Nucleon structure probed in elastic electron scattering

Bogdan Wojtsekhowski, JLab

- Elastic electron-nucleon scattering
- Flavor structure of the nucleon & diquark
- Future form factor experiments at JLab

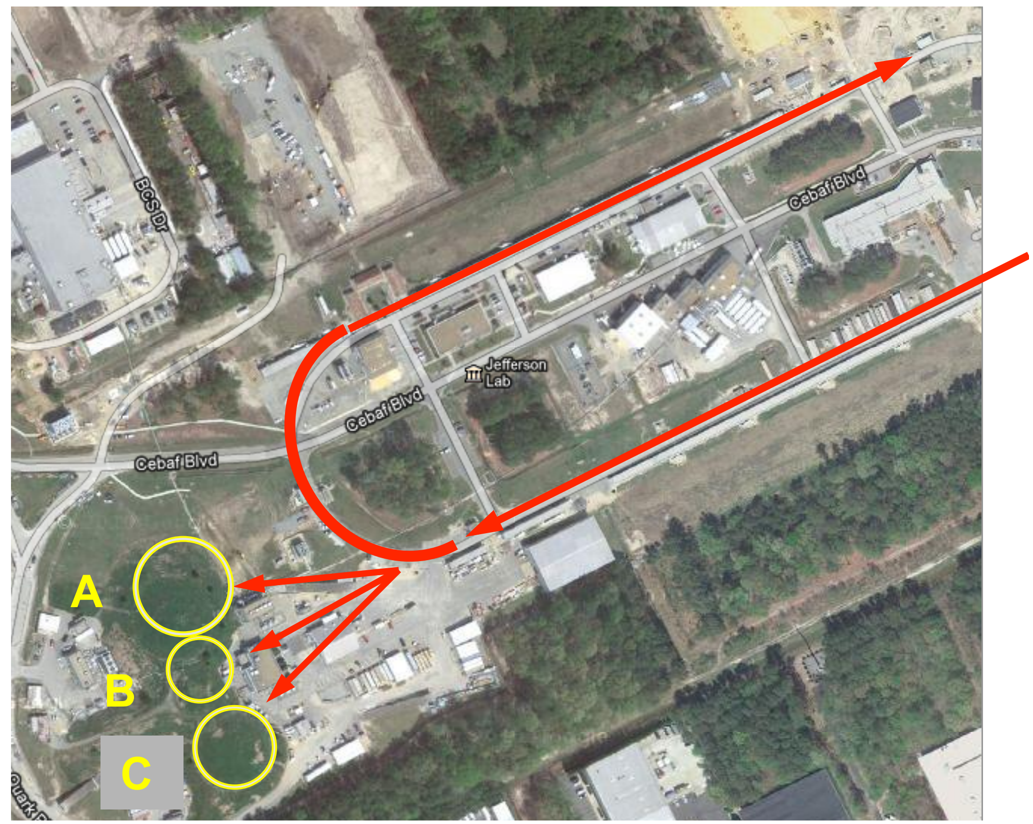
Jefferson Laboratory

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

A 12-GeV upgrade is completed

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:

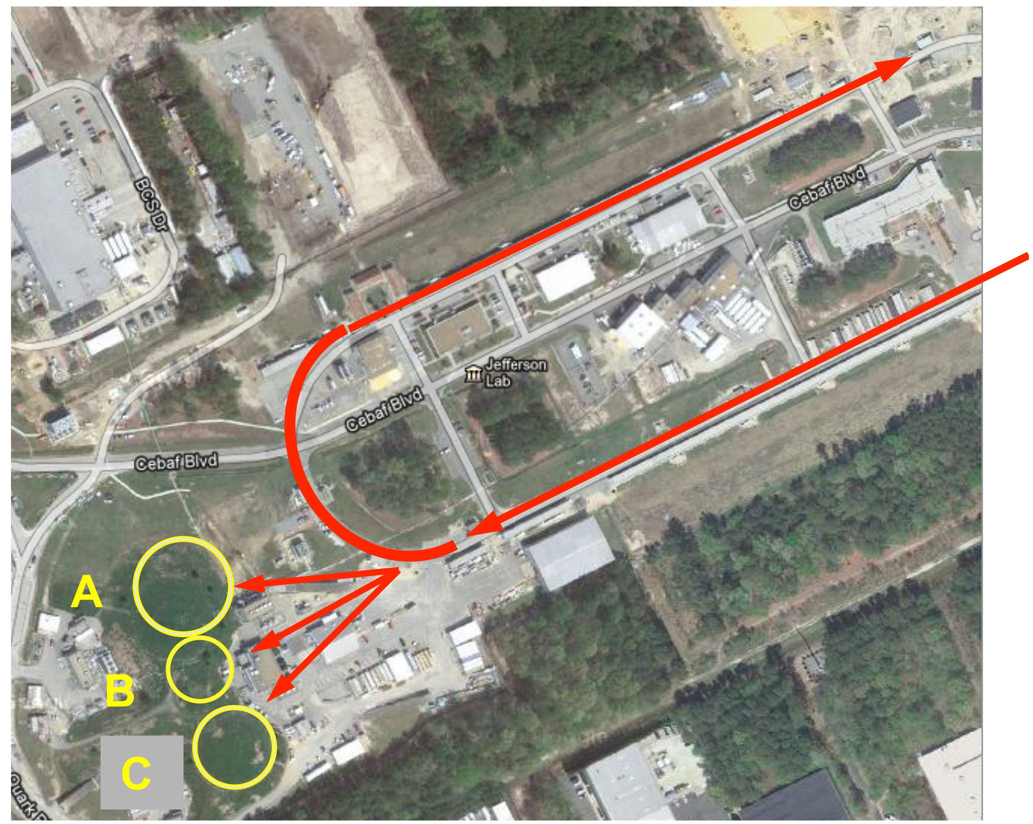
energy up to 12 GeV
intensity up to 180 μA
polarization 85%
pol. flip systematic 10^{-9}
time structure 2-4 ns

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)
^3He: L ~10^{36} cm^{-2}/s



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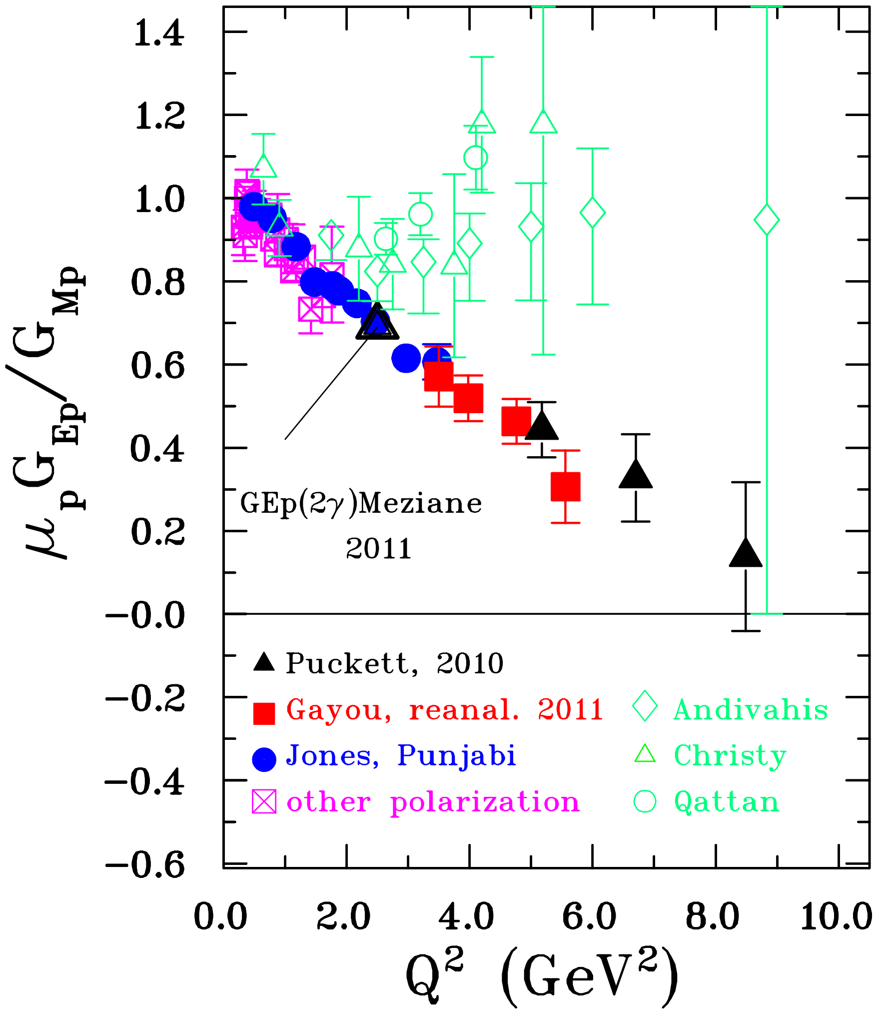
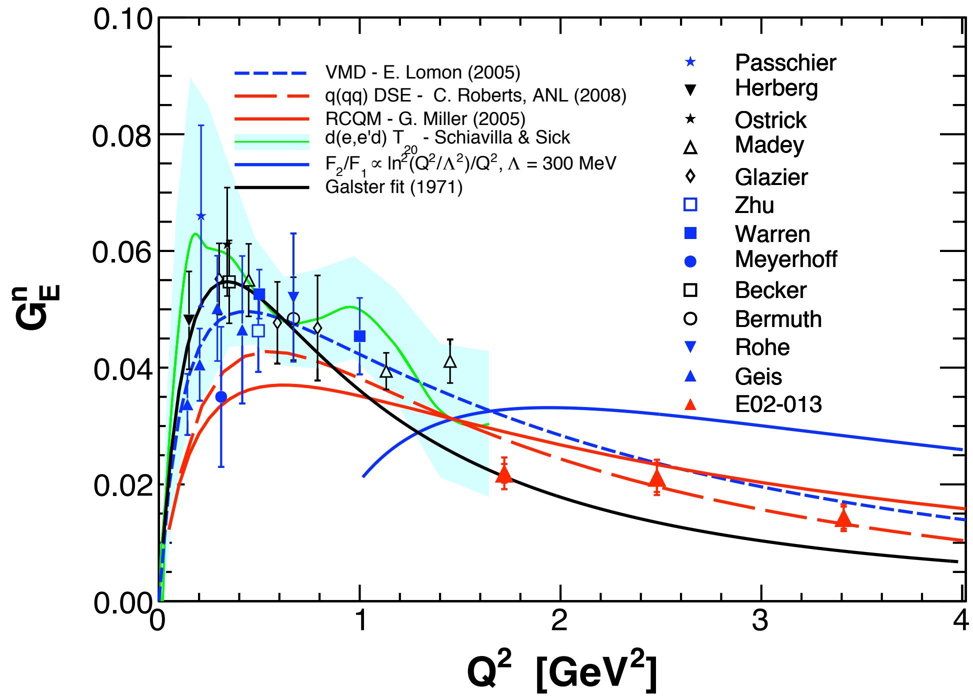
The major research highlights include:

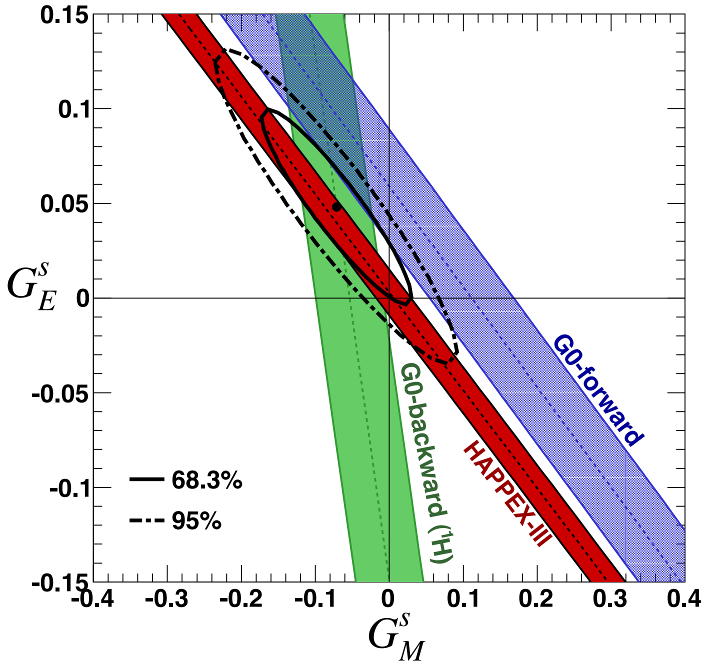


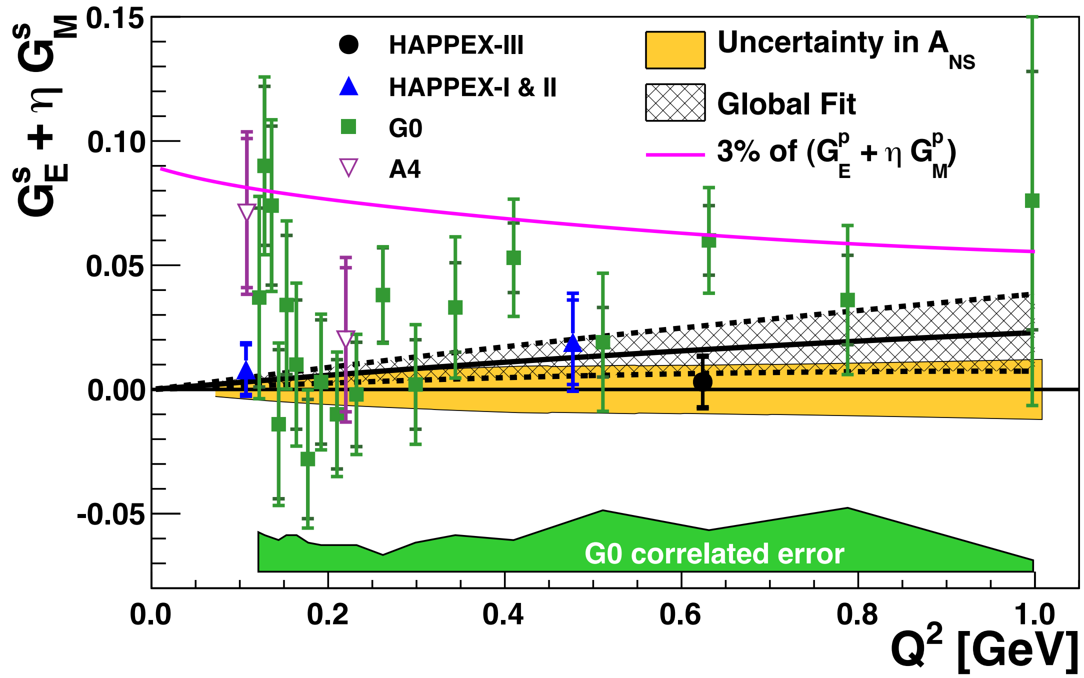
Proton and Neutron Electromagnetic Form Factors



Jefferson Laboratory

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

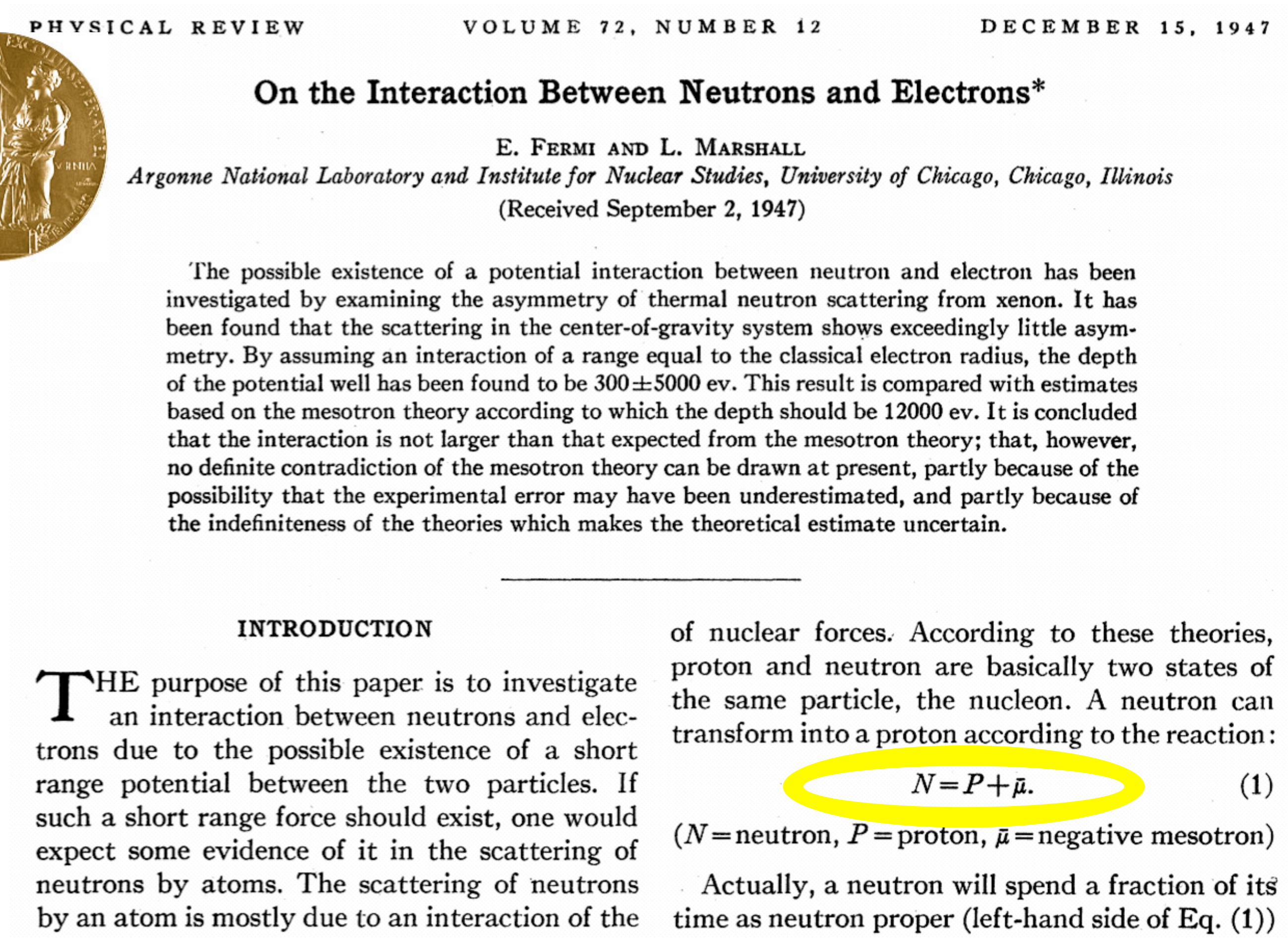




Composite structure of the nucleon

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.*



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))

E.Fermi, 1947

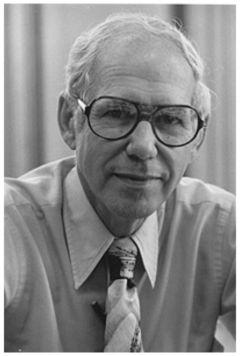
Introduction of the Form Factors

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

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

SLAC results for the proton Form Factors

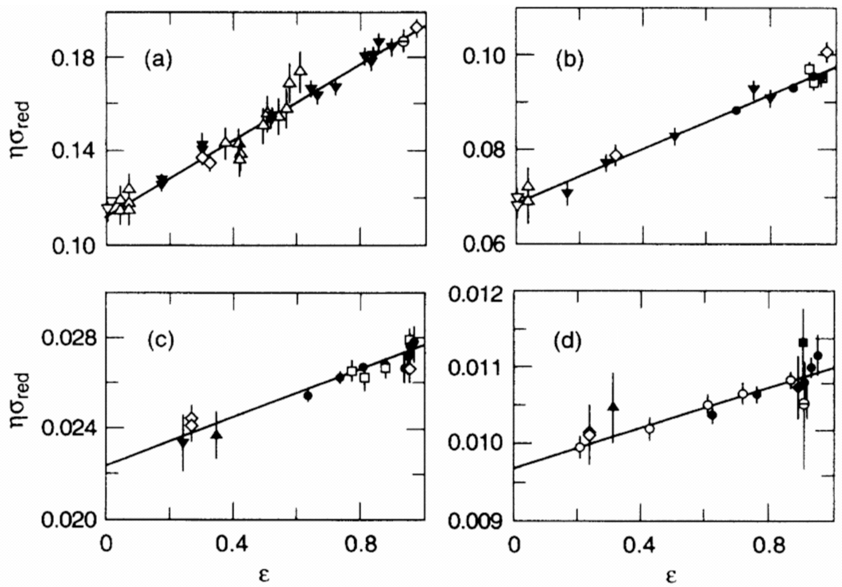
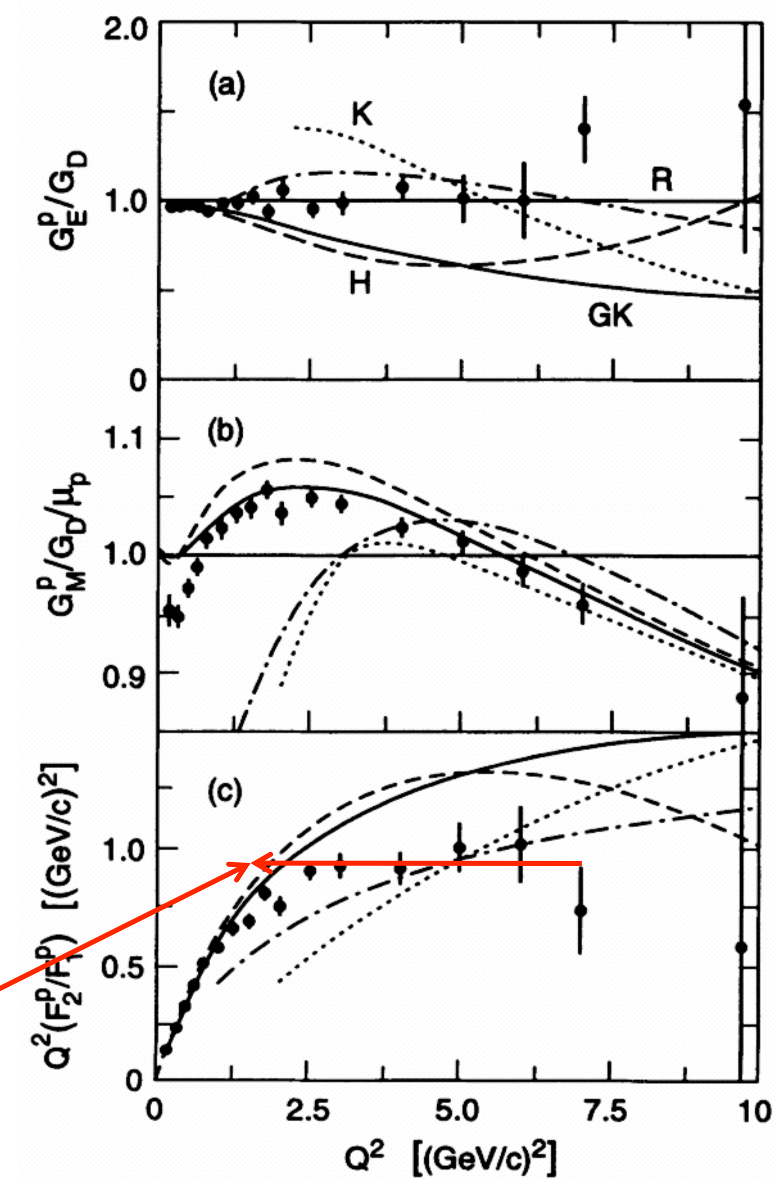


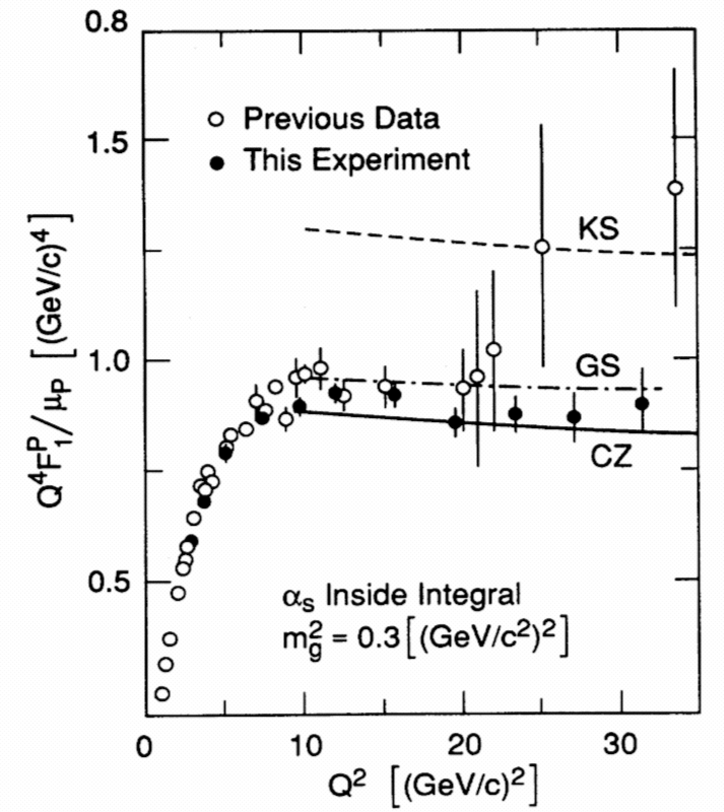
FIG. 9. Four typical Rosenbluth fits for the form factor extraction from the global data set at (a) $Q^2 = 0.6$, (b) $Q^2 = 1.0$, (c) $Q^2 = 2.0$, and (d) $Q^2 = 3.0$ $(\mathrm{GeV}/c)^2$.



Walker et al,1993

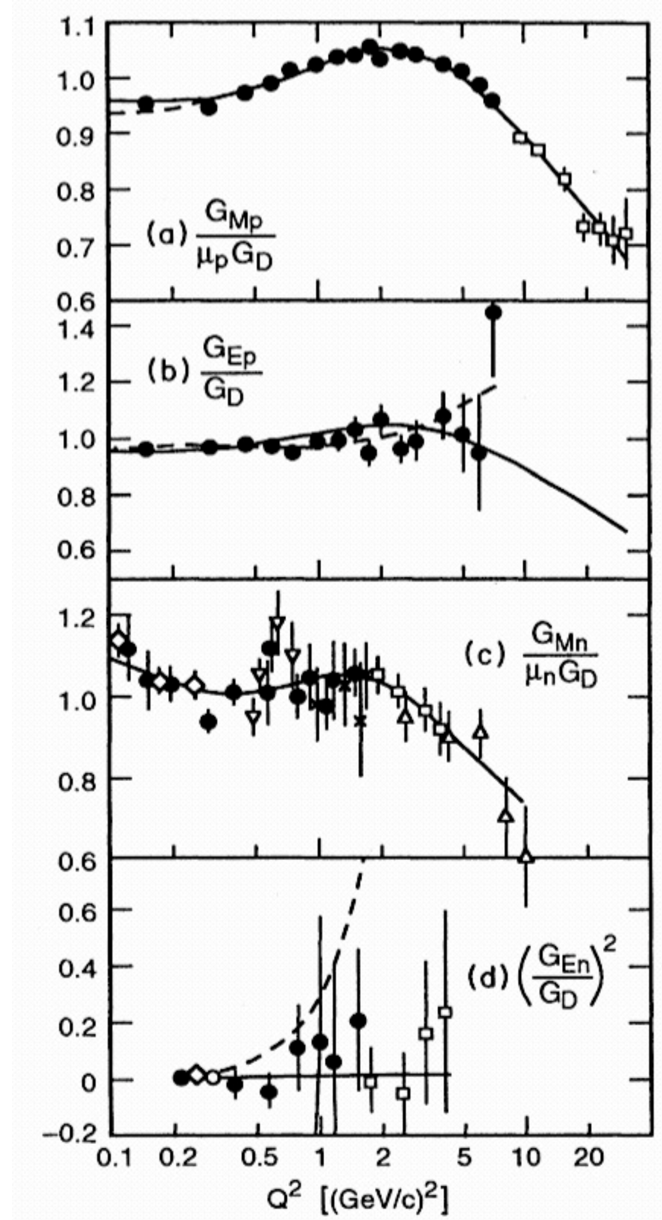
The onset of the pQCD scaling?

SLAC results for the Form Factors

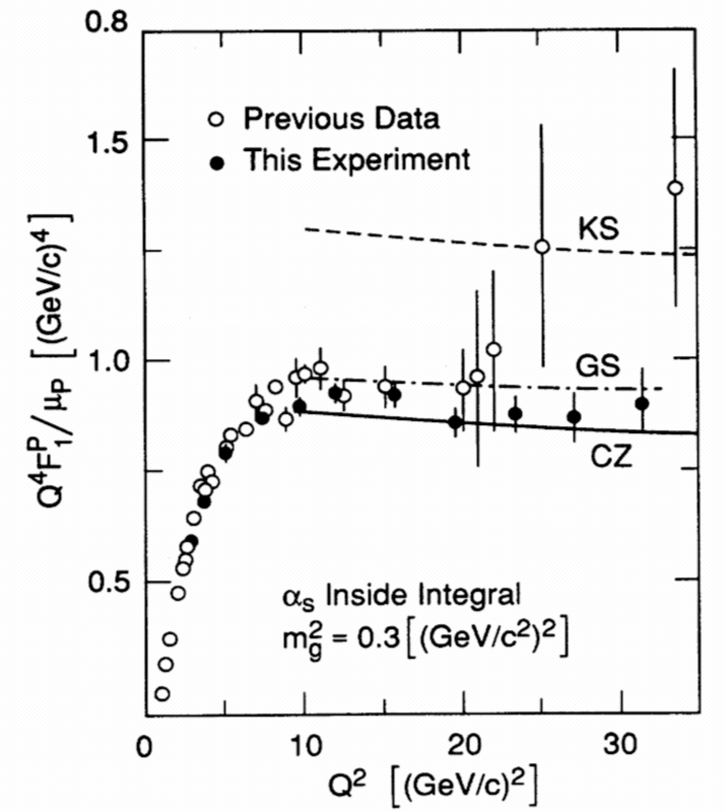


Sill et al,1993

Bosted,1995

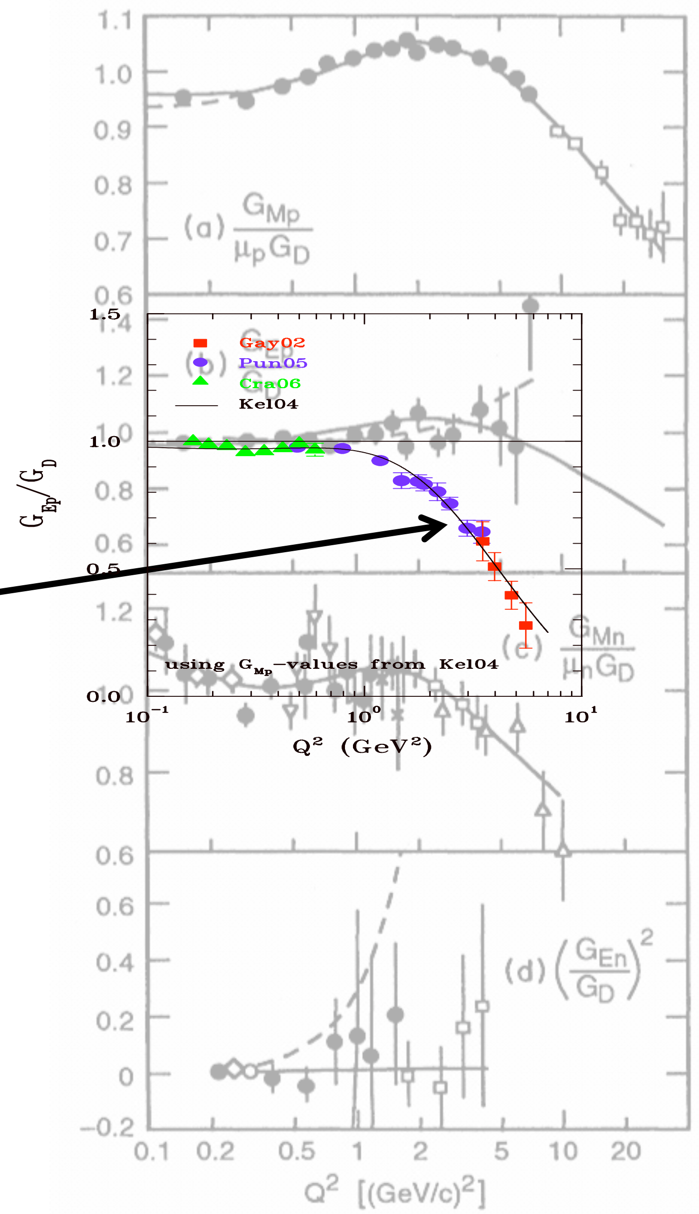


Results for the Form Factors

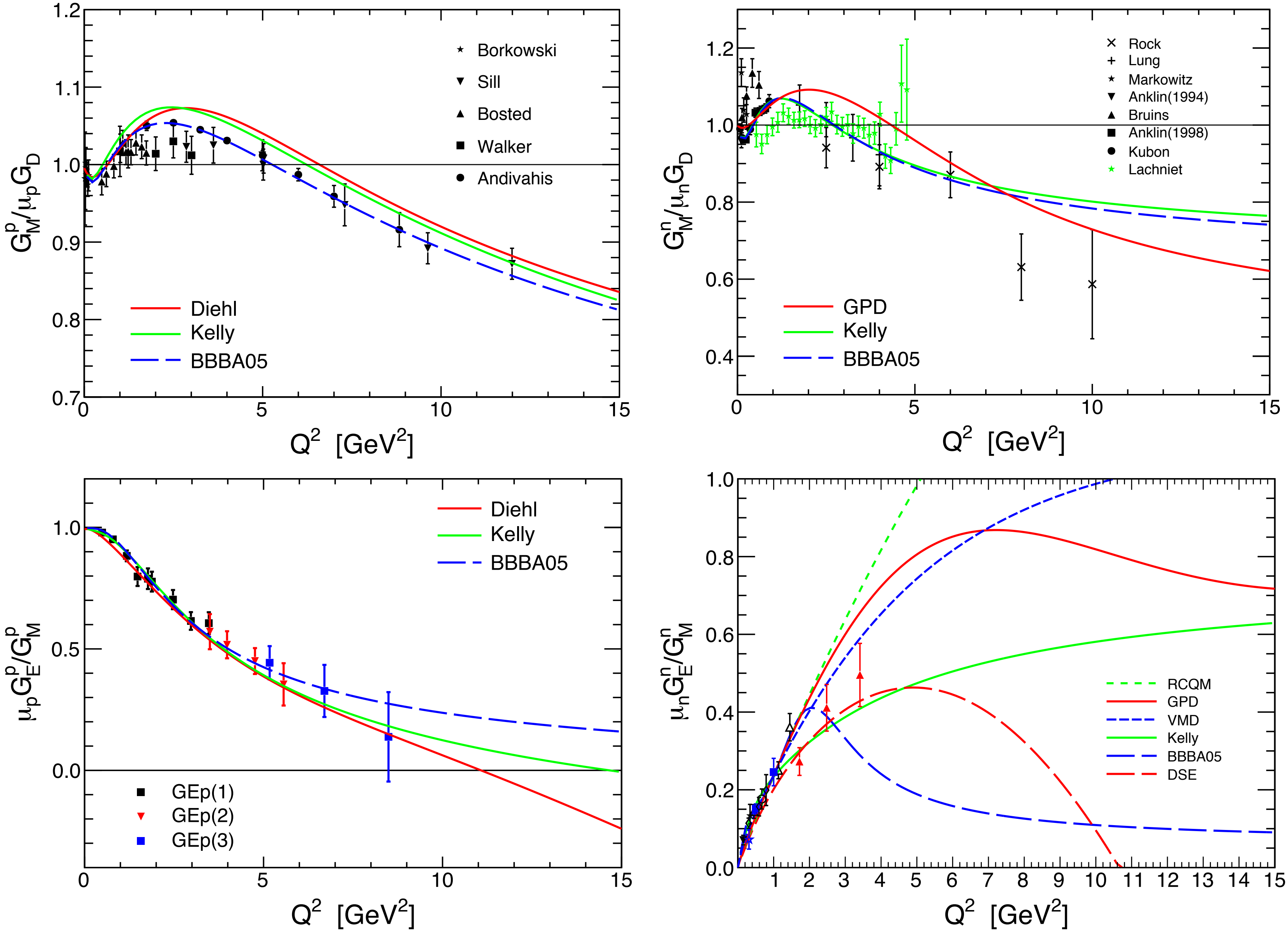


Sill et al,1993

Perdrisat, 2001



Sachs Form Factors of the nucleon

