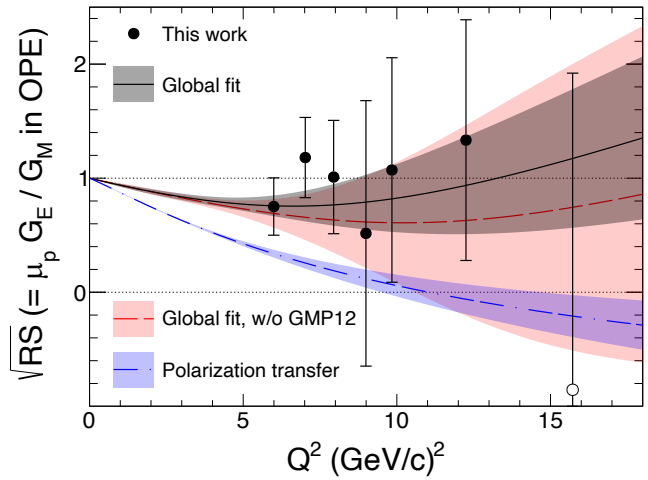




The GMp12 experiment

Phys.Rev.Lett. 128 (2022) 10, 102002





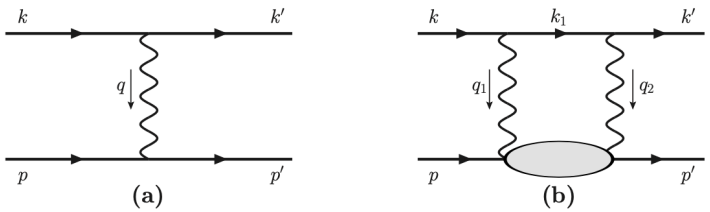
GMp12 fit:

$$G_M = \mu_p (1 + a_1\tau)/(1 + b_1\tau + b_2\tau^2 + b_3\tau^3),$$
$$\mathrm{RS} = 1 + c_1\tau + c_2\tau^2.$$

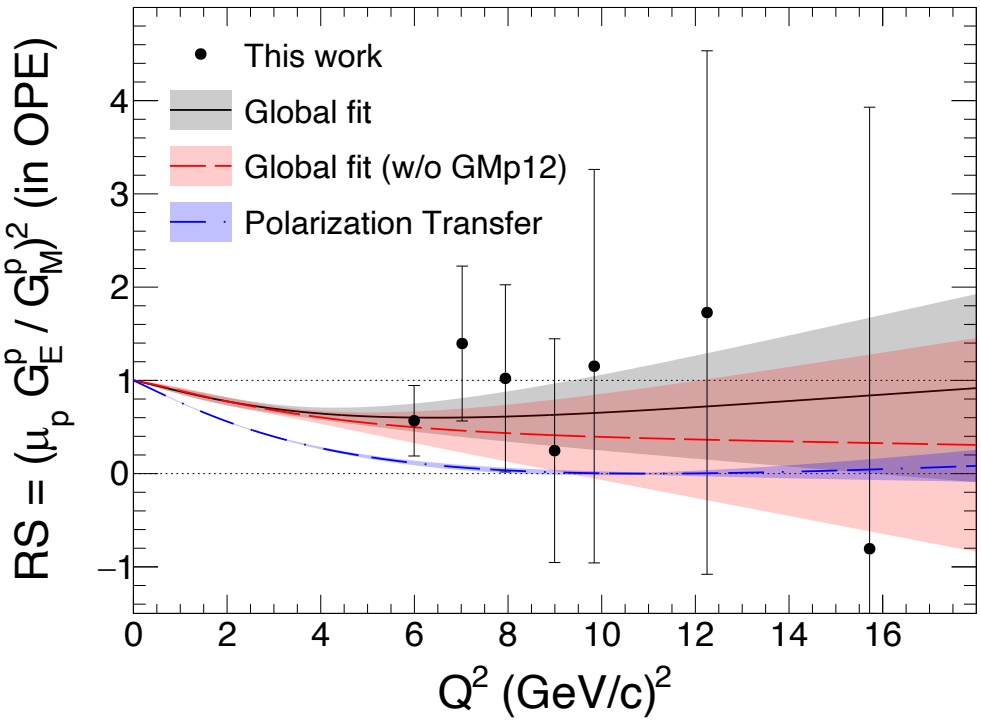
a_1	b_1	b_2	b_3	c_1	c_2
0.072(22)	10.73(11)	19.81(17)	4.75(65)	-0.46(12)	0.12(10)

courtesy of A. Gramolin and A. Puckett

Proton E/M from cross section



$$\sigma_R = \tau\, G_M^2(Q^2) + \varepsilon\, G_E^2(Q^2) = \sigma_T + \varepsilon\, \sigma_L$$
$$= G_M^2(Q^2)(\tau + \varepsilon\, RS(Q^2)/\mu_p^2),$$



Fast moving quarks can not produce a sharp minimum.

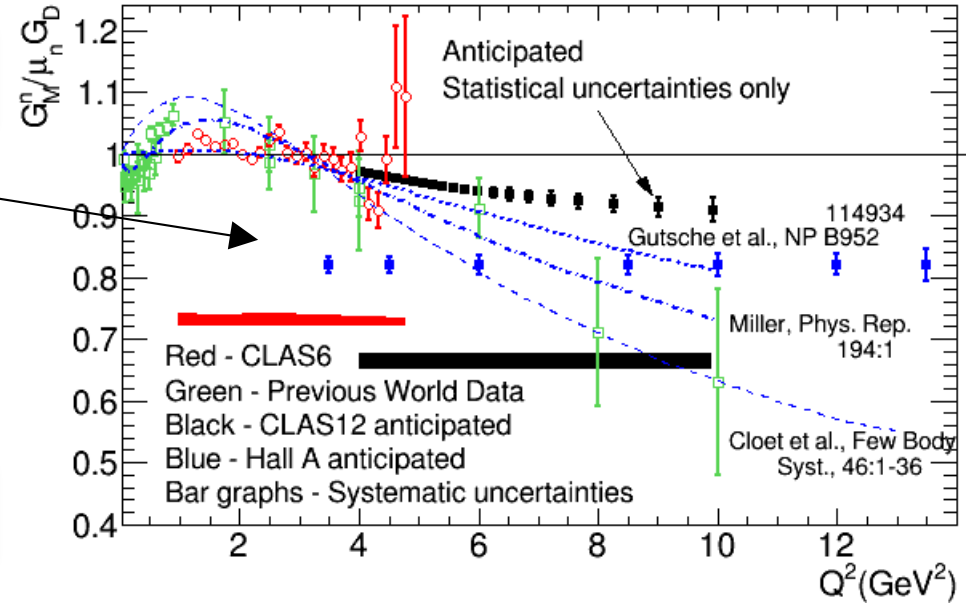
Can a diquark lead to a “minimum” in the form factor? Yes, according to the DSE approach.

Can a diquark play a role in the two-photon exchange contribution?

Neutron Magnetic Form Factor in CLAS12

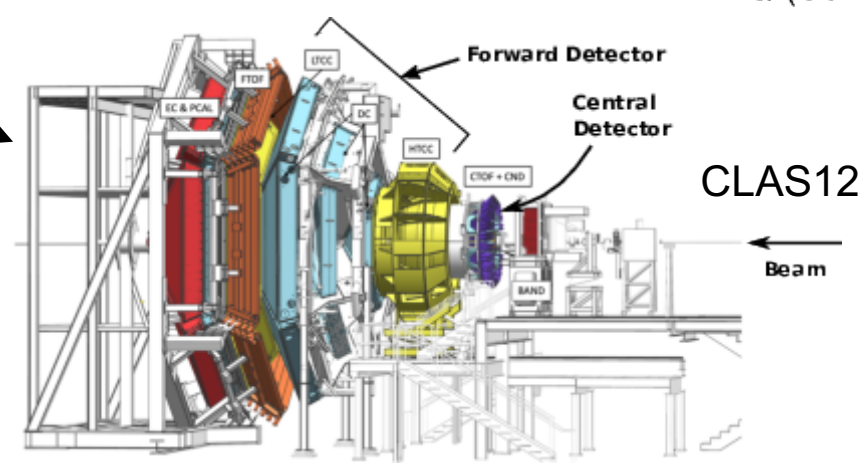
G_M^n Measurement with CLAS12 in Hall B

- Complementary to Hall A measurement – different systematic uncertainties.
- Uses the same *R=e-n/e-p* ratio method.
- Different Q^2 coverage than Hall A – higher angular density, smaller range.
- Run Group B, Lamya Baashen (FIU) thesis.



The CLAS12 Detector

- Covers most of 4π.
- Forward Detector covers Θ = 5 - 40 deg.
- Over 100,000 readouts in 40 layers.



The Data Set – CLAS12 Run Group B

- 43 Billion triggers at 10.2, 10.4, and 10.6 GeV.
- Average beam polarization ~86%.
- 43% of approved beamtime used.
- All runs have completed cooking/pass 1.

courtesy of J. Gilfoyle

Neutron Magnetic Form Factor in CLAS12

Event Selection: Quasielastic (QE) e-p events

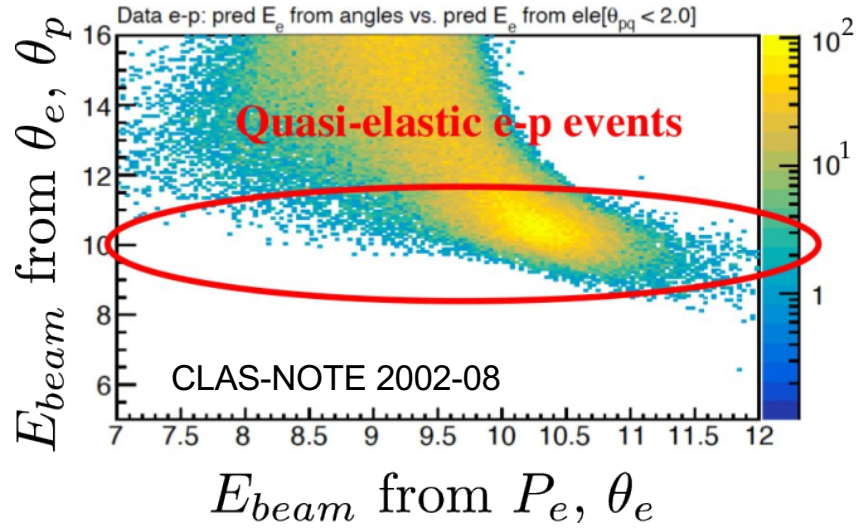
- Assume QE scattering.
- Get E_{beam} using electron P_e and Θ_e AND
- Get E_{beam} using electron Θ_e and Θ_p . Apply cut.
- Require $\Theta_{pq} < 2.0$ *deg* where Θ_{pq} is between the 3-momentum transfer and the proton direction to remove inelastic background.

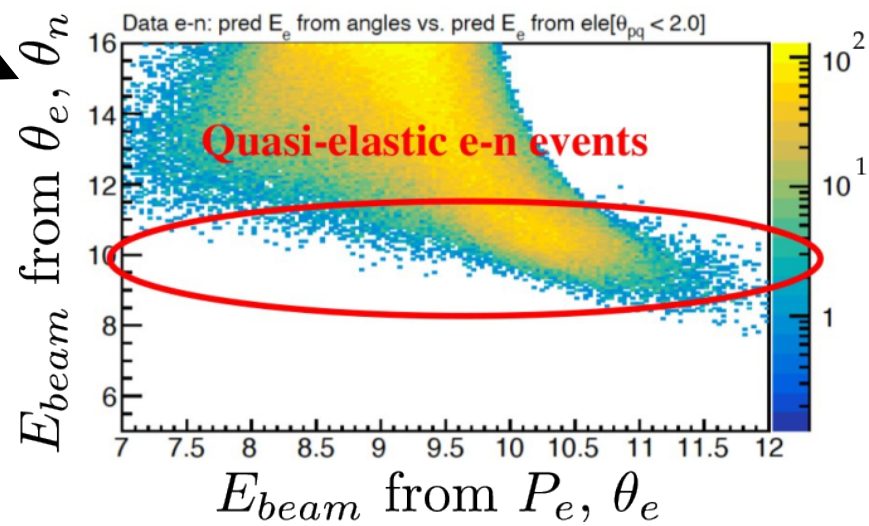
Event Selection: Quasielastic e-n events

- Assume QE scattering and follow the procedure above except use the neutron angle Θ_n .
- Require $\Theta_{pq} < 2.0$ *deg* for the neutron.

Acceptance Matching of *n* and *p* solid angles.

- For each good electron assume QE scattering and calculate proton and neutron trajectories.
- If both trajectories hit CLAS12, keep the event.



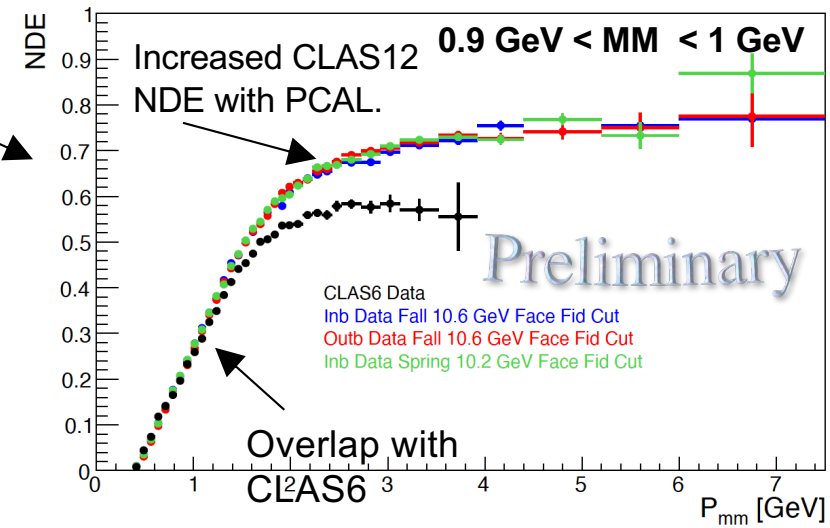


courtesy of J. Gilfoyle

Neutron Magnetic Form Factor in CLAS12

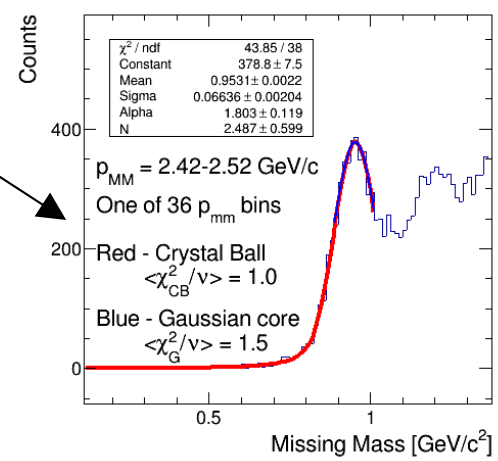
Neutron Detection Efficiency (*NDE*)

- Needed to correct *e-n* yield in the ratio.
- Use the ^{1}H(e,e'π^+n) reaction and the CLAS12 Run Group A data set.
- Use only the e' π^+ information and identify the neutron events with the missing mass.
- Predict the location of the neutron (expected).
- Search for the neutron near that location (detected). *NDE* is ratio of detected/expected.



Status

- Have major components of *R* and *NDE* in hand.
- Validating and testing algorithms with simulations, different methods,…



Exploring fits to the missing mass in 36 missing momentum bins to extract the neutron yield and obtain the *NDE*.

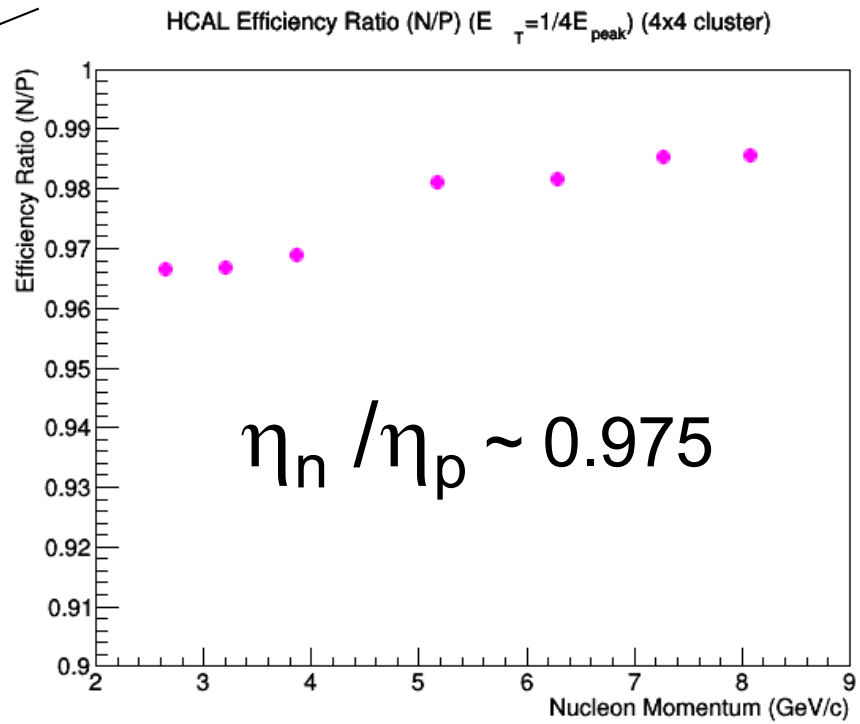
To Do List

- Extract systematic uncertainties.
- More corrections (energy loss, Fermi motion, …)
- Proton detection efficiency

courtesy of J. Gilfoyle

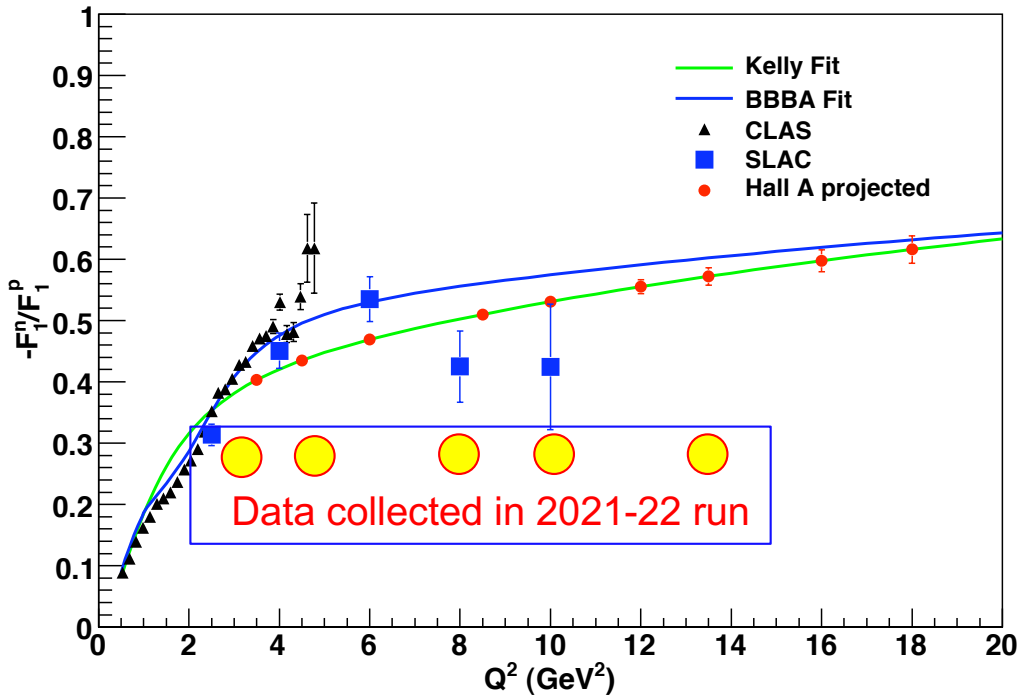
Neutron Magnetic Form Factor with SBS

D(e,e'n)/D(e,e'p) – Durand 1959



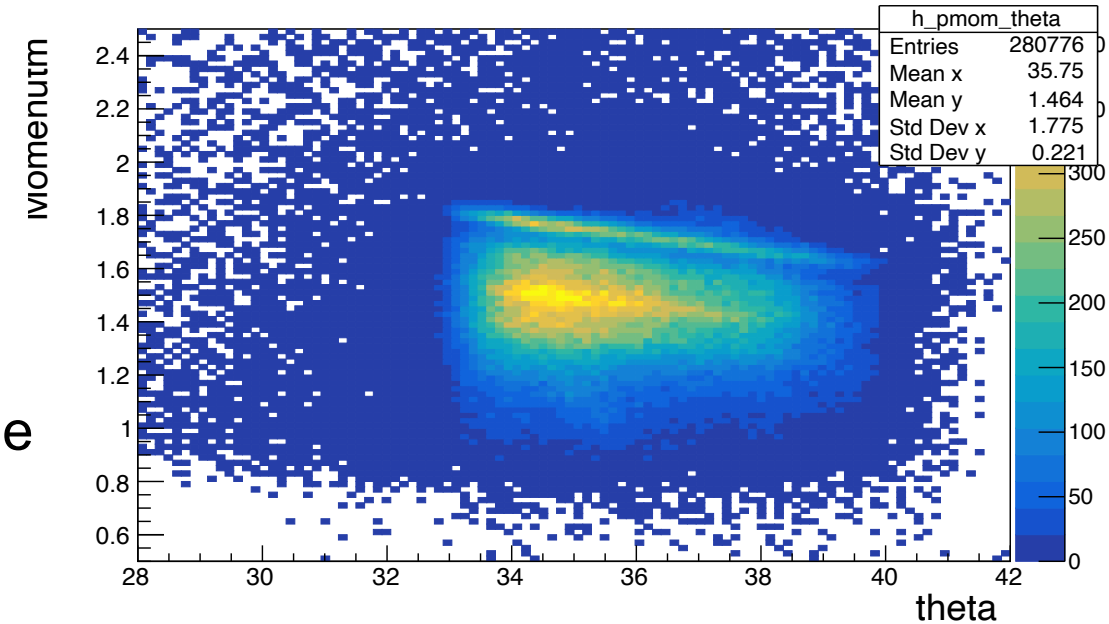
Neutron Magnetic Form Factor with SBS

D(e,e'n)/D(e,e'p) – Durand 1959

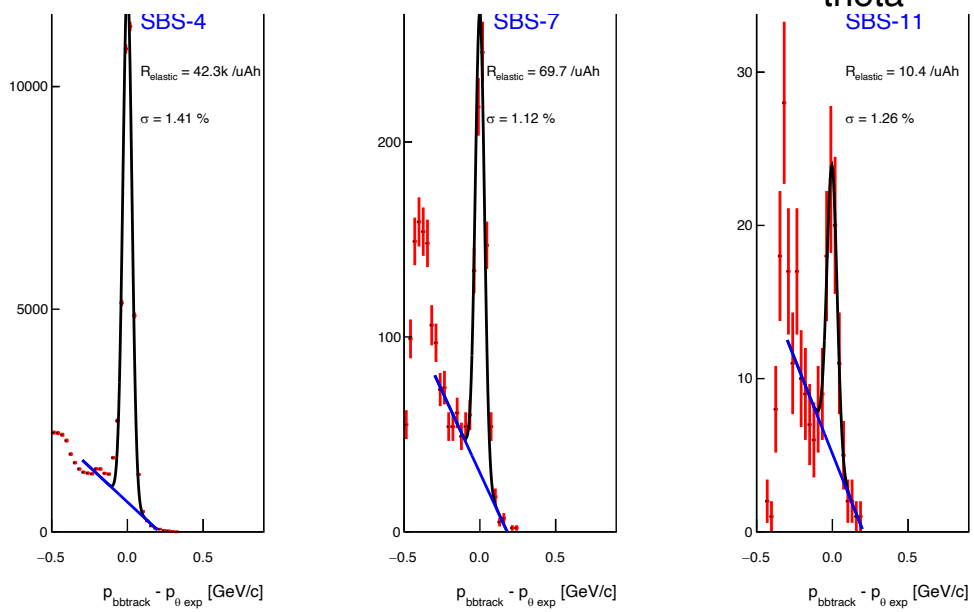


Neutron Magnetic Form Factor with SBS

Electron arm momentum vs. scattering angle



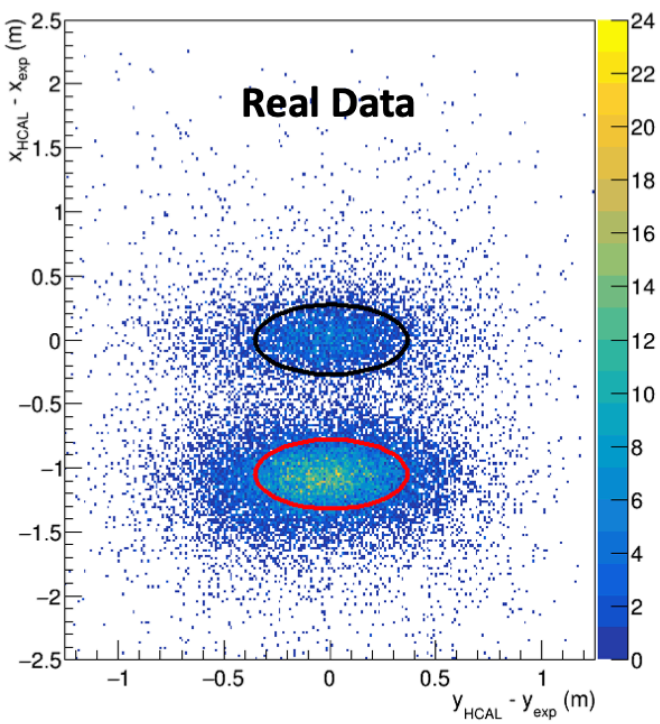
Elastic electron-proton scattering

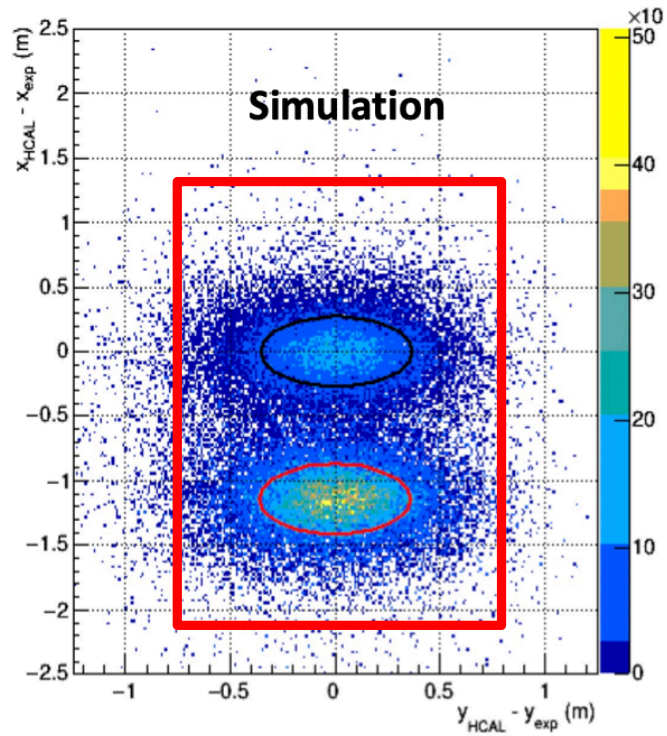


courtesy of D. Hamilton

Neutron Magnetic Form Factor with SBS

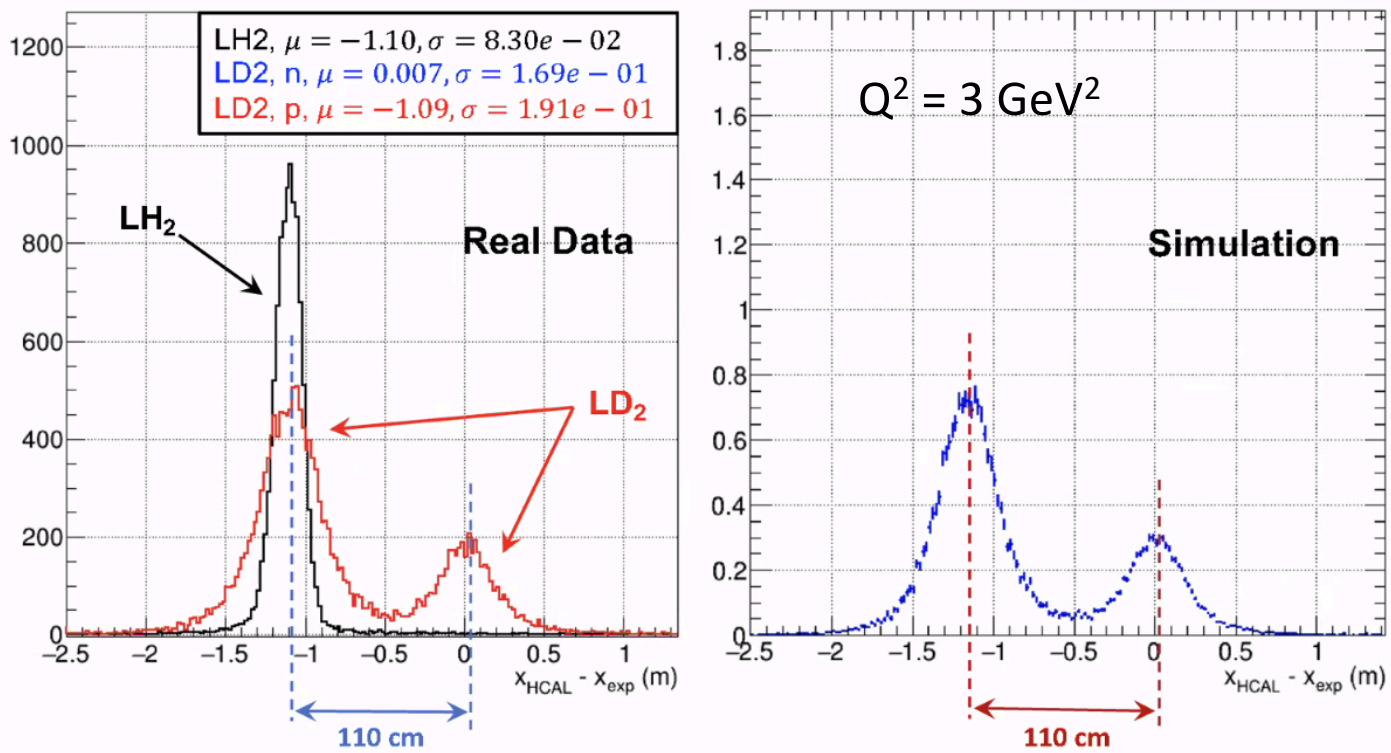
Real Data vs Simulation (LD_2 data) contd.





courtesy of A. Puckett

Neutron Magnetic Form Factor with SBS

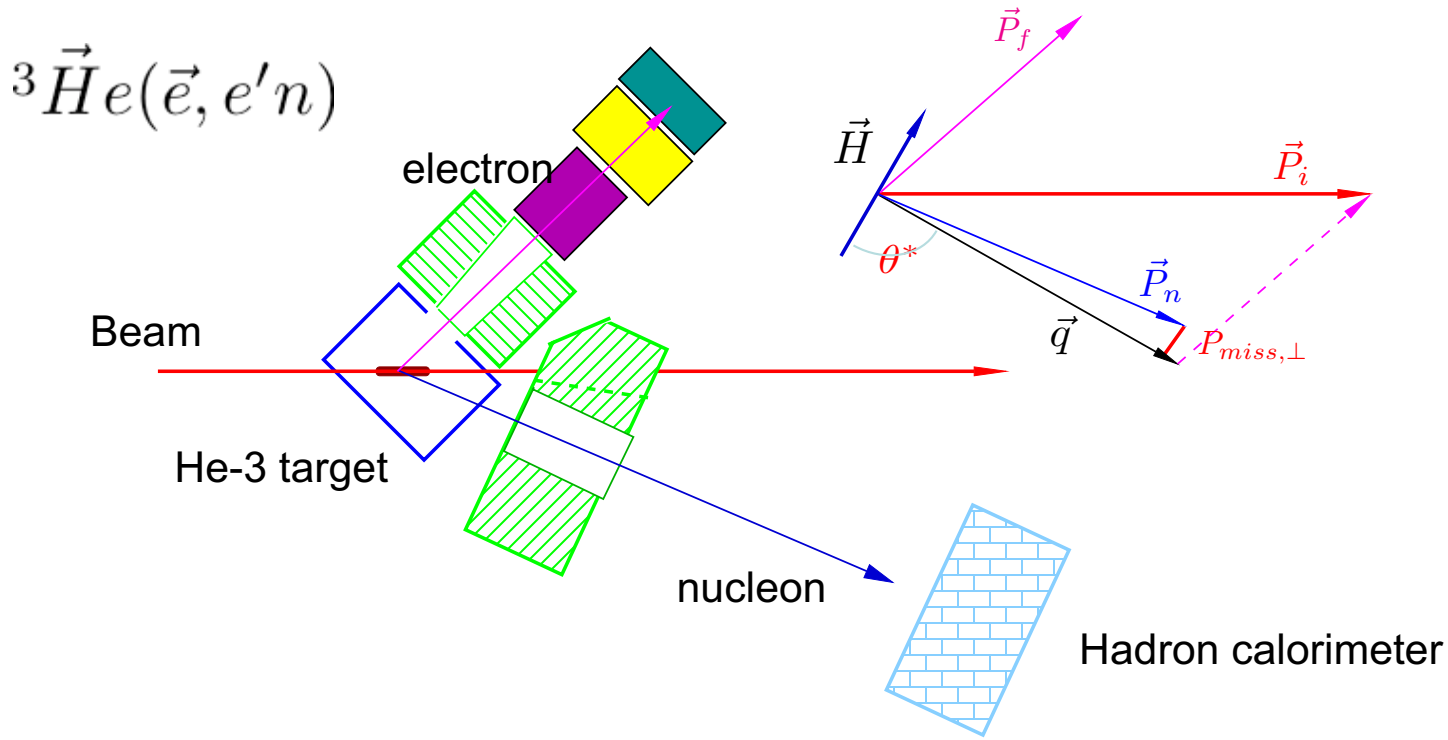


- Ratios of peak heights assuming no inelastic contamination (simulation is pure quasi-elastic):
- VERY ROUGH numbers
- REAL DATA: 186/480 = 0.39
- SIMULATION: 0.29/0.72 = 0.40

courtesy of A. Puckett

GEn-II: E12-09-016

$$A_{phys} = A_{\perp} + A_{\parallel} = \frac{a \cdot G_E G_M \sin\theta^\star \cos\phi^\star}{G_E^2 + c \cdot G_M^2} + \frac{b \cdot G_M^2 \cos\theta^\star}{G_E^2 + c \cdot G_M^2}$$



Polarized He-3 target performance

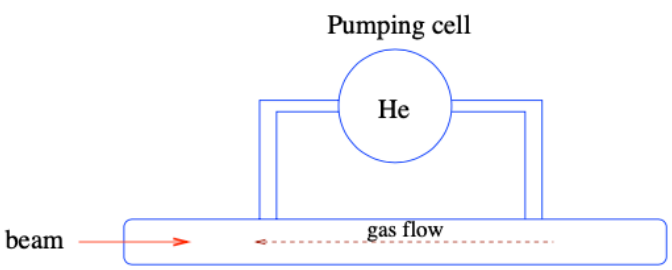
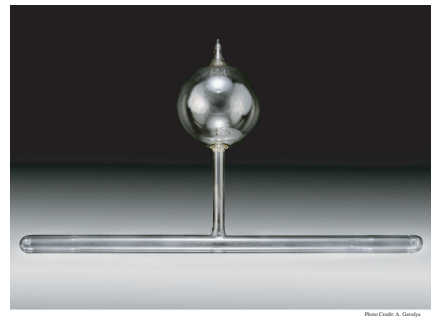
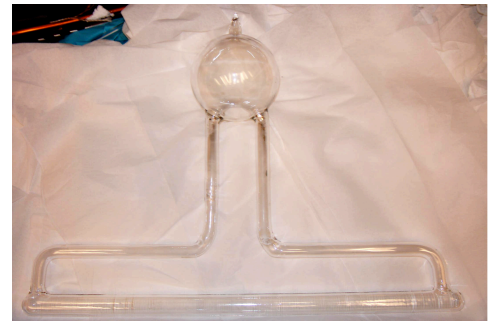
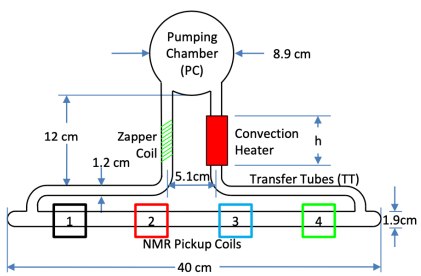


Figure 3. The target cell with two attachments to the pumping cell which allow the gas flow.

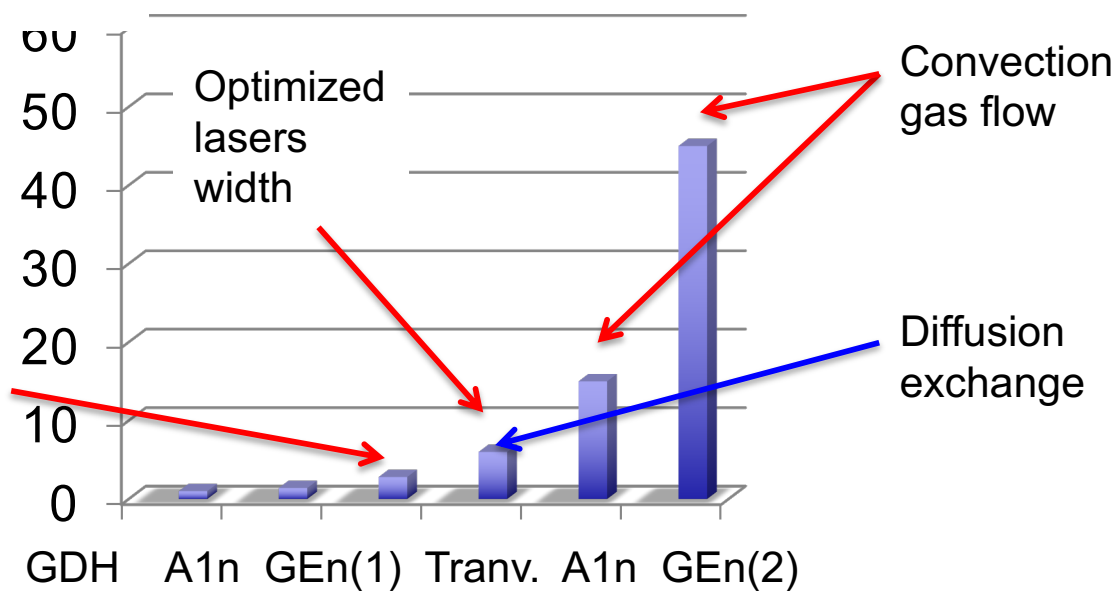




BW, Hi-t workshop 2002,
arXiv:1706.02747

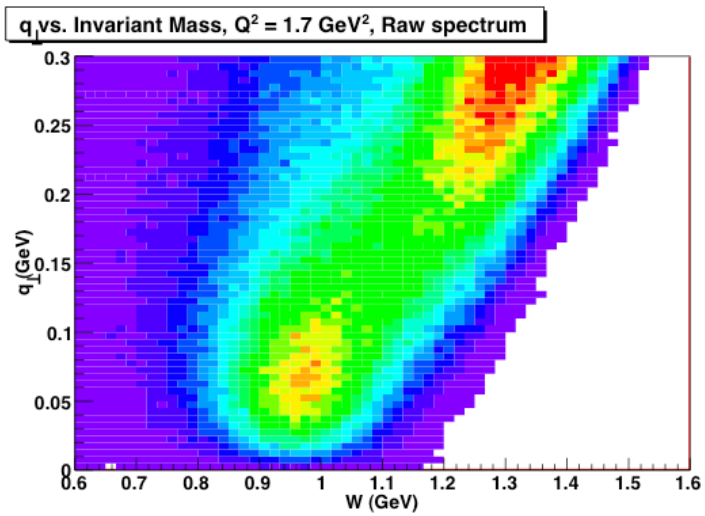


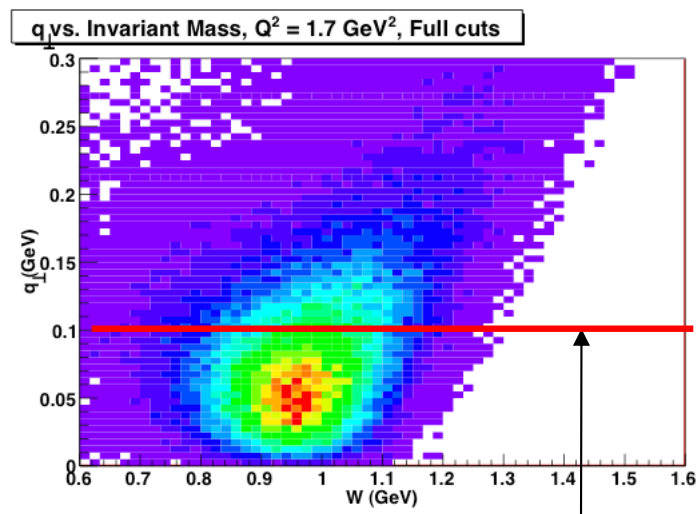
P.A.M. Dolph et al,
Phys.Rev.C 84 (2011) 065201

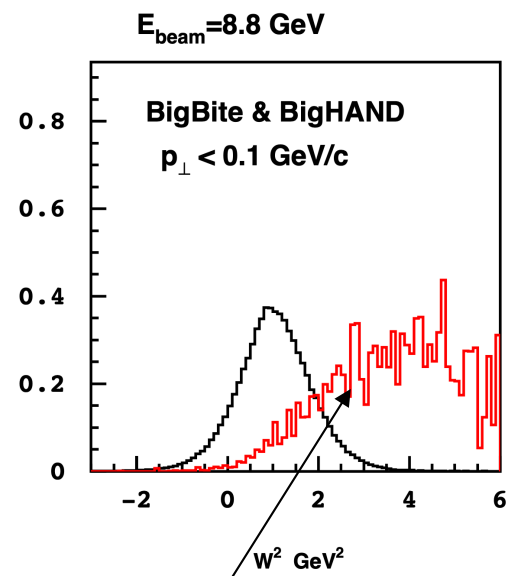


courtesy of G. Cates

Data analysis, GEn-1 and projected for high Q2







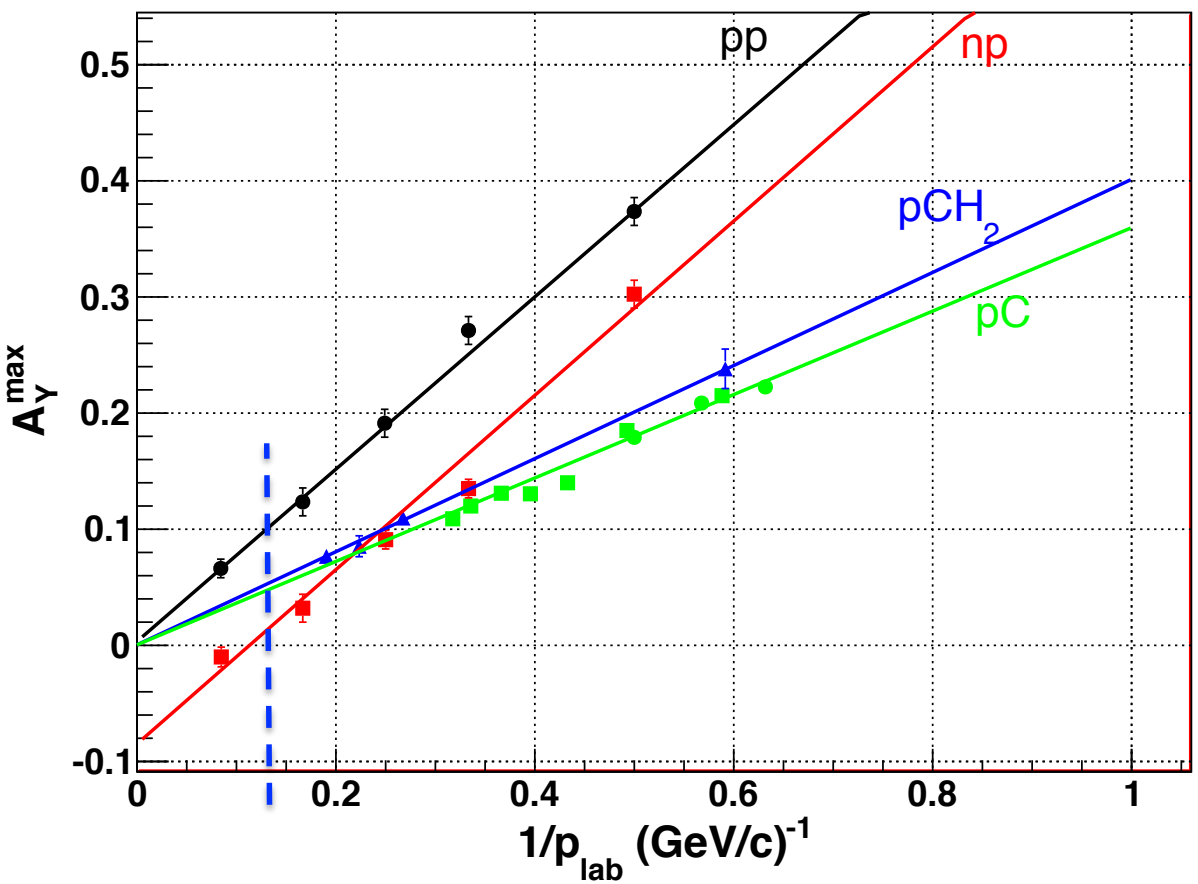
Quasi elastic events dominates after Full Cuts applied

max value of used perp. q

Large internal momentum in He-3 => inelastic contamination at high Q2

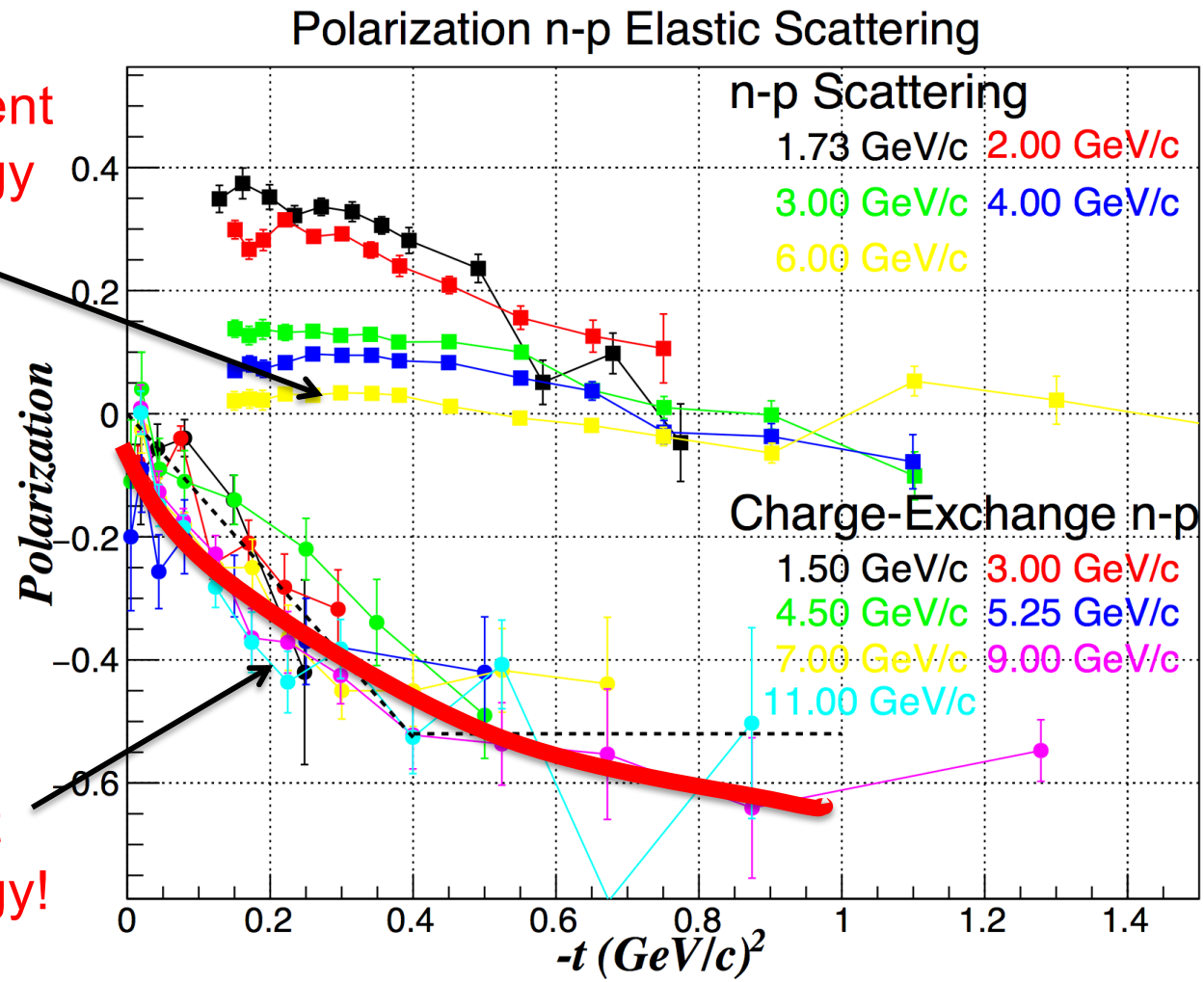
D($\vec{e}$, e' $\vec{n}$) is better for very high Q^2 (due to lower p_F)
but need efficient polarization analyzer for the neutron

Limitation of the traditional p-p scattering in the recoil polarimeter experiment



Forward and Charge-exchange n-p scattering

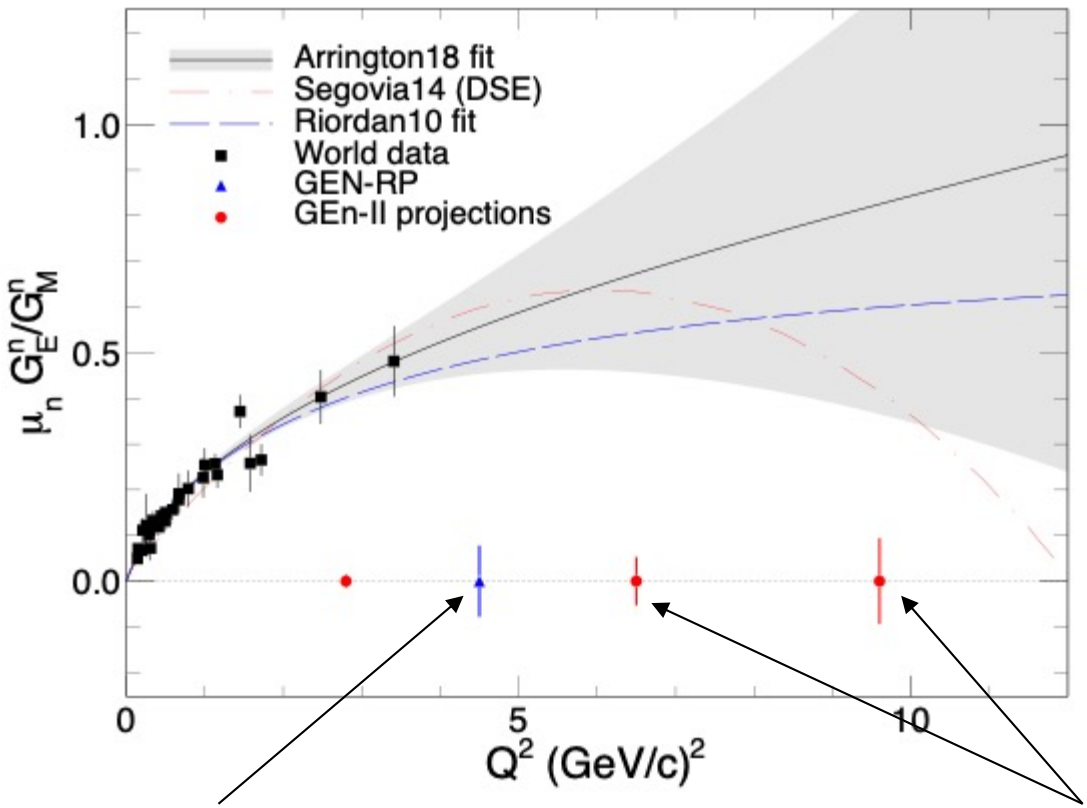
Drops fast with the incident nucleon energy



Independent of the incident nucleon energy!

courtesy of J. Annand

Projected accuracy in GEn-II: E12-09-016



test D($\vec{e}$, e' $\vec{n}$) with Charge Exchange polarimeter

$\vec{He}$-3($\vec{e}$, e' n)

Electromagnetic form factors

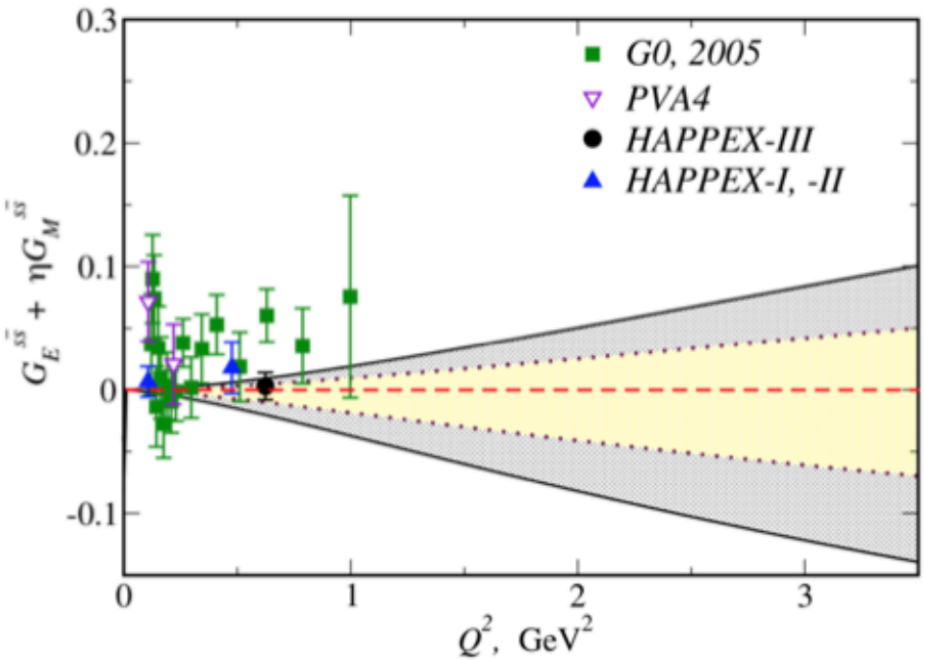
$$F_i^p = e_u F_i^u + e_d F_i^d + e_s F_i^s \,,$$
$$F_i^n = e_u F_i^d + e_d F_i^u + e_s F_i^s \,,$$

$$\int_0^1 \mathrm{d}x \big[s(x) - \bar{s}(x) \big] = 0$$

$$F_1^s(0) = 0 \qquad F_2^s(0) = \mu_s$$

Currently obtained limit on sFF

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)

$G_s/G_D \sim 1$ is not excluded

Impact of sFF on flavor decomposition

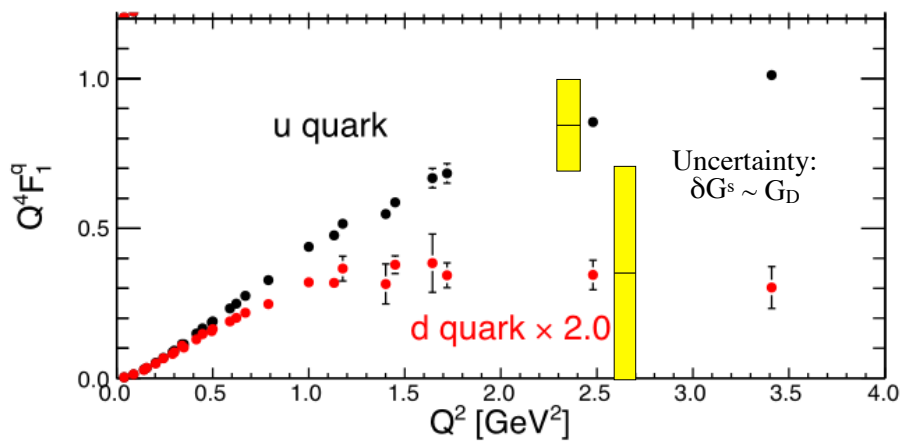
$$F_{1p} = e_u\, F_1^u \;+\; e_d\, F_1^d \;+\; e_s\, F_1^s$$

$$F_{1n} = e_u\, F_1^d \;+\; e_d\, F_1^u \;+\; e_s\, F_1^s$$

$$F_1^u = 2F_{1p} + F_{1n} - F_1^s \qquad F_1^d = 2F_{1n} + F_{1p} - F_1^s$$

Assuming $\delta G^s_{E,M} \sim G_D \sim 0.048 \longrightarrow \delta(Q^4 F_1^u) \sim \pm\, 0.17$

$$F_1 = \frac{G_E + \tau G_M}{1+\tau} = \frac{G_E + 0.7 G_M}{1.7} \sim \frac{G_D}{1.7}$$



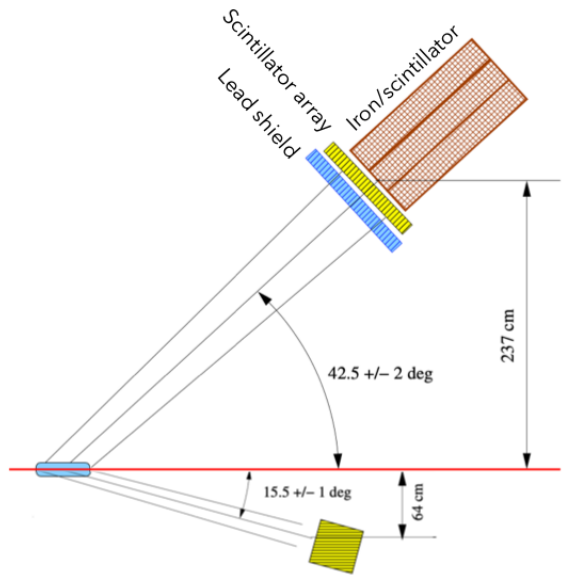
courtesy of K. Paschke

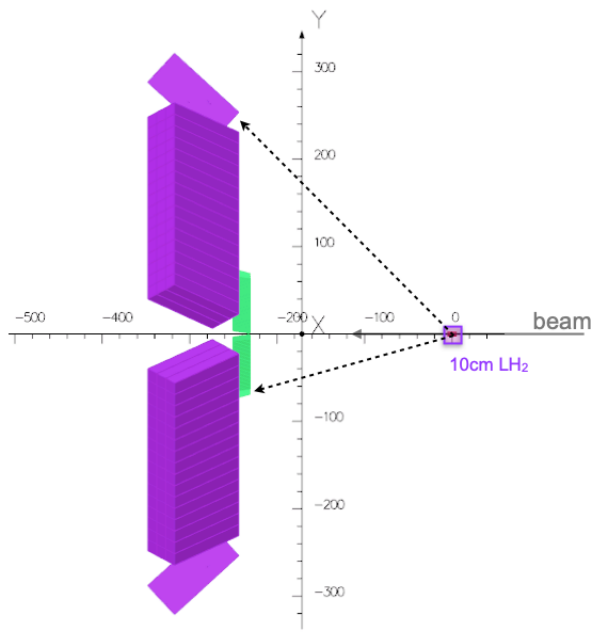
- Form factors are a crucial constraint on GPDs, and the flavor content must be understood
- Whatever future data informs GPDs and the nucleon femtography project, form-factors will remain an important constraint
- The quark flavor content of the form-factor must be known for this purpose!

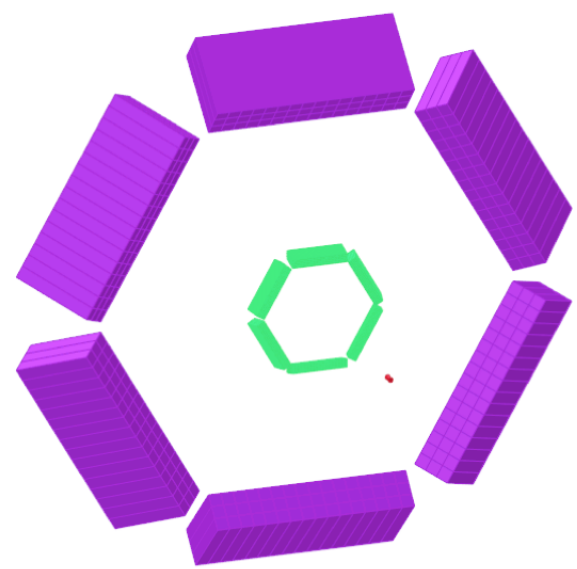
Concept of the high Q2 parity experiment

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

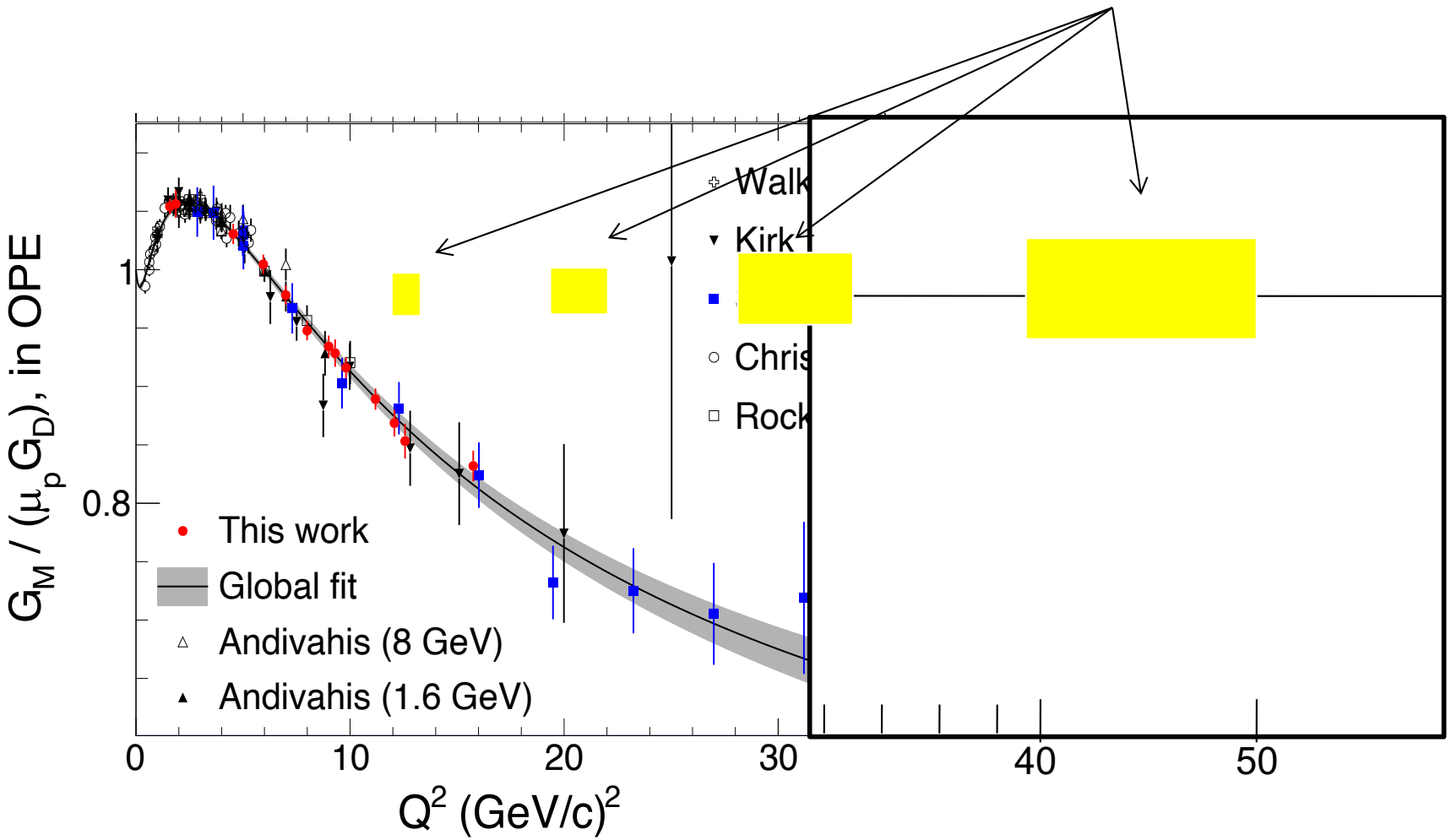
- 6.6 GeV beam
- Scattered electron at 15.5 degrees
- Scattered proton at 42.4 degrees
- 10 cm LH_2 target, 60 μA, $\mathcal{L}$ =1.6 x 10^{38} cm^{-2}/s







GMp Form Factor with EIC



$$F_1(t) \approx G_M \sim \mu_p G_{Dipole} = \mu_p[1 + Q^2/0.71]^{-2}$$

Summary

- Accurate measurement of the Nucleon Form Factors at high Q^2 will significantly boost understanding of QCD.
- JLab 12-GeV is providing beam and critical infrastructure with large acceptance and rate capability for experiments.
- GMp results are published, two GMn experiments took data, GEn will start in three weeks, in 2023 will be a SBS/GEp experiment.

Experiments are diamonds

Form Factors are forever