Baryon Form Factors Program at JLab

Bogdan Wojtsekhowski, Jefferson Lab

- TJNAF electron beam
- Baryon EMFFs
- FF flavor decomposition
- 12-GeV era EMFF experiments

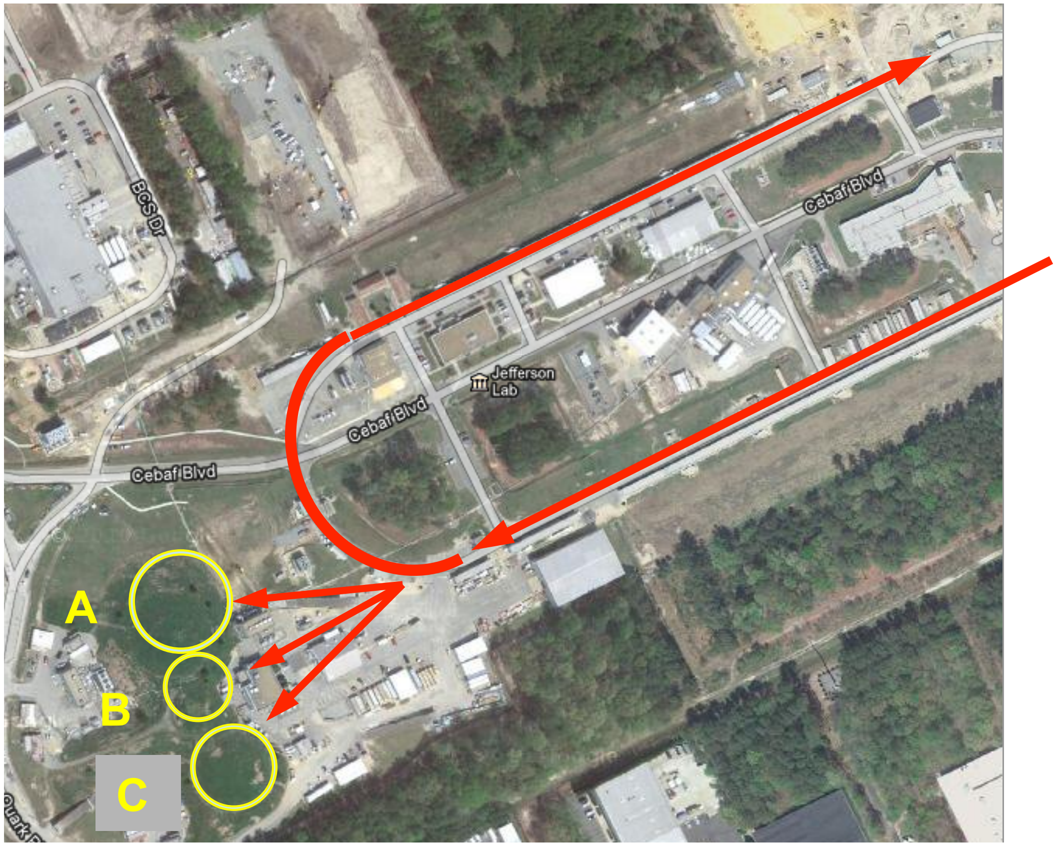
Jefferson Laboratory

The laboratory, founded in 1984 in Newport News, Virginia, operates a 6 GeV continuous electron beam accelerator.

A 12-GeV upgrade of the accelerator is underway.

Three experimental halls (A, B, C) are equipped to study electron and photon induced reactions.

A new hall D is being constructed for searches of the exotic states produced in γp interactions.



Jefferson Laboratory

Beam parameters:

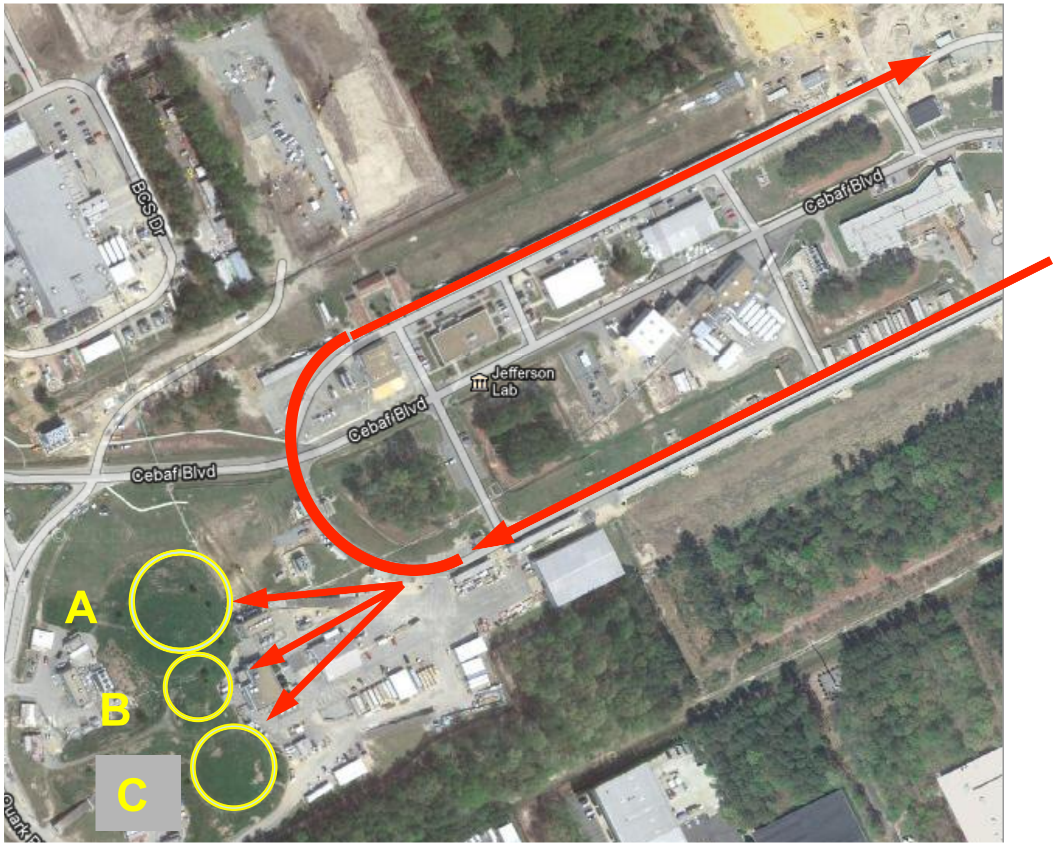
energy up to 12 GeV
intensity up to 180 μA
polarization 85%
pol. flip systematic 10^{-9}
time structure 2 ns

Luminosity: 10^{39} cm^{-2}/s

Detector systems: many

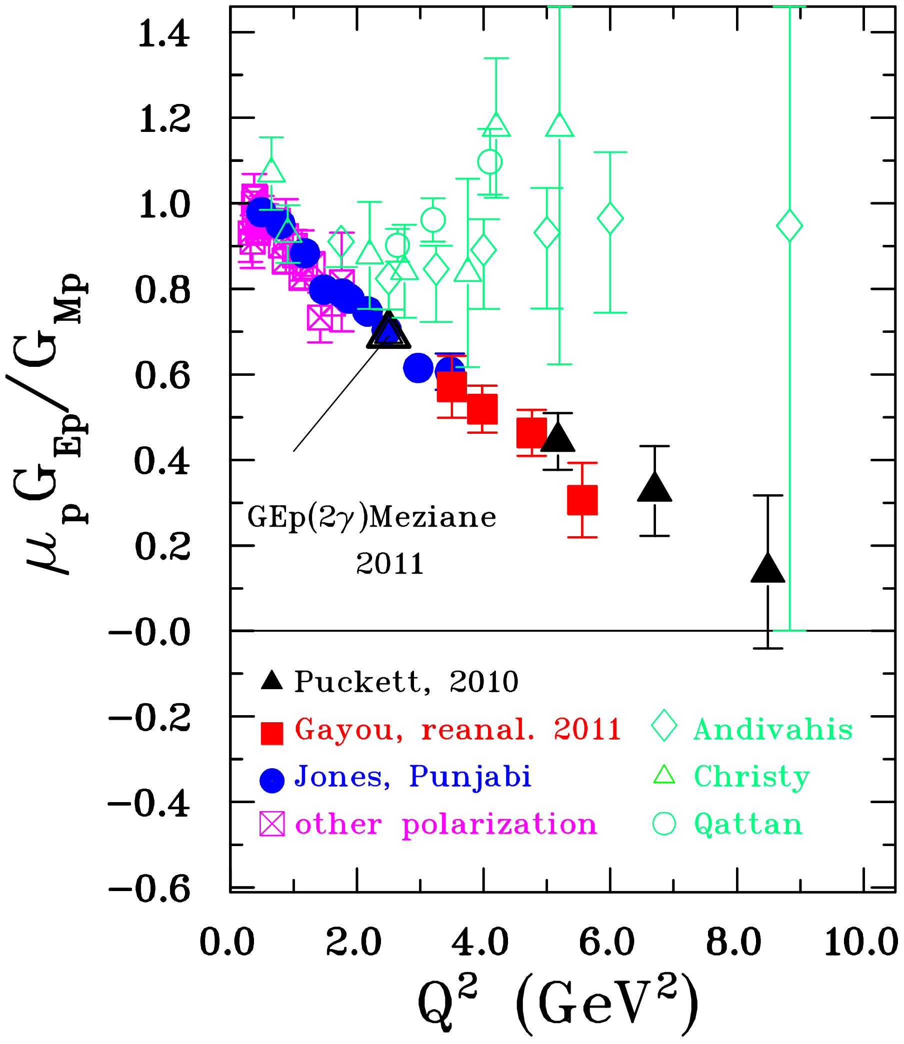
Polarized targets (used):

NH_3/ND_3: L ~10^{35} cm^{-2}/s
HD (for the photon beam)
^{3}He: L ~10^{36} cm^{-2}/s

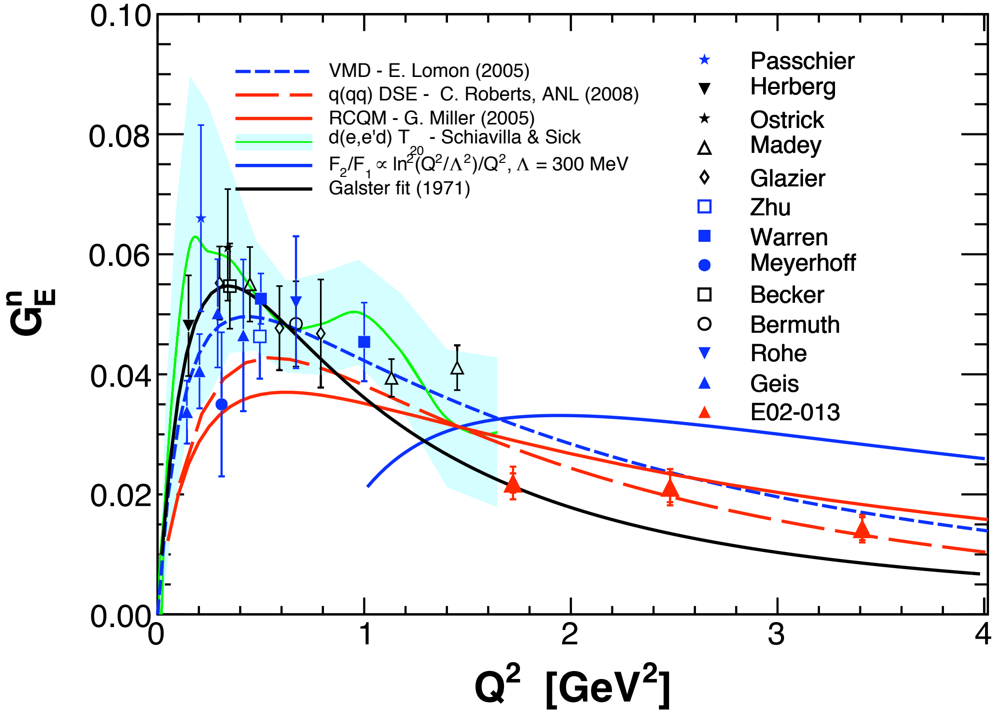


Jefferson Laboratory

The major research highlights include:



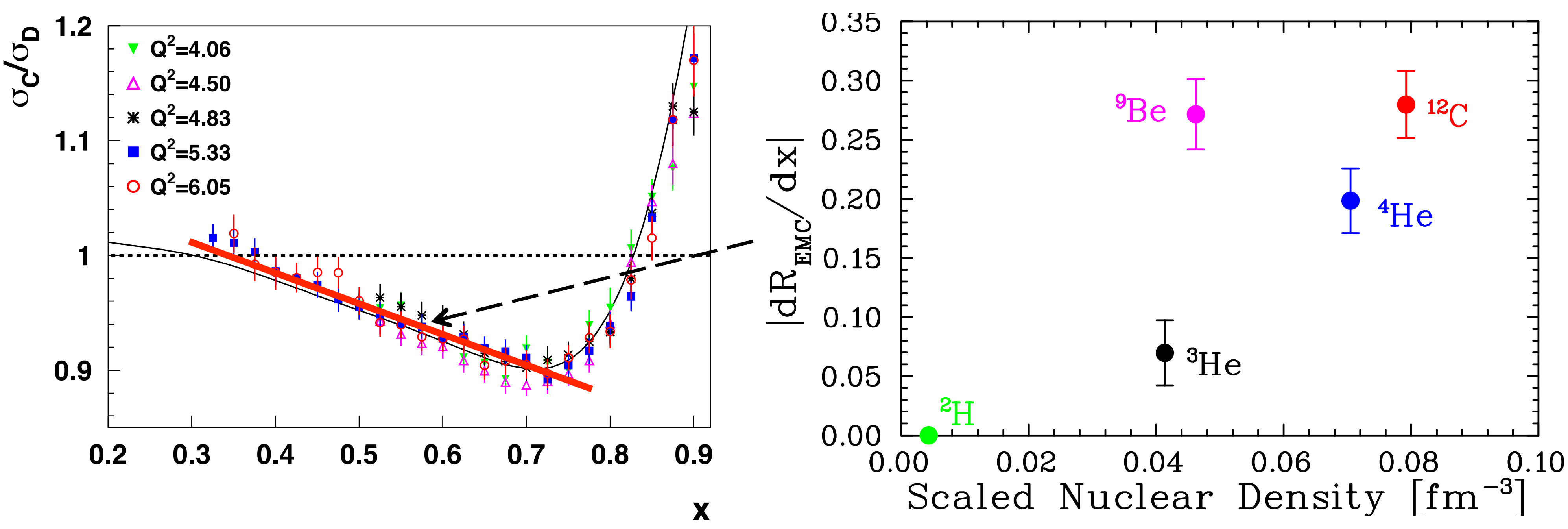
Proton and Neutron Electro-Magnetic Form Factors



Jefferson Laboratory

The major research highlights include:

EMC effect in the light nuclei: local vs. average densities

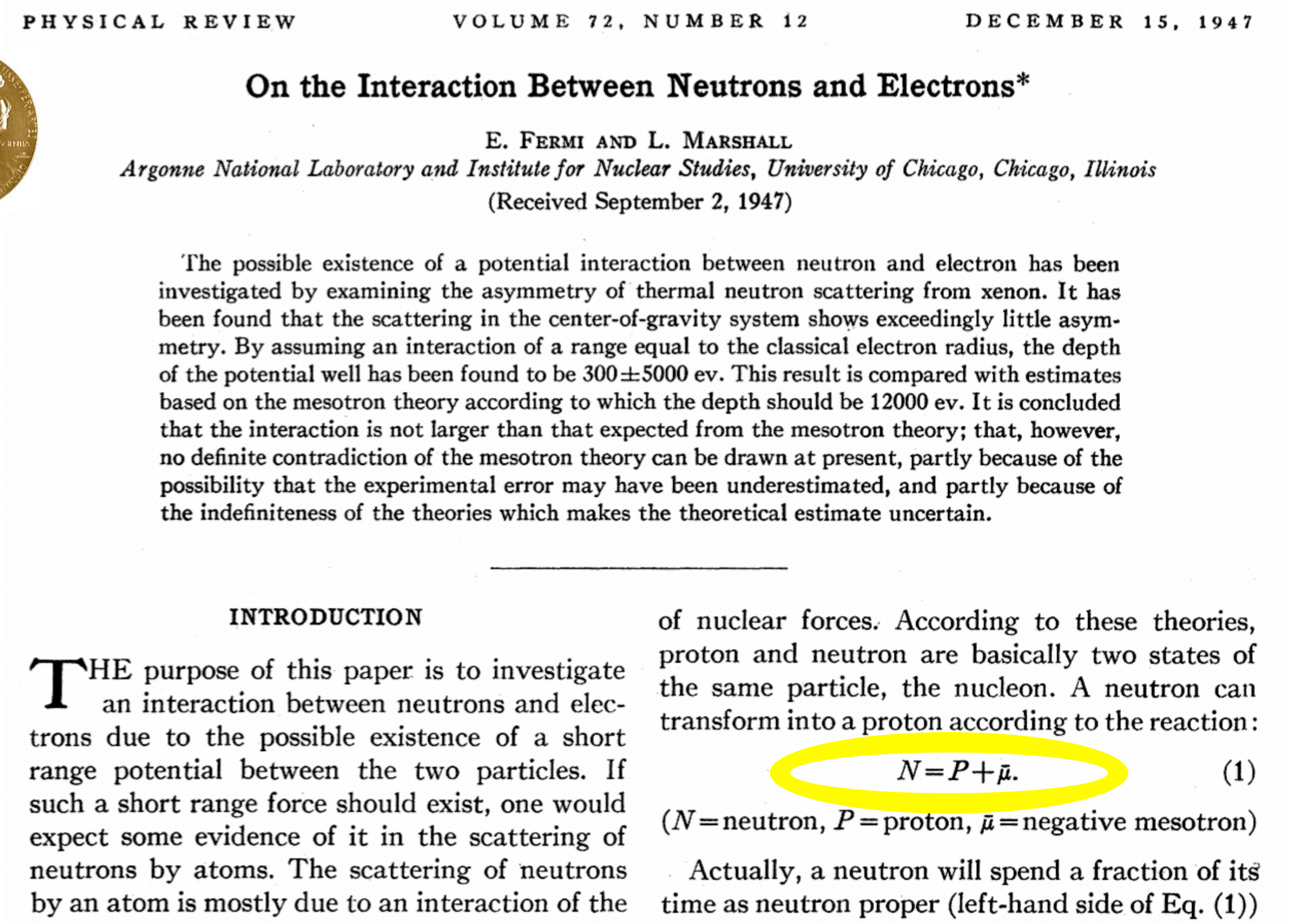


Composite structure of the nucleon

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.*

O.Stern,1937

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 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))

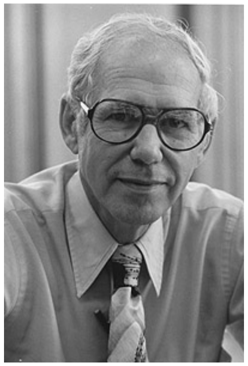
Introduction of the Form Factors

Nucleon current, one-photon approximation, $\alpha_{em} = 1/137$,

Rosenbluth,1950

$$\mathcal{J}^{\mu}_{hadron} = ie\bar{N}(p_f)\,[\gamma^{\nu} F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_{\nu}}{2\,M} F_2(Q^2)]N(p_i)$$

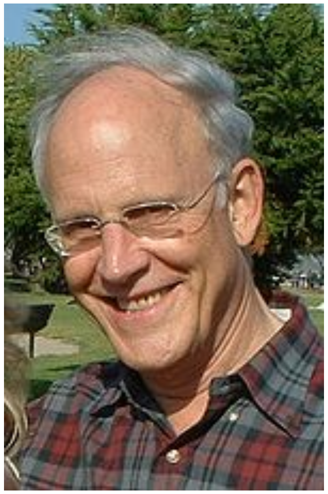
$$\frac{d\sigma}{d\Omega}(E,\theta) = \frac{\alpha^2 E'\cos^2(\frac{\theta}{2})}{4E^3\sin^4(\frac{\theta}{2})}[(F_1^2 + \kappa^2\tau F_2^2) + 2\tau(F_1 + \kappa F_2)^2\tan^2(\frac{\theta}{2})]$$



Sachs,1962

$$\frac{d\sigma}{d\Omega}(E,\theta) = \sigma_M[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2\tan^2(\frac{\theta}{2})]$$

The goal is understanding of QCD

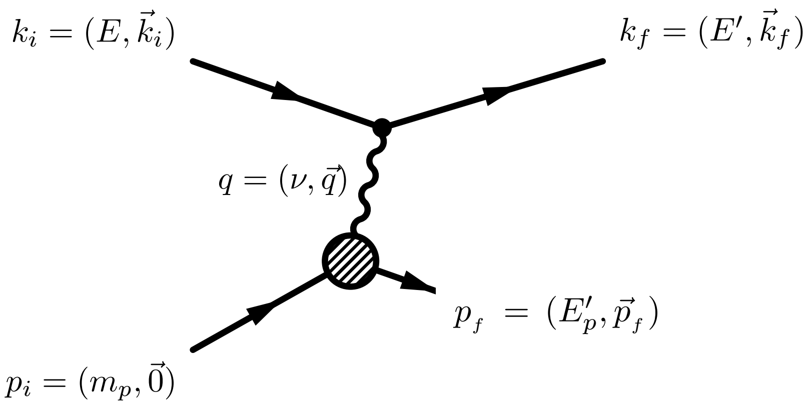


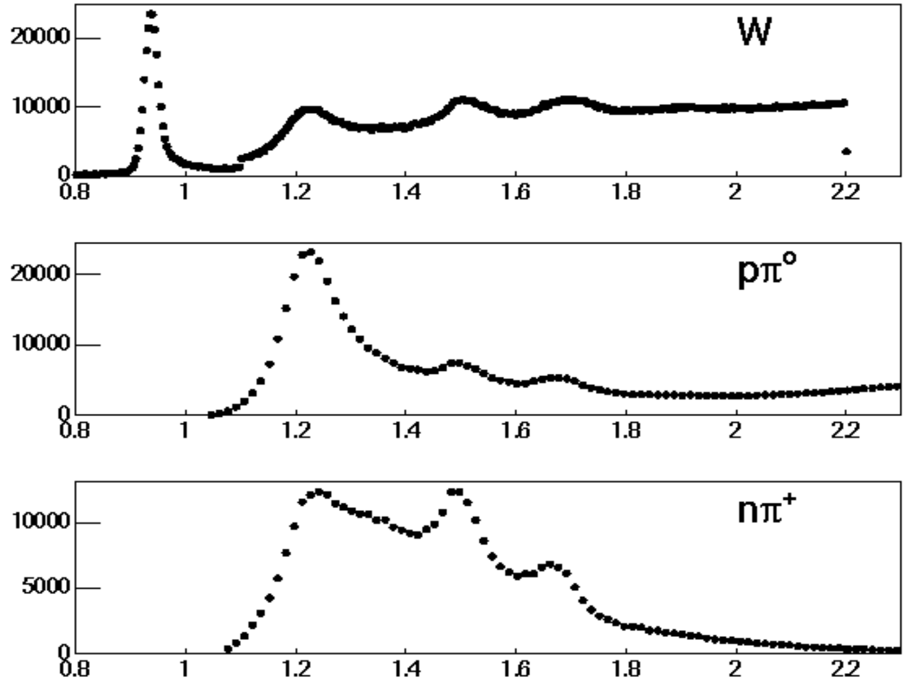
from the D. Gross Nobel Lecture:

"It is sometimes claimed that the origin of mass is the Higgs mechanism that is responsible for the breaking of the electroweak symmetry that unbroken would forbid quark masses.

This is incorrect. Most, 99%, of the proton mass is due to the kinetic and potential energy of the massless gluons and the essentially massless quarks, confined within the proton."

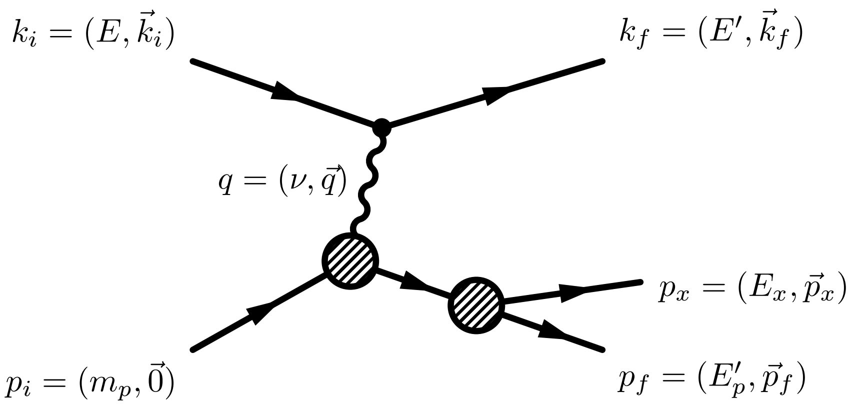
The goal is understanding of the nucleon

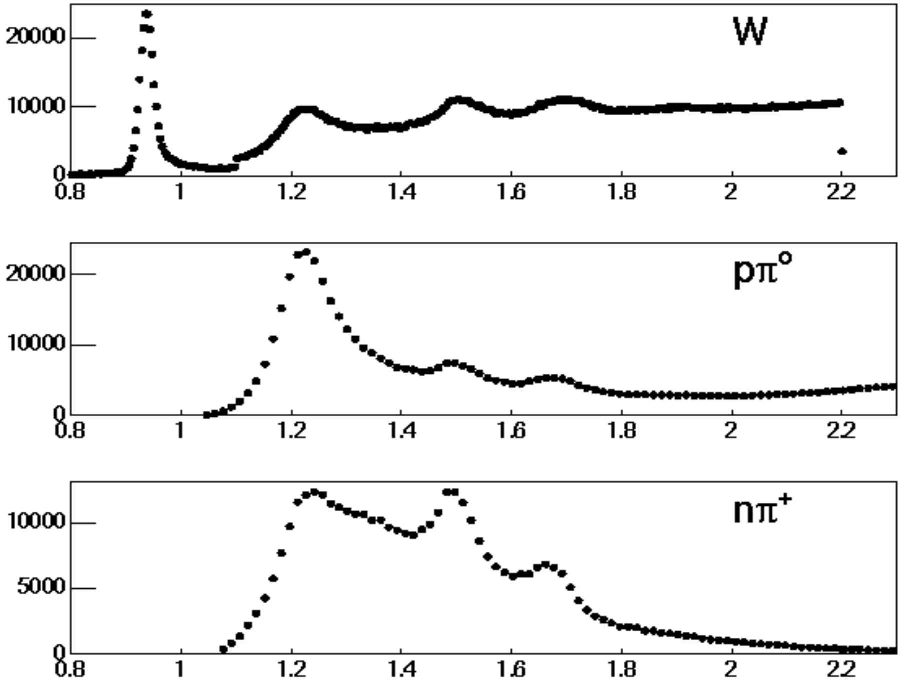




Elastic FFs of the proton and neutron: $F_1(Q^2)$, $F_2(Q^2)$

The goal is understanding of the nucleon

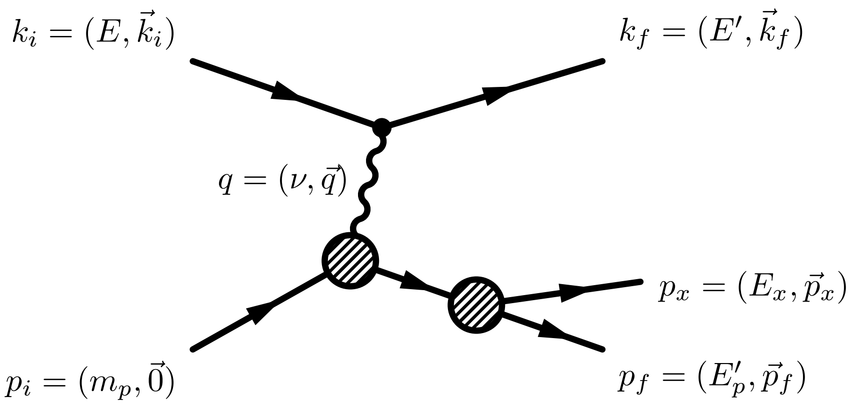


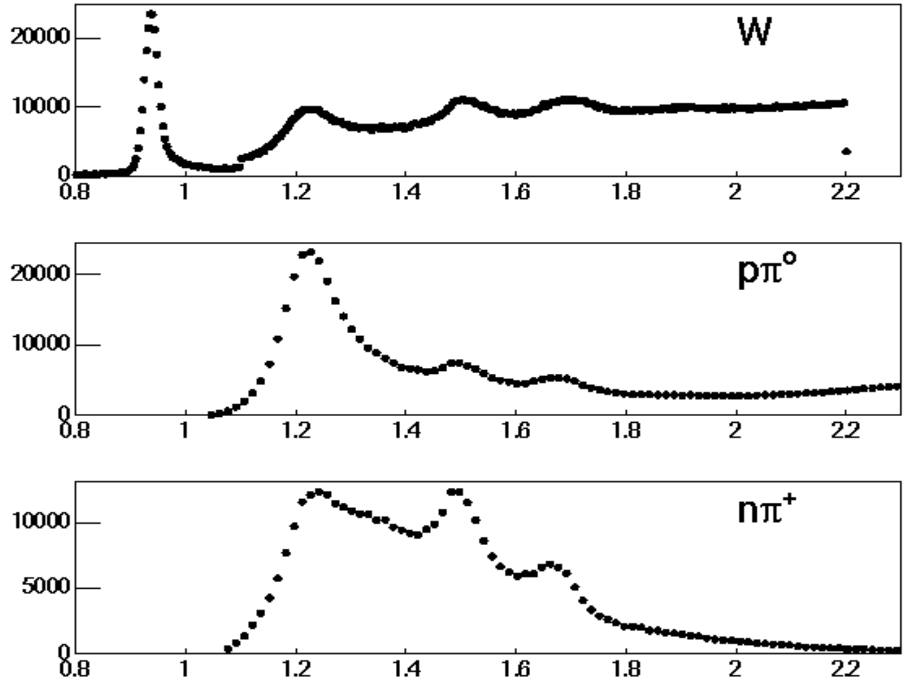


Elastic FFs of the proton and neutron: $F_1(Q^2)$, $F_2(Q^2)$

Transition FFs of the $P_{33}(1232)$: $A_{1/2}$, $A_{3/2}$, $S_{1/2}$;
$S_{11}(1535)$, $P_{11}(1440)$: $A_{1/2}$, $S_{1/2}$

The goal is understanding of the nucleon





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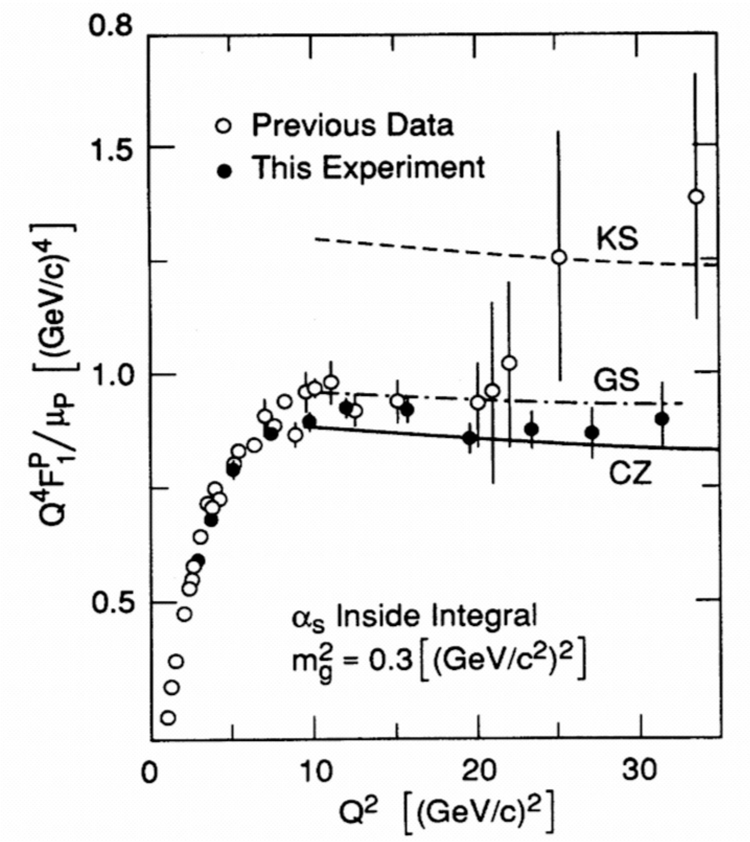
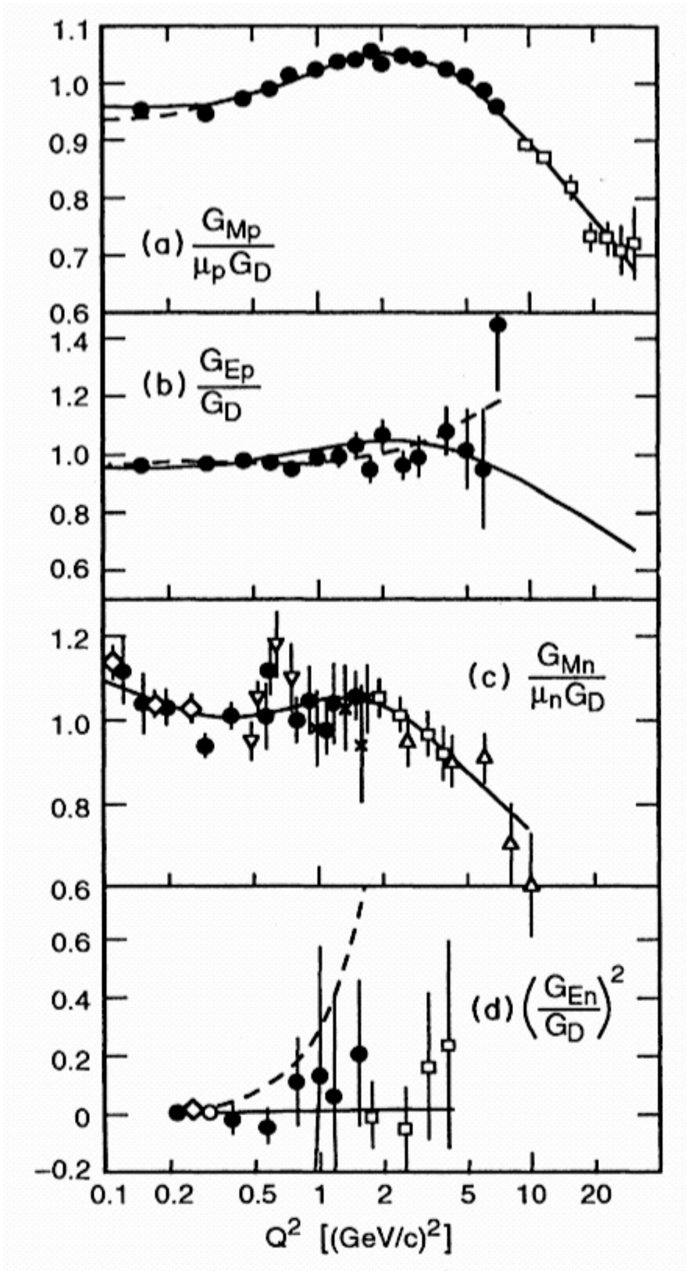
Form factors of the Compton scattering: $R(Q^2)$,R_V, R_A

SLAC results for the Form Factors



Sill et al,1993

Bosted,1995

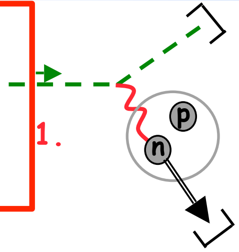


The double polarization method and Form Factors of the nucleon

Akhiezer, 1957, JETP. F_2 contribution vs. Q^2.
Double polarization approach will allow accurate measurements of the form factors

F. Gross, 1980,
CEBAF
white paper

5 key mini-proposals to motivate the accelerator



1. Charge distribution of the neutron (very small!):
   - coincidence measurement
   - polarized beam
2. Charge distribution of the deuteron (masked by other contributions)
   - coincidence measurement
   - polarized beam
3. Single nucleon emission (distribution and motion of nucleons)
   - coincidence measurement
4. Excited states of the nucleon and search for “missing” states
   - coincidence measurement
   - multiple particle detection
5. Study of strangeness in nuclei
   - coincidence measurement
   - high resolution

The double polarization method and electric FF of the nucleon

Akhiezer, 1957

F_2 contribution vs. Q^2. Double polarization approach will allow accurate measurements

Arnold, Carlson, Gross, 1980

GEp via polarization transfer at CEBAF

GEn up to 3 GeV^2 as an important goal

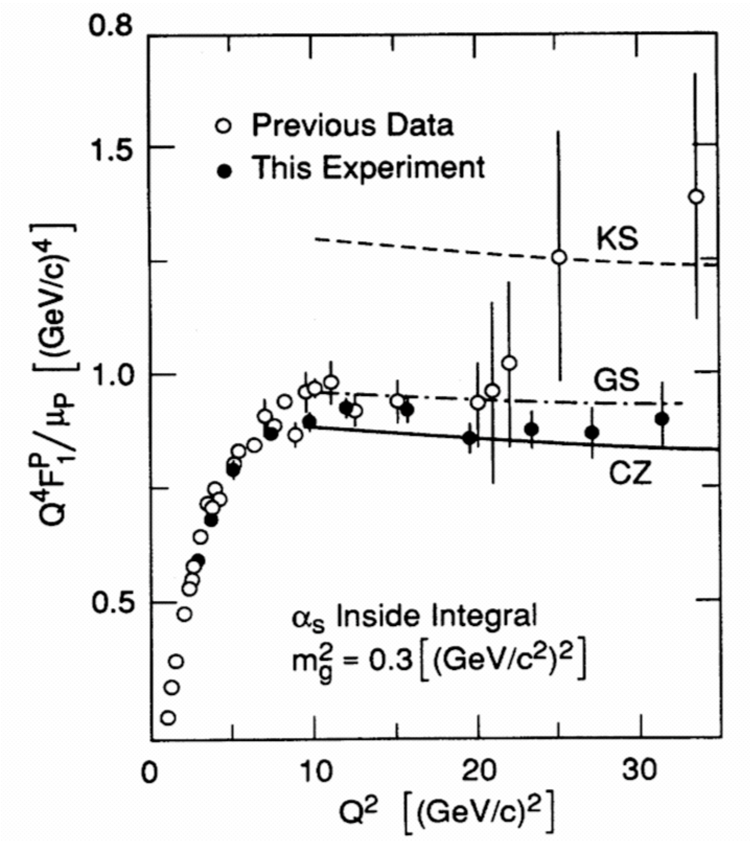
$$d\sigma = d\sigma_{NS}\left\{\varepsilon (G_E)^2 + \tau (G_M)^2\right\} \cdot \left[1 + h_e A(G_E, G_M)\right]$$

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

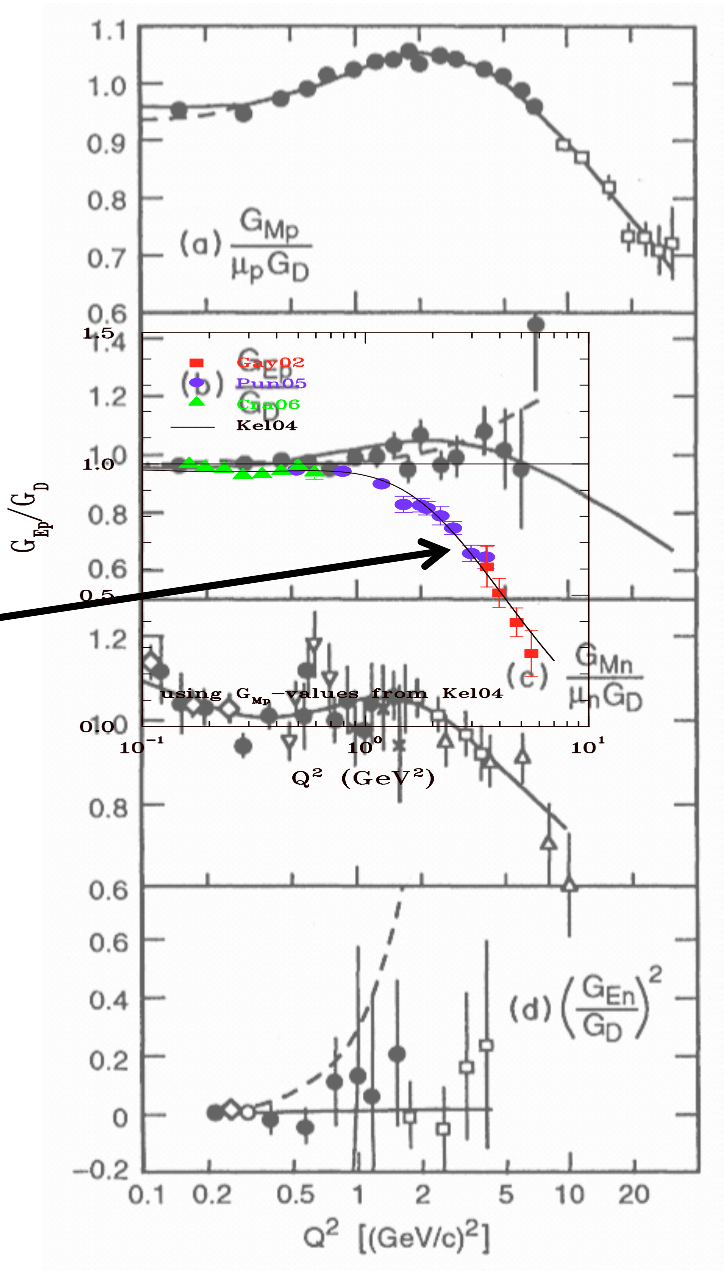
Perdrisat, Punjabi, 1989

Precision experiment with a polarimeter behind a dipole magnet which provides spin rotation

Results for the Form Factors

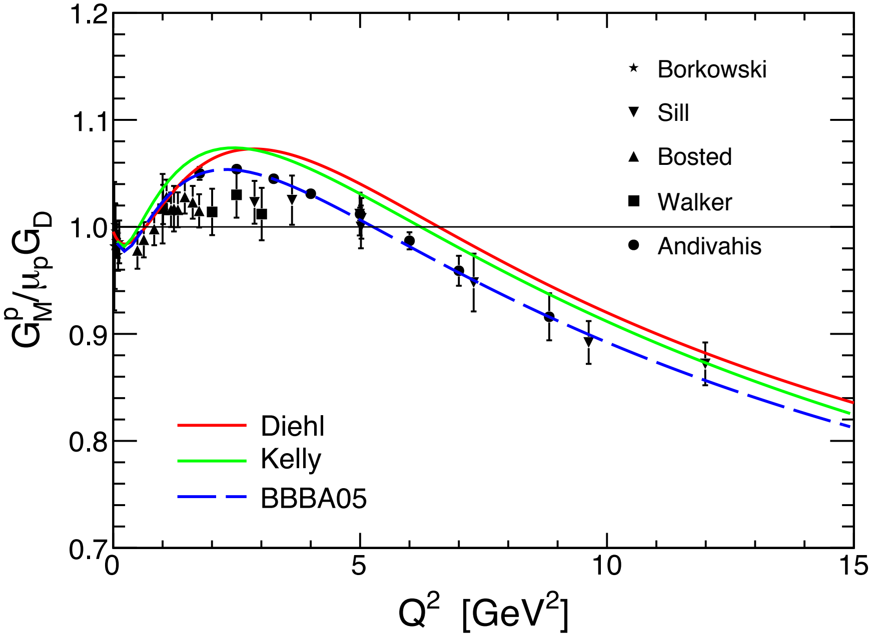


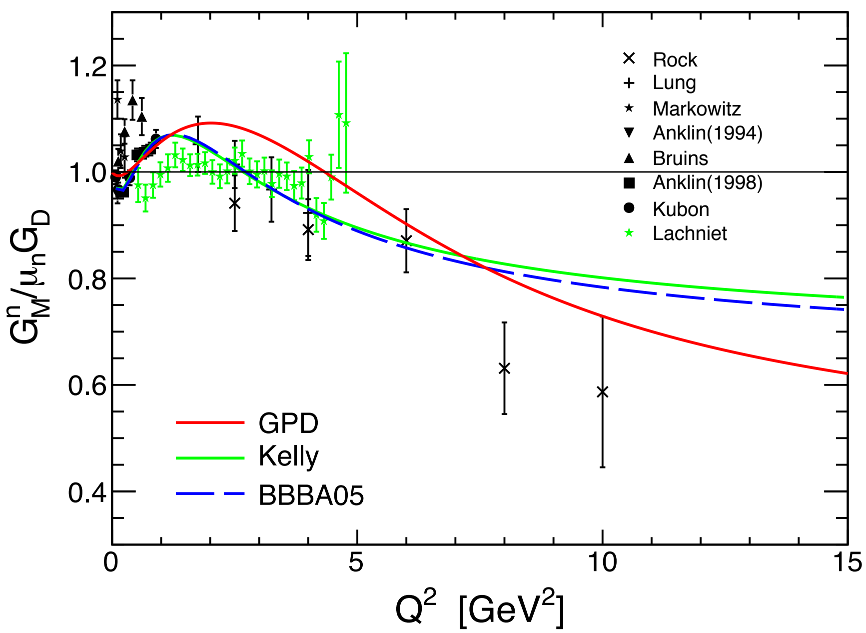
Sill et al,1993

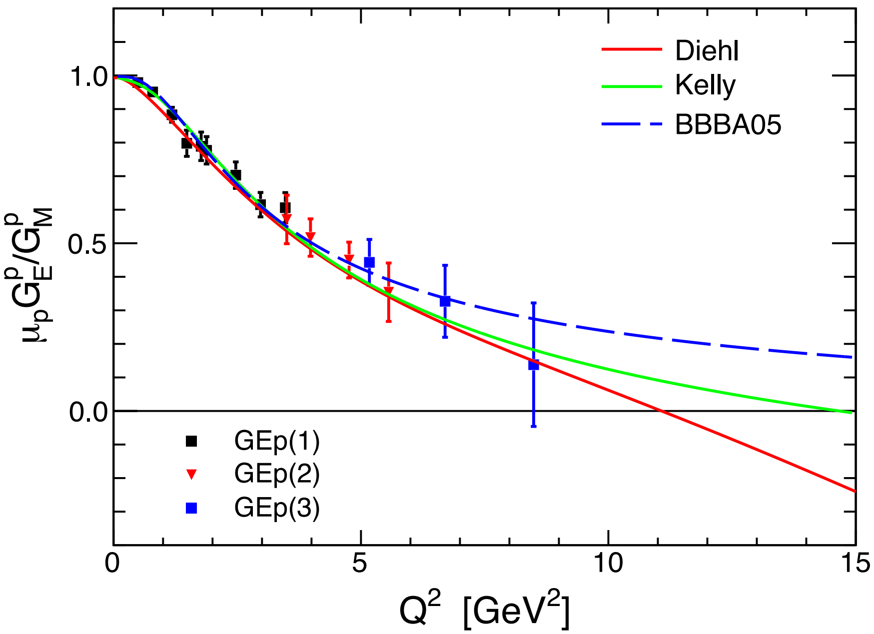


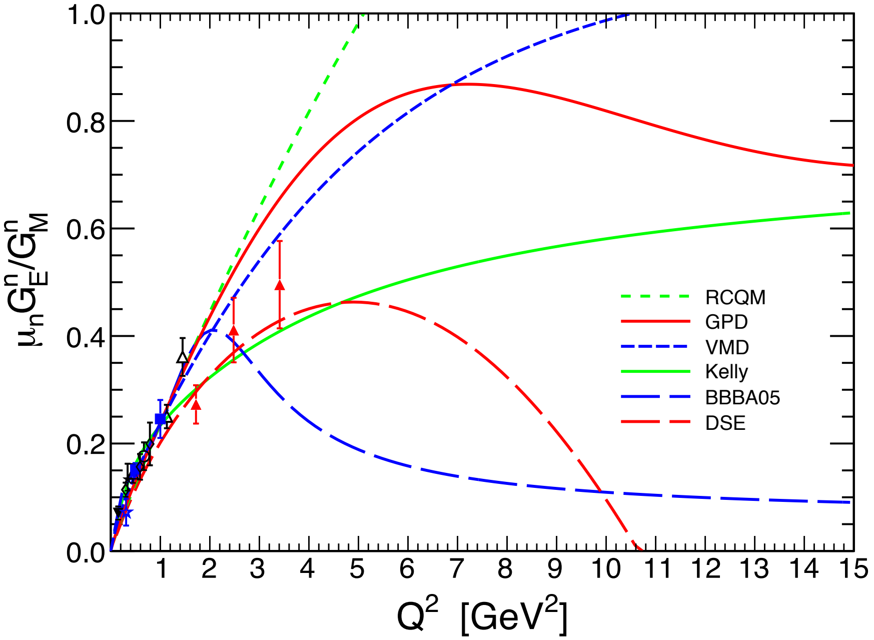
Perdrisat, 2001

Sachs Form Factors of the nucleon









The goal is understanding of the nucleon

From the Sachs FFs to the ratio F2/F1 and the BJY “log” scaling

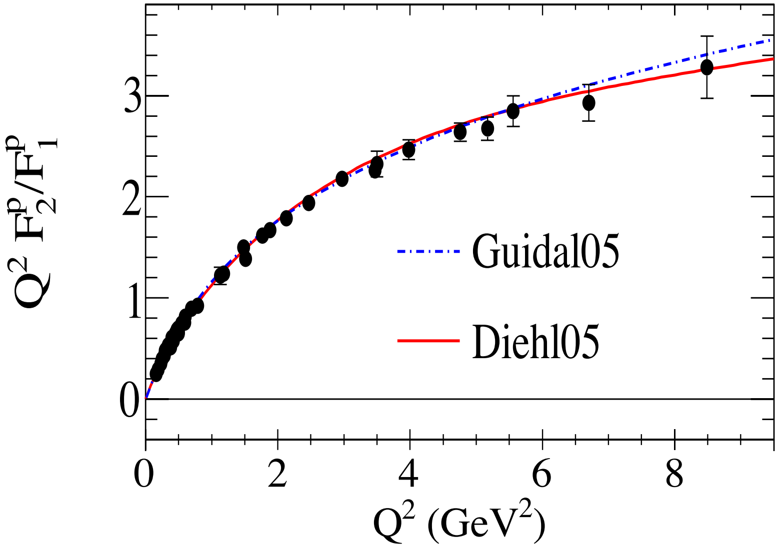
$$F_1 = \frac{G_E + \tau G_M}{1+\tau} \quad F_2 = -\frac{G_E - G_M}{1+\tau}$$

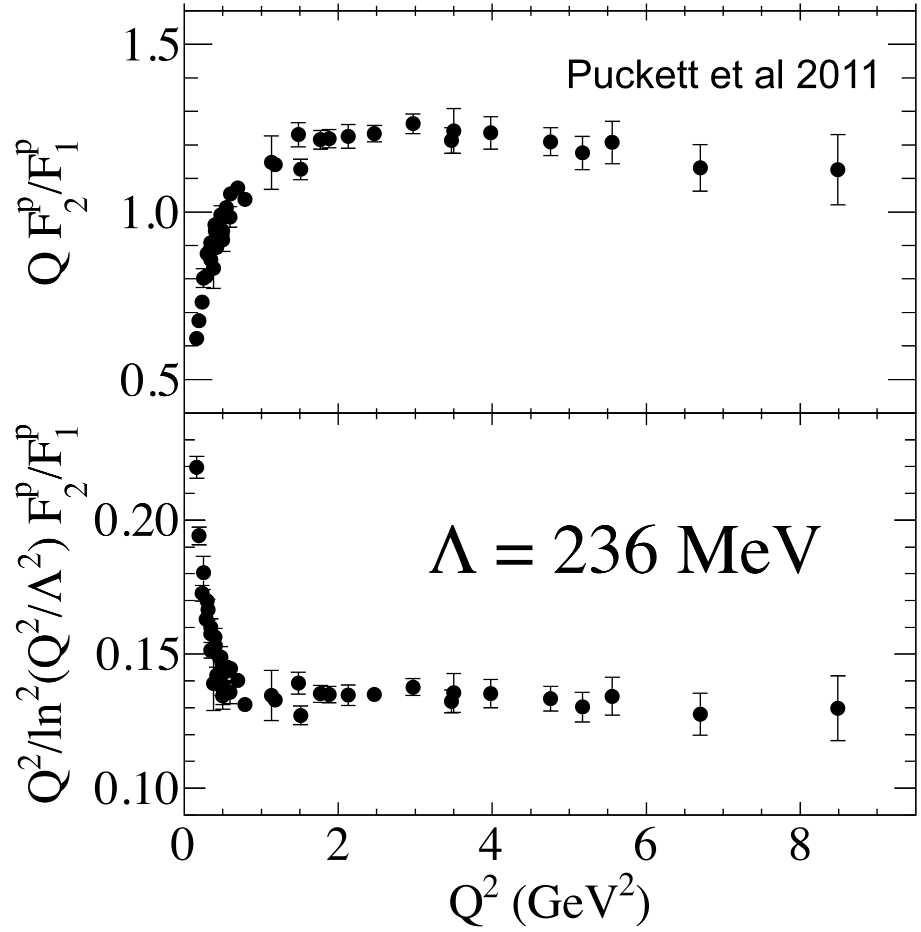
$$\tau = Q^2/4M^2$$

$$Q^2 \, F_2/F_1 \propto \frac{1 - G_E/G_M}{1 + \left[G_E/G_M\right]/\tau}$$

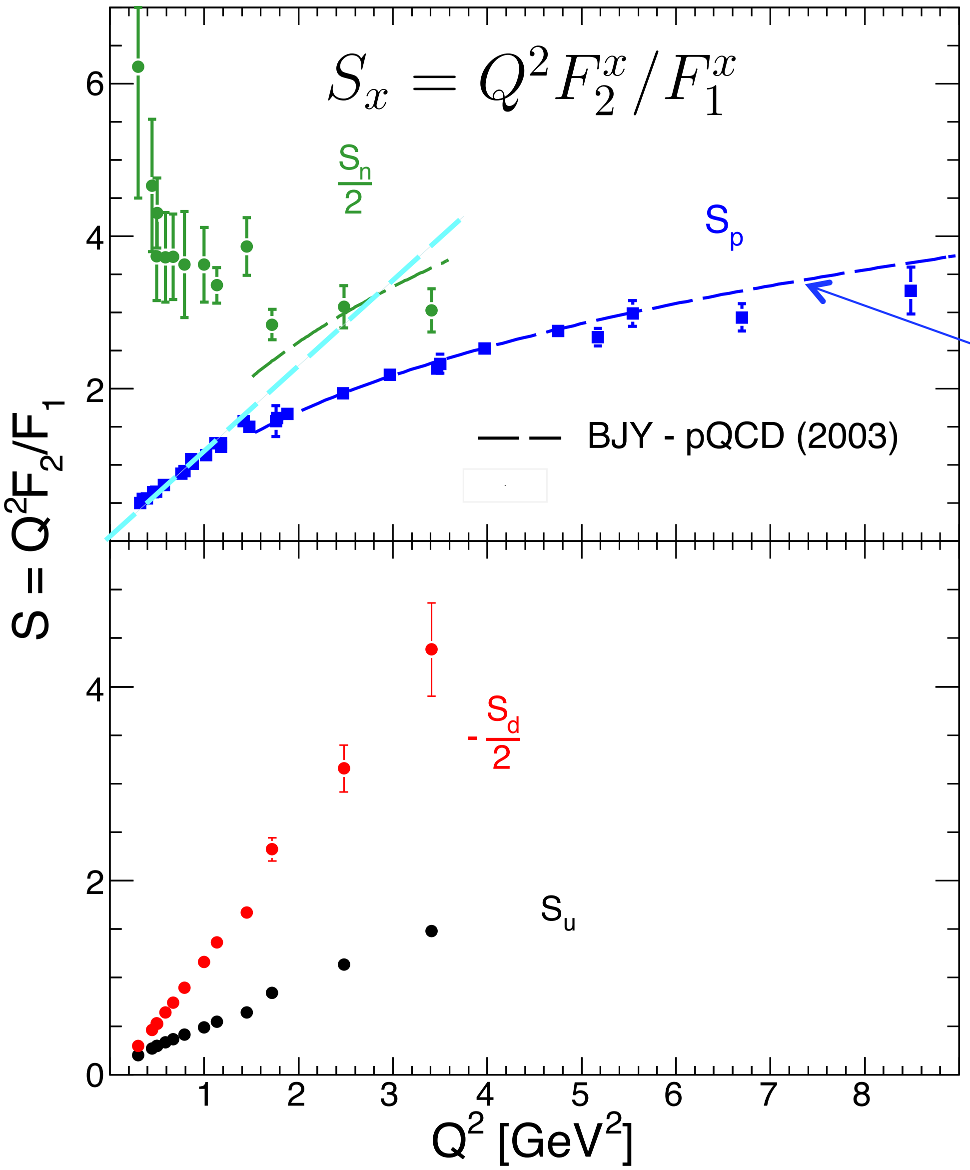
G.Miller: Orbital moment!

Balitsky-Ji-Yuan: modified scaling due to the orbital moment w.f.





The goal is understanding of the nucleon



pQCD prediction for large Q^2:

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

pQCD updated prediction:

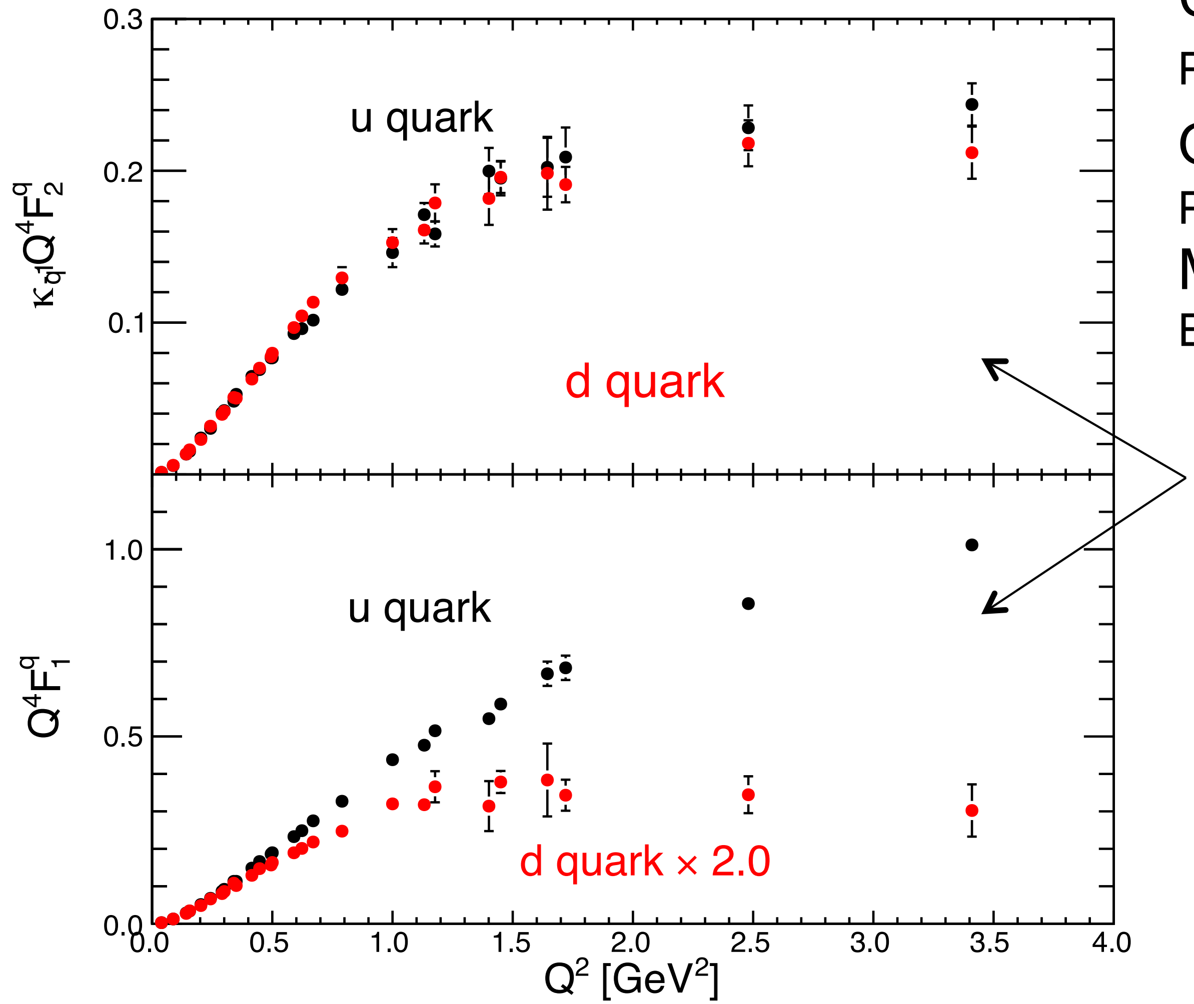
$$S \to \left[Q^2/\ln^2(Q^2/\Lambda^2)\right] F_2/F_1$$

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

The lines for individual flavor
are straight!

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

The flavor disparity in the nucleon



CJRW (u/d with new GEn data)

Phys. Rev. Lett. 106 (2011)

Qattan, Arrington (2-γ effects)

Phys.Rev. C86 (2012) 065210

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

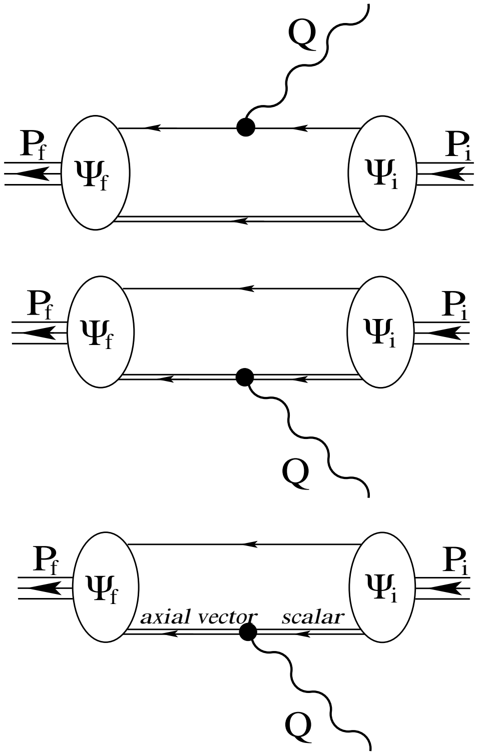
When the virtual photon of 3 GeV^2 interacts with the down quark

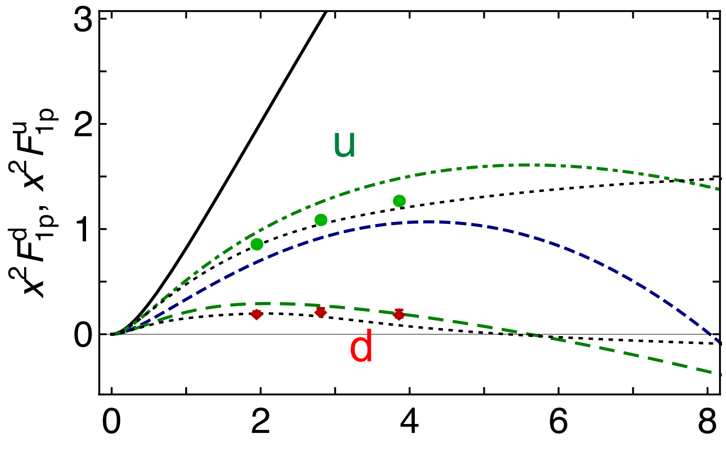
the proton more likely falls apart than in the case of the up quark

The goal is understanding of the nucleon

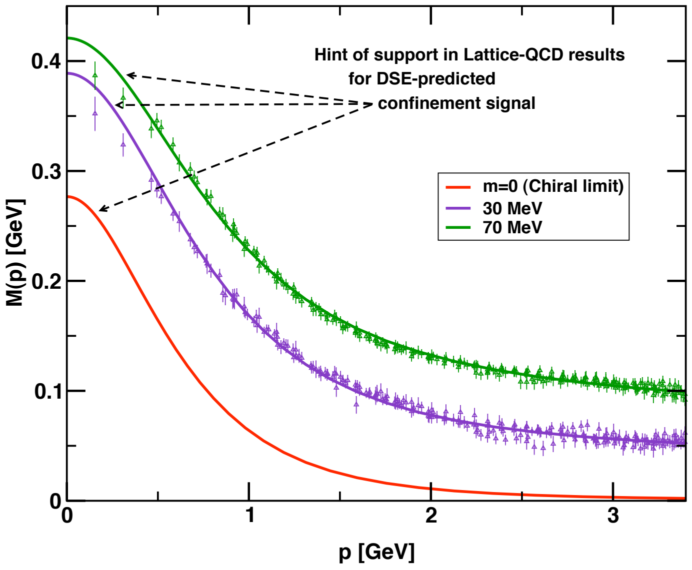
Nucleon and Roper electromagnetic elastic and transition form factors

Wilson, Cloet, Chang, Roberts, PRC 85, 025205 (2012)



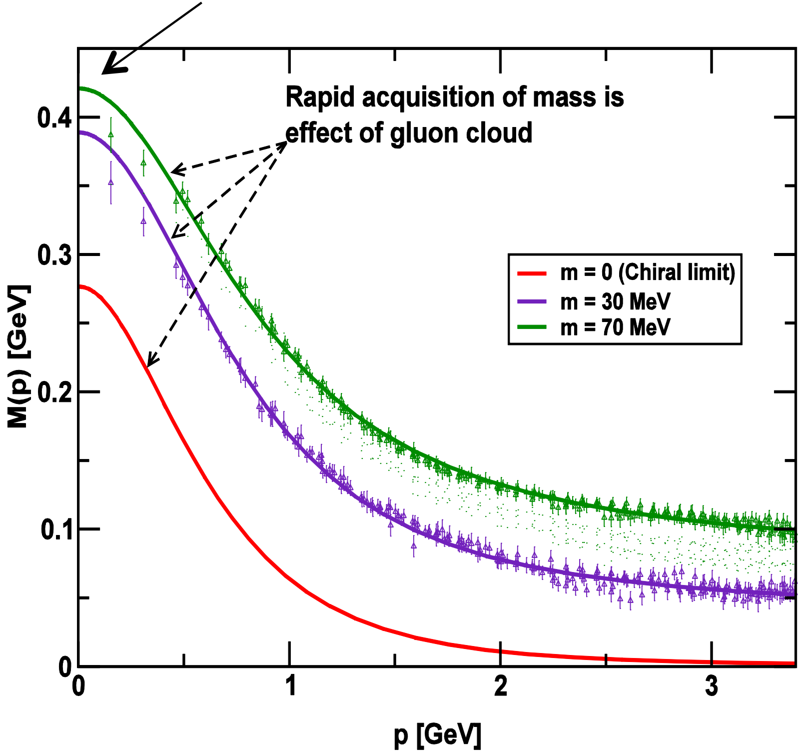


Interplay between
the [qq] and {qq} diquarks
creates a zero crossings



Cloet, Eichmann,
El-Bennich, Klahn and
C. D. Roberts,
arXiv:0812.0416

The goal is understanding of the nucleon


quark/gluon confinement

Rapid acquisition of mass is effect of gluon cloud

- LQCD - P.O.Bowman, et al., PRD **71**, 054505 (2005) (points with error bars)
- DSE QCD – C.D.Roberts, Prog. Part. Nucl. Phys. **61,** 50 (2008) (lines)

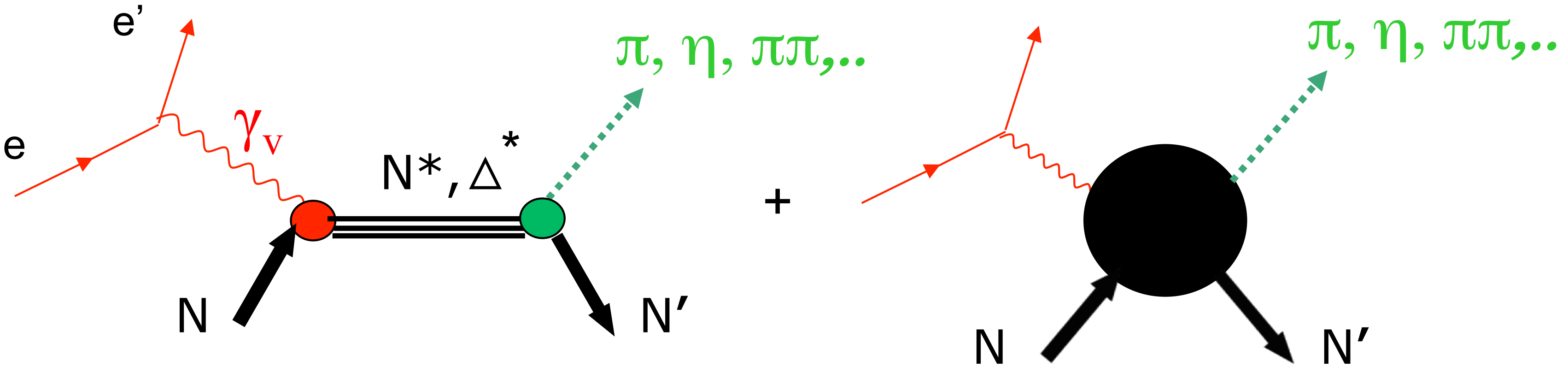
- More than 98% of dressed quark masses as well as their dynamical structure are generated non-perturtbatively through dynamical chiral symmetry breaking (DCSB). The Higgs mechanism accounts for less than 2% of the nucleon & N* mass

- The momentum dependence of the dressed quark mass reflects the transition from quark/gluon confinement to asymptotic freedom

The goal is nucleon transition form factors

Resonant amplitudes

Non-resonant amplitudes



- $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, $S_{1/2}(Q^2)$

  or
- $G_1(Q^2)$, $G_2(Q^2)$, $G_3(Q^2)$

  or
- $G_M(Q^2)$, $G_{E(}Q^2)$, $G_C(Q^2)$

N*'s photo-/electrocouplings $\gamma_v NN^*$ are defined at $W=M_{N^*}$ through the N* electromagnetic decay width Γ_γ :

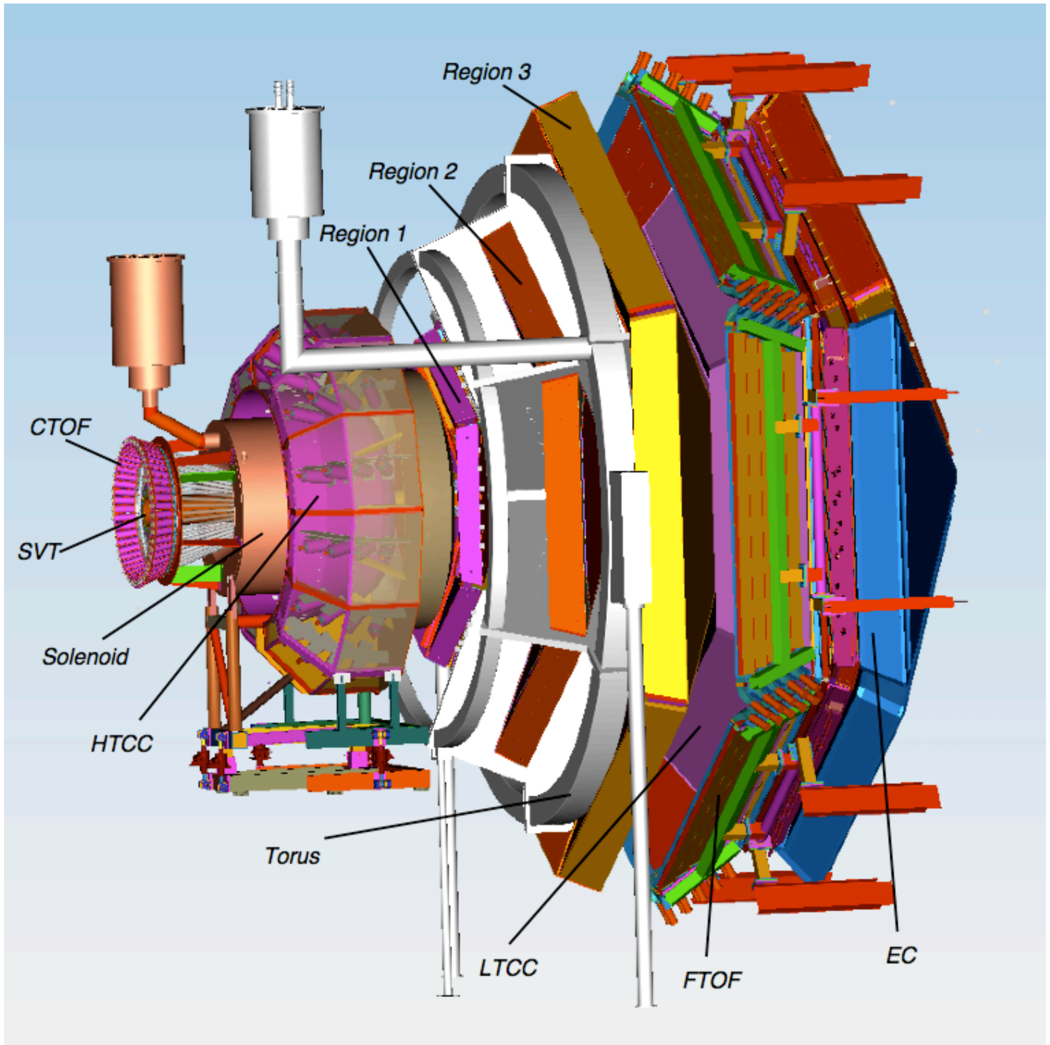
Aznauryan & Burkert, Progr. Part. Nucl. Phys. 67, 1 (2012)

$$\Gamma_\gamma = \frac{q_{\gamma r}^2}{\pi}\frac{2M_N}{(2J_r+1)M_{N^*}}\left[|A_{1/2}|^2+|A_{3/2}|^2\right]$$

The Cebaf Large Acceptance Spectromer

Central detector

Forward detector



CLAS12 supports a broad program in hadronic physics.

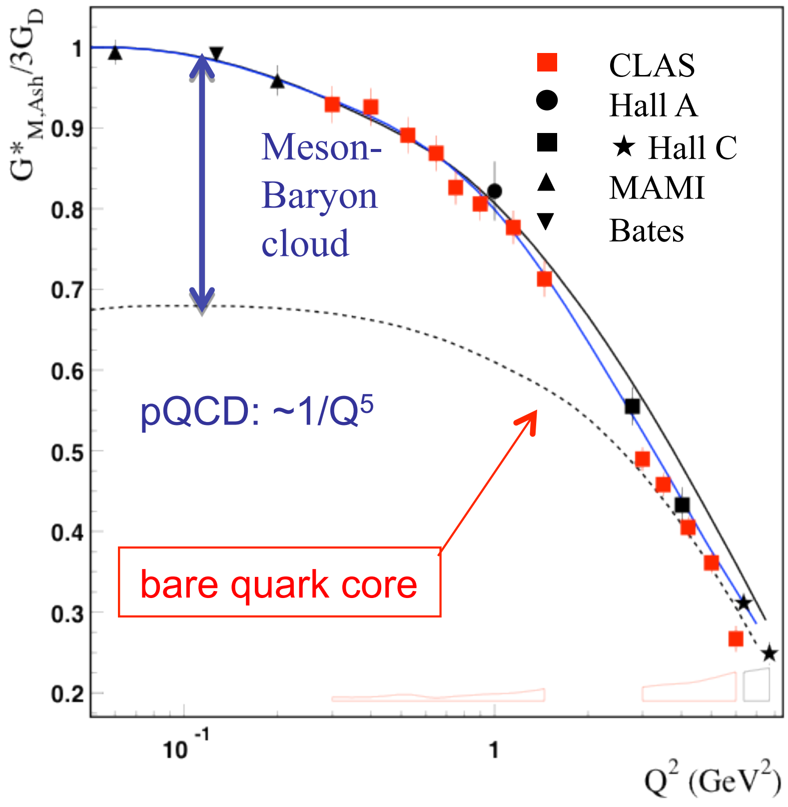
12-GeV plans to study excited baryons and mesons includes:

- Search for hybrid mesons& baryons
- Spectroscopy of Ξ^* , Ω^-
- N* Transition FFs at high Q^2.

The goal is understanding of the nucleon

$P_{11}(1232)$ transition Form Factors

Magnetic Dipole Form Factor

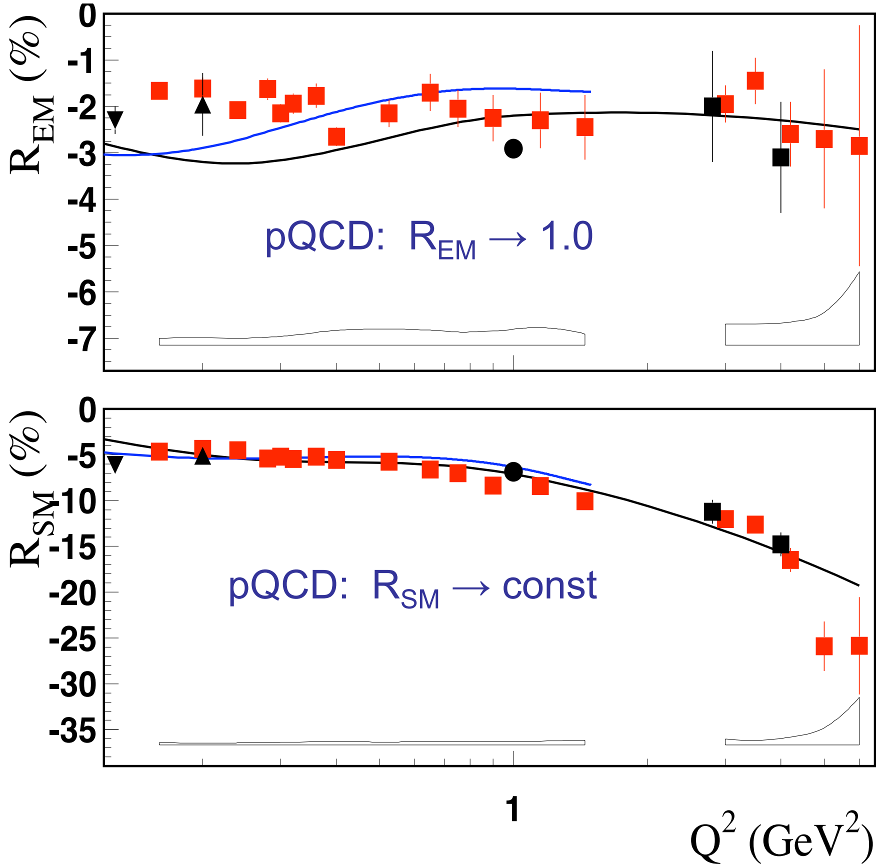


Meson-Baryon cloud

pQCD: ~$1/Q^5$

bare quark core

Quadrupole Ratios

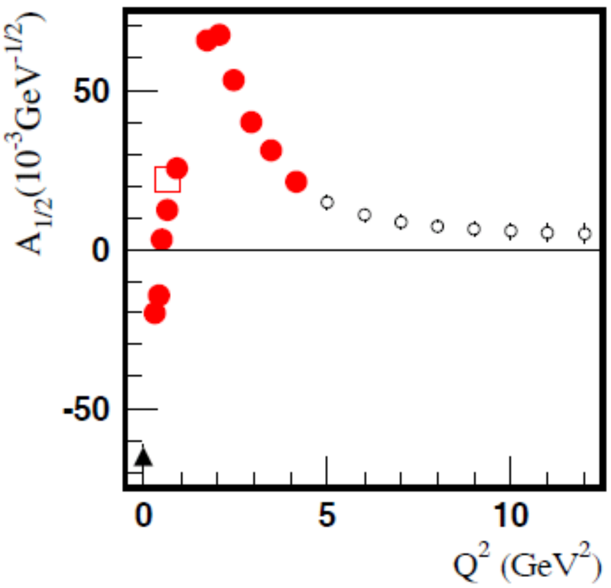


pQCD: $R_{EM} \rightarrow 1.0$

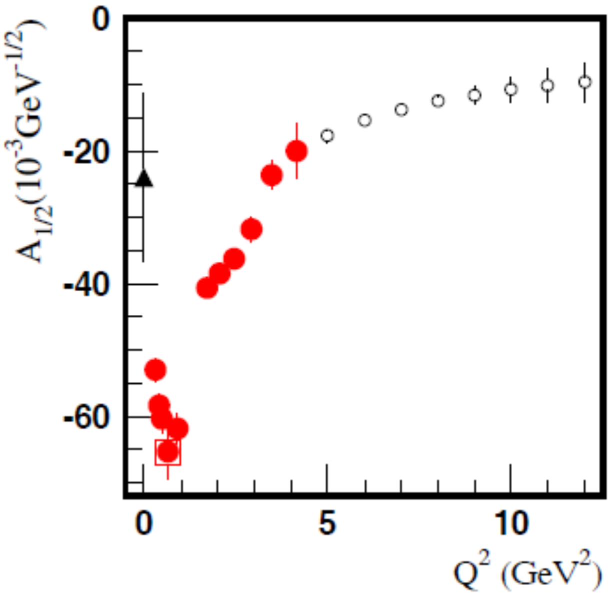
pQCD: $R_{SM} \rightarrow$ const

The goal is understanding of the nucleon

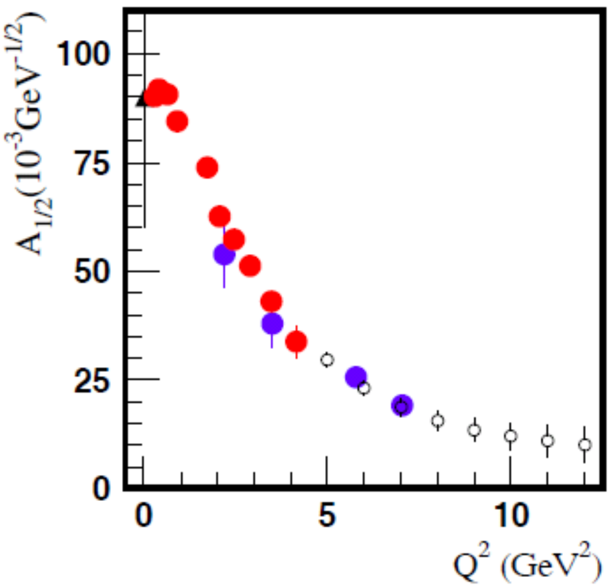
Other transition Form Factors



$P_{11}(1440)$

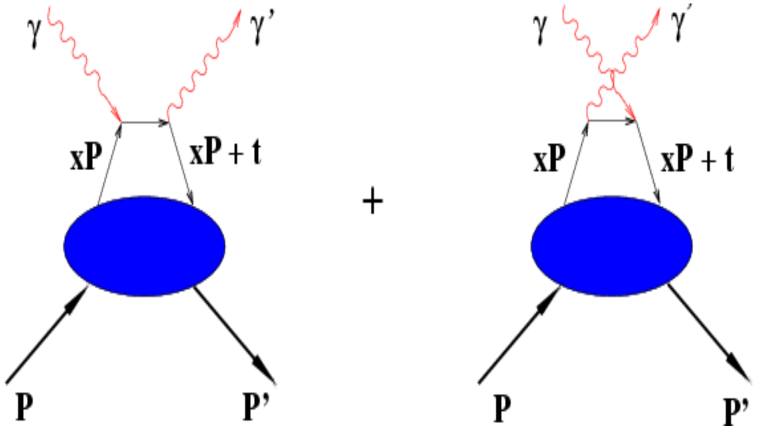


$D_{13}(1520)$

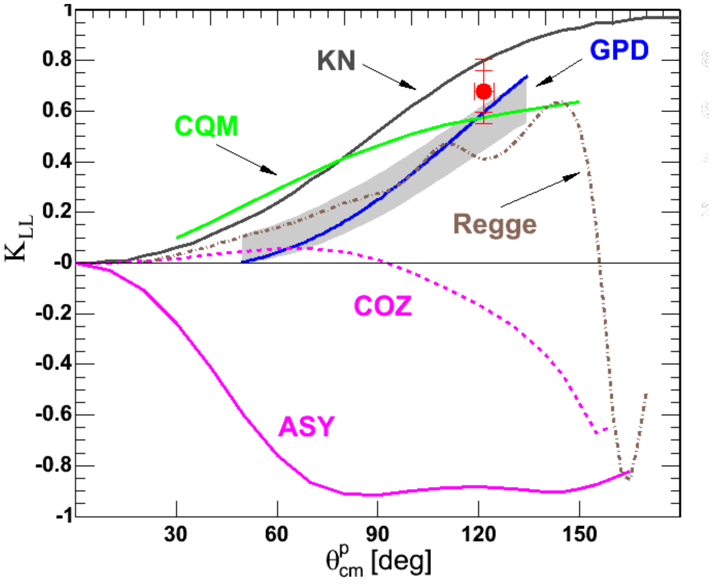


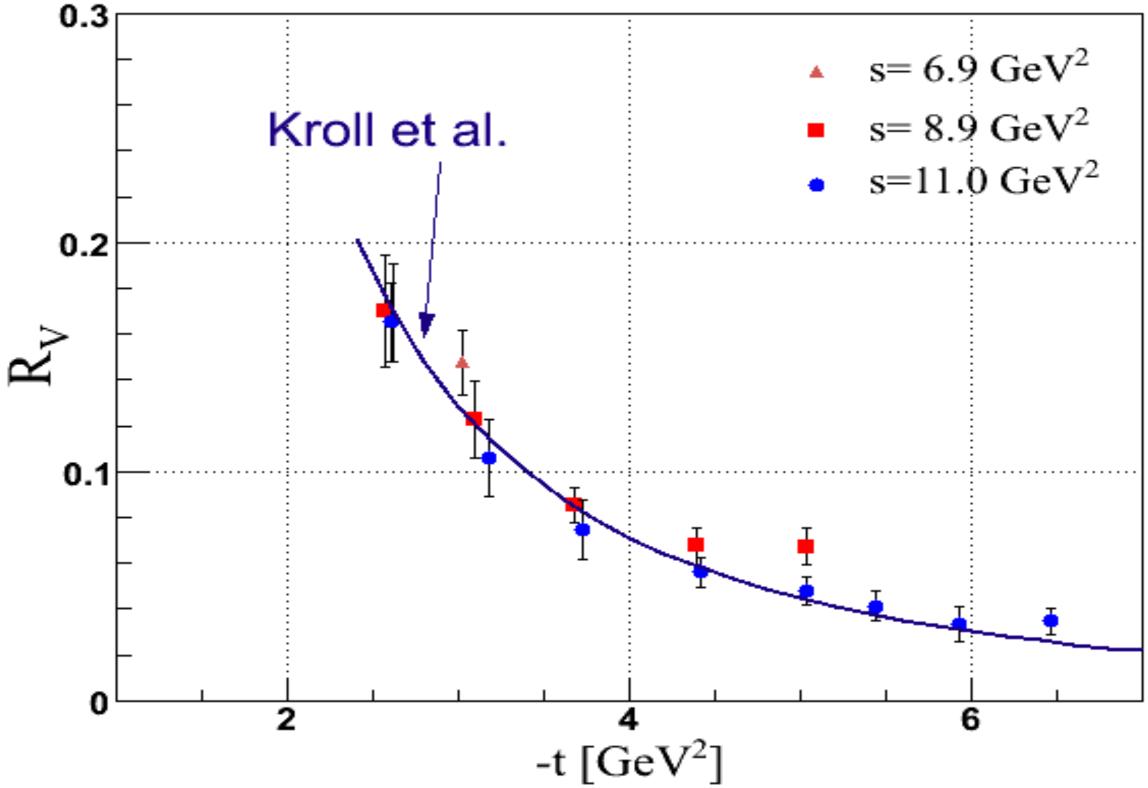
$S_{11}(1535)$

The Compton process from the proton



$$\frac{d\sigma_{\mathrm{RCS}}}{d\sigma_{\mathrm{KN}}} = \frac{(\hat{s}-\hat{u})^2}{\hat{s}^2+\hat{u}^2} R_V^2(t) + \frac{2\hat{s}\hat{u}}{\hat{s}^2+\hat{u}^2} R_A^2(t)$$





Optimization of the experimental setup

Energy; Solid angle; Efficiency

$$\text{Form factor} \propto Q^{-4}$$

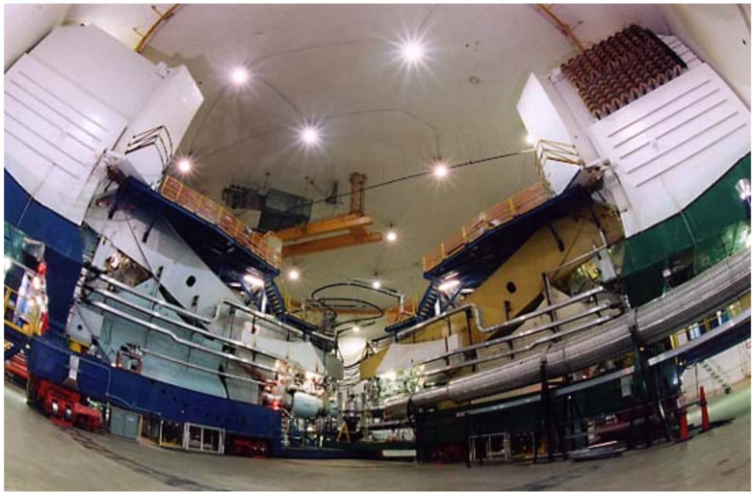
$$\text{Cross section} \propto E^2/Q^4 \times Q^{-8}$$

$$\text{Figure-of-Merit } \epsilon A_Y^2 \times \sigma \times \Omega$$

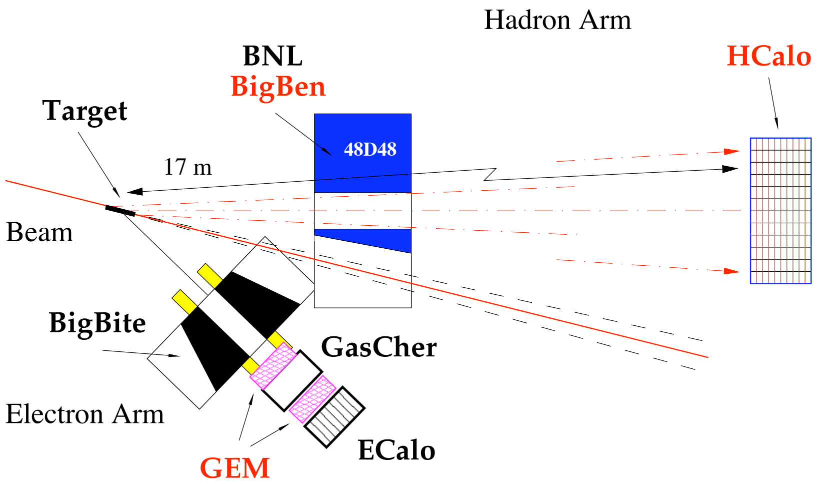
$$\propto E^2/Q^{16}$$

Optimization of the experimental setup

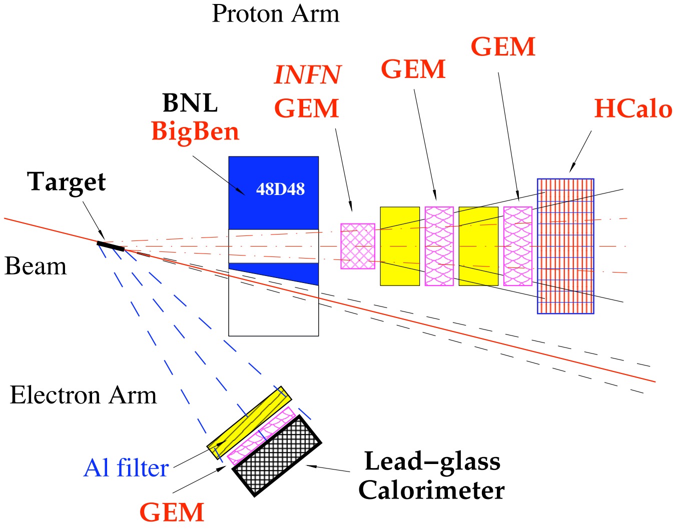
Proton magnetic form factor: E12-07-108



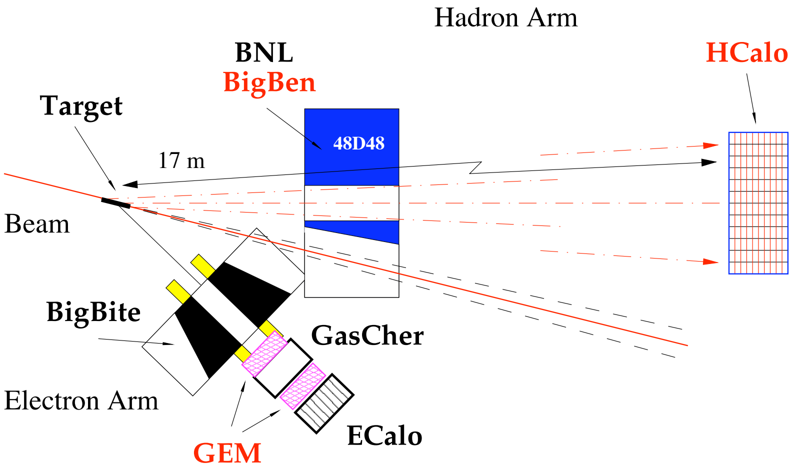
Neutron/proton form factors ratio: E12-09-019



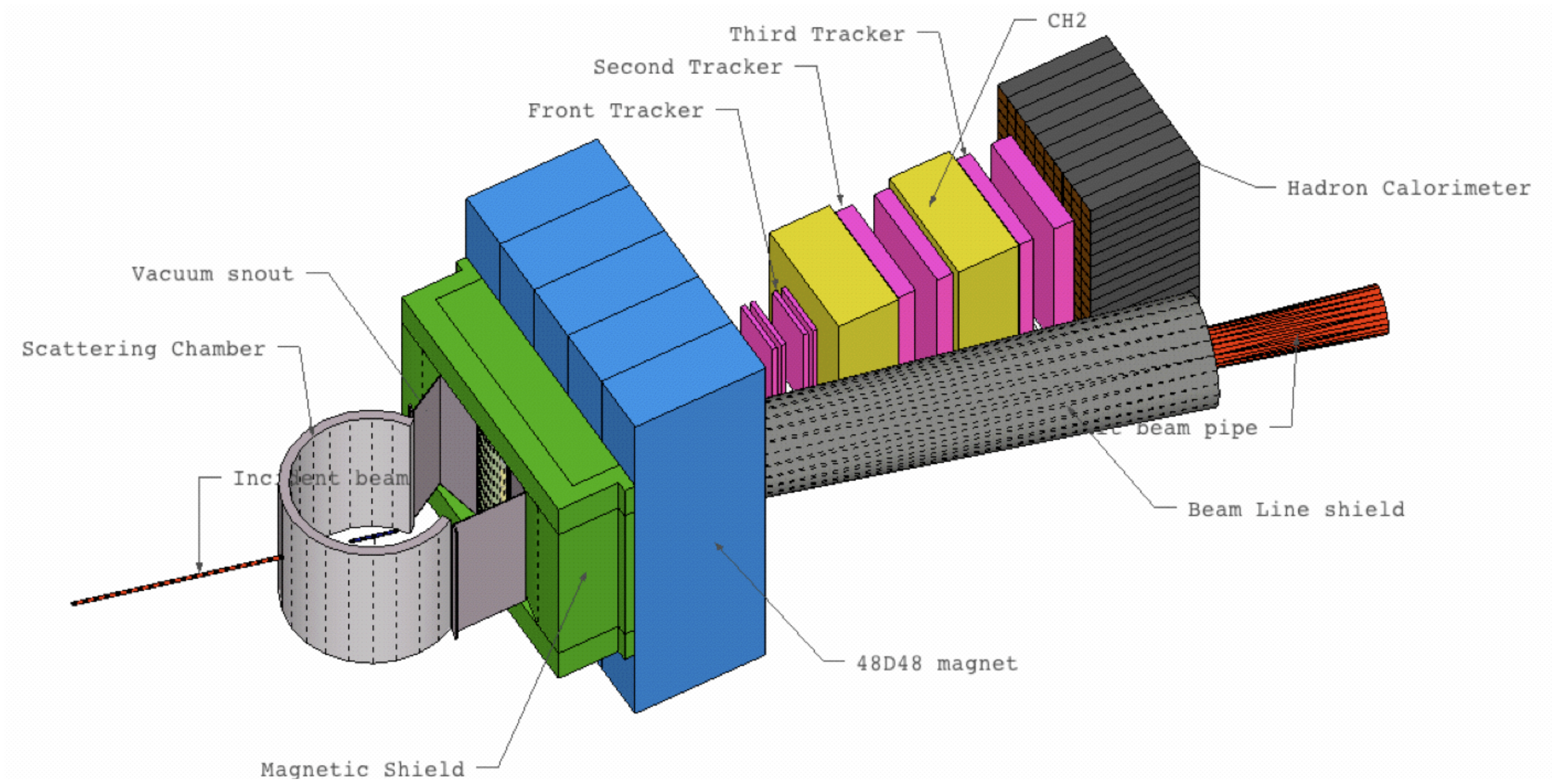
Proton form factors ratio, GEp(5): E12–07–109



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

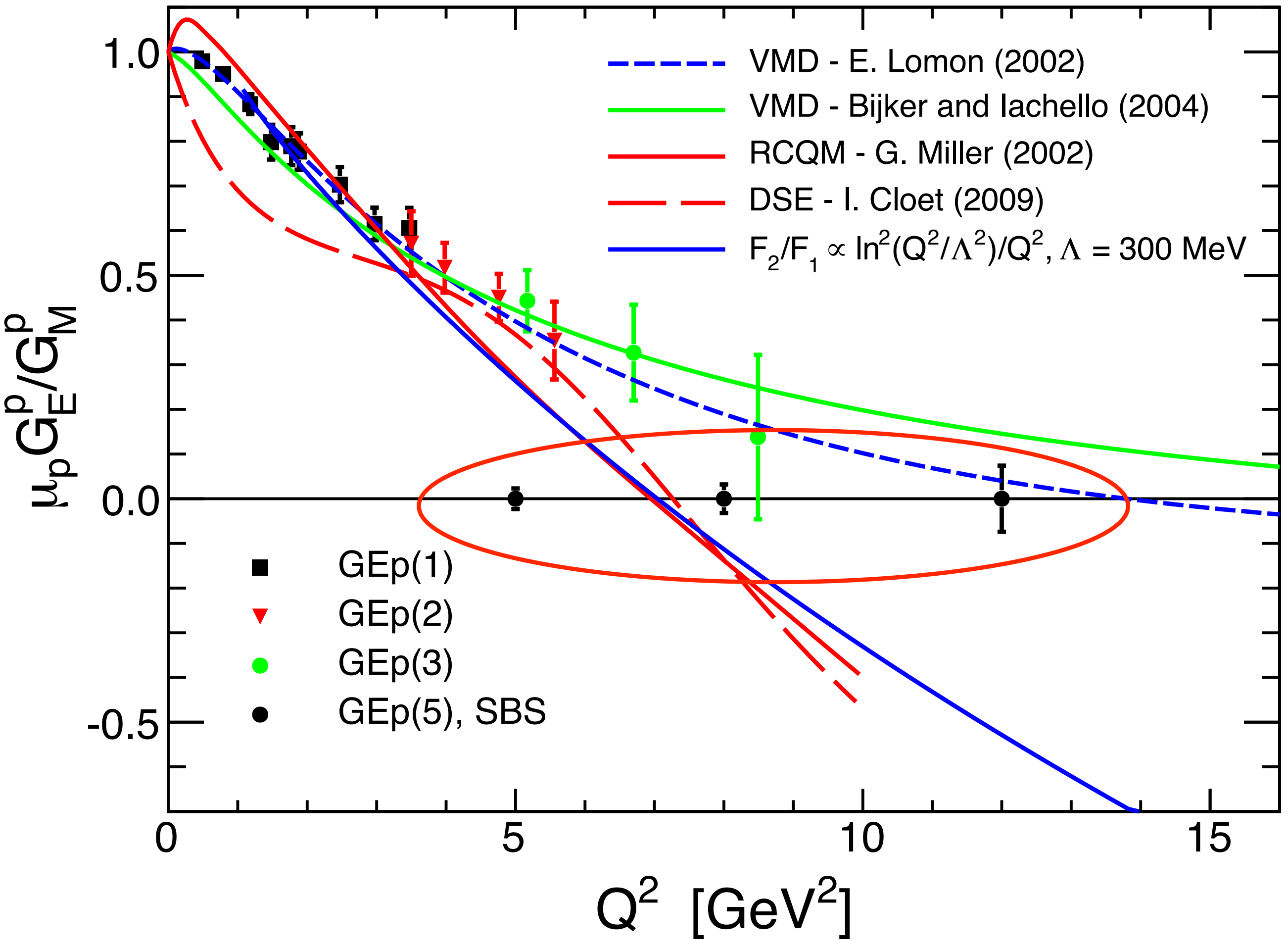


Super Bigbite Spectrometer in GEp



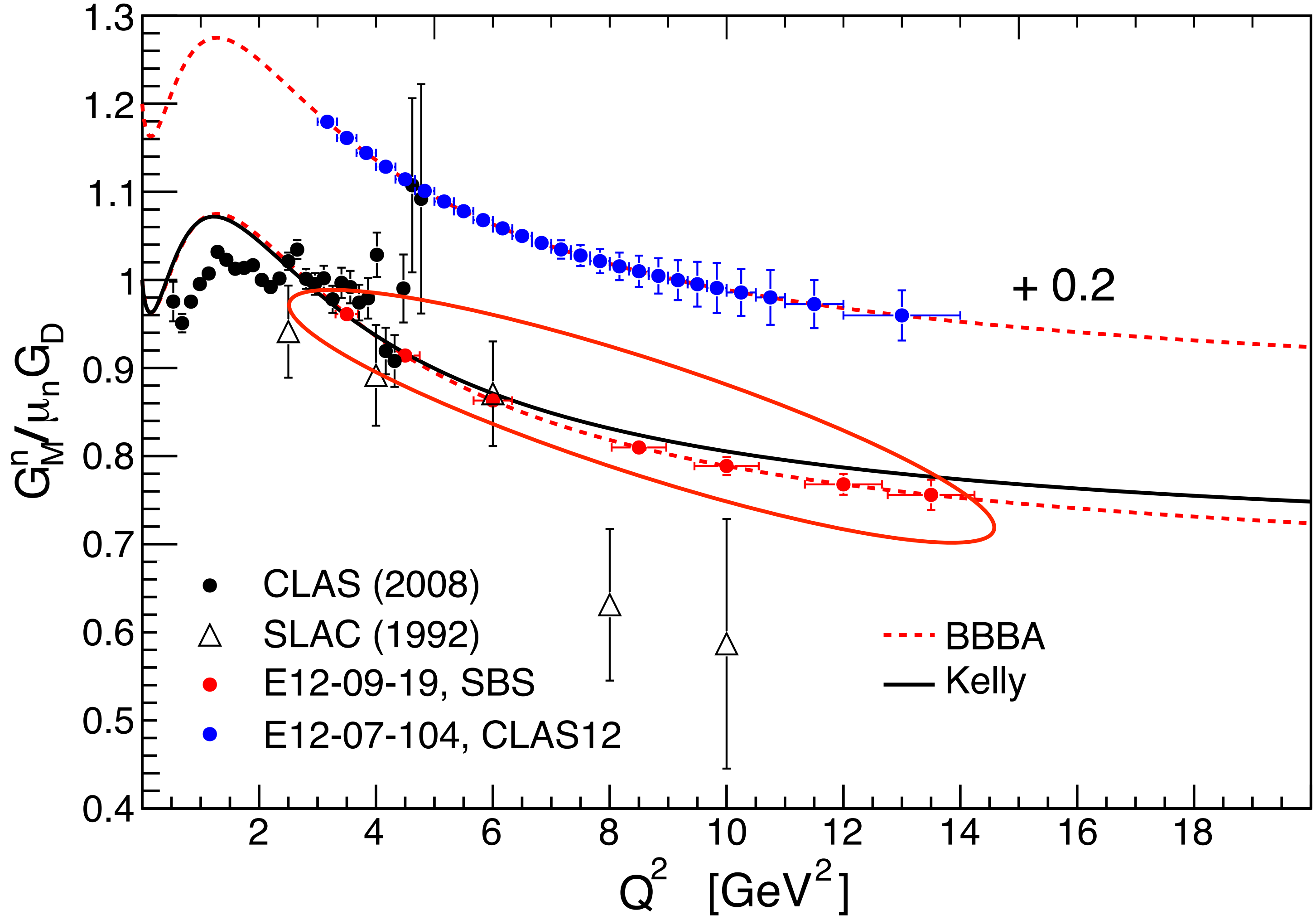
12 GeV GEp experiment

Transverse polarization of the proton
in the polarized electron-proton scattering



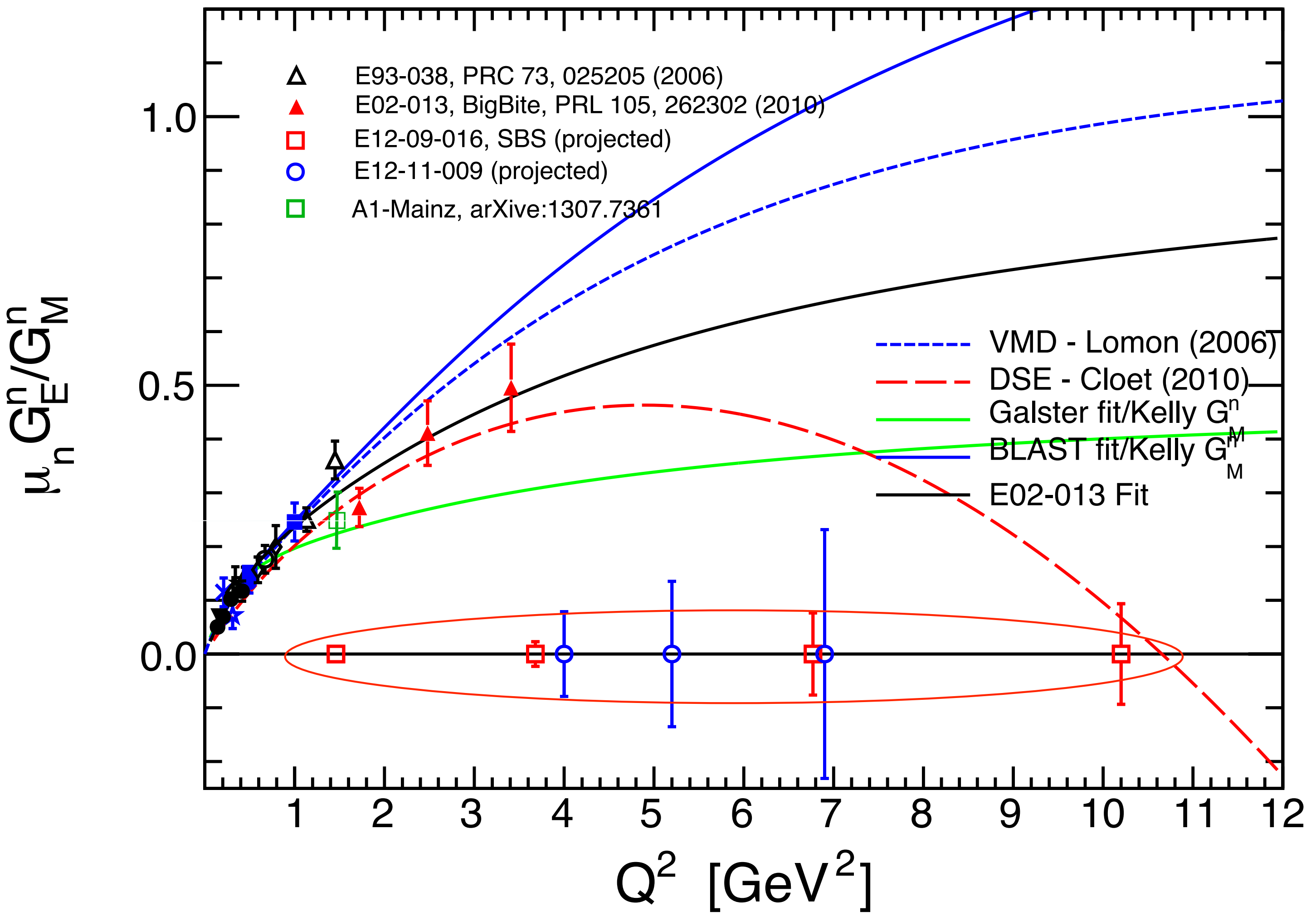
12 GeV GMn experiment

Ratio of the cross sections $D(e,e'n)$ and $D(e,e'p)$



12 GeV GEn experiment

Asymmetry in the polarized electron scattering from the polarized ^{3}He

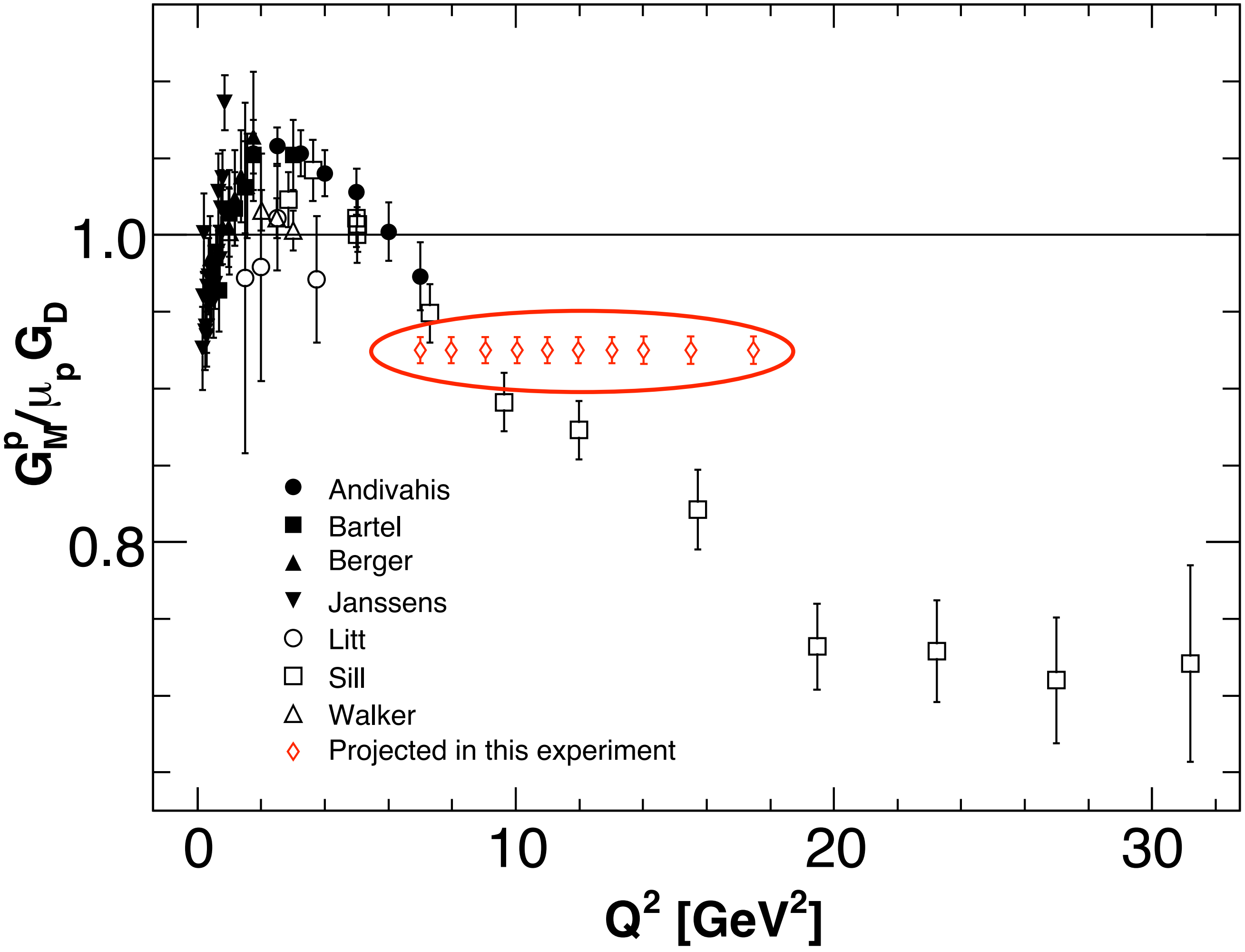


12 GeV GMp experiment

High precision (of 1%) cross section measurements

The cross section
of H(e,e')p.

By using two existing
Hall A High Resolution
Spectrometers
with several new ideas
for improved control
of systematic.



The JLab FF measurements which were not presented

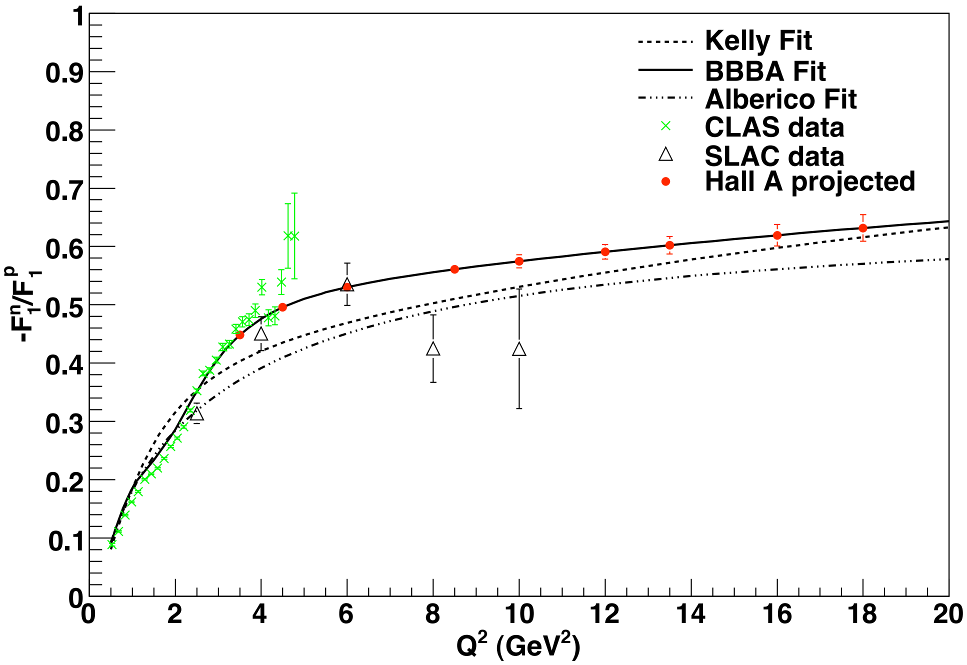
- High precision GEp/GMp Rosenbluth and “SR” results
- High precision 2-photon experiments
- High precision low Q^2 proton FF ratio results
- Experiments GEp/GMp on the polarized target
- Neutron GMn from the double polarized ^{3}He(e,e’)
- GMn/GMp with a large acceptance CLAS12 detector
- GEn/GMn with the neutron polarimeters

Summary

- Nucleon Form Factors, first investigated 60 years ago, is an active field which has many questions to be answered.

- Baryon Form Factor physics at large Q^2 has a huge program at JLab with the 12-GeV beam

GMn/GMp and GPDs

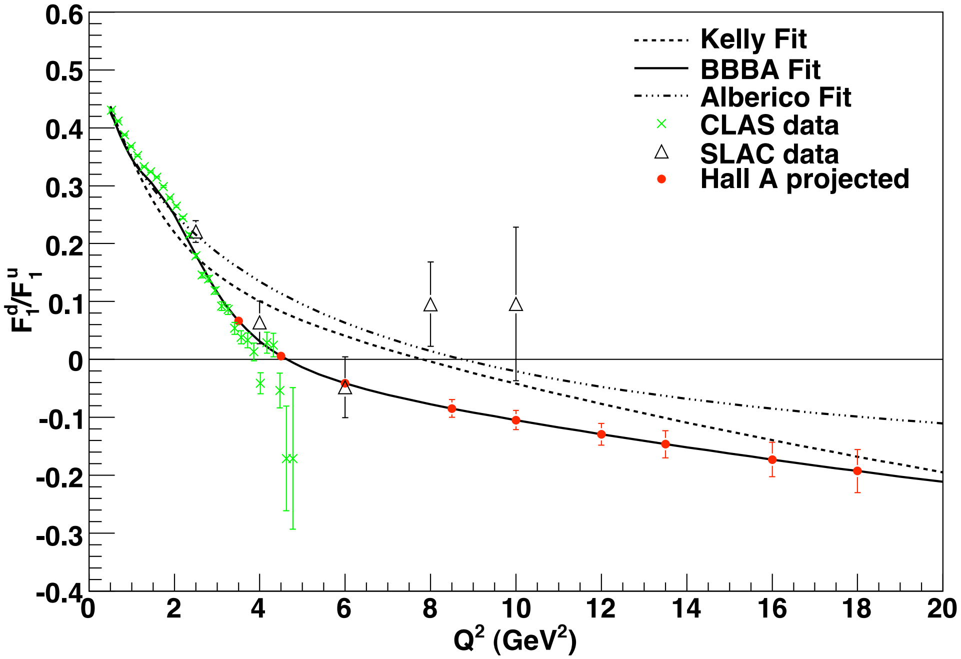


GPD model (Guidal etal):

$$F_1^u(t) = \int_0^1 dx u_v(x) e^{-t\alpha' \ln x},$$

$$F_1^d(t) = \int_0^1 dx d_v(x) e^{-t\alpha' \ln x}.$$

$F_1^d < 0$ presents an interesting challenge to such a model



GEn/GMn update from Mainz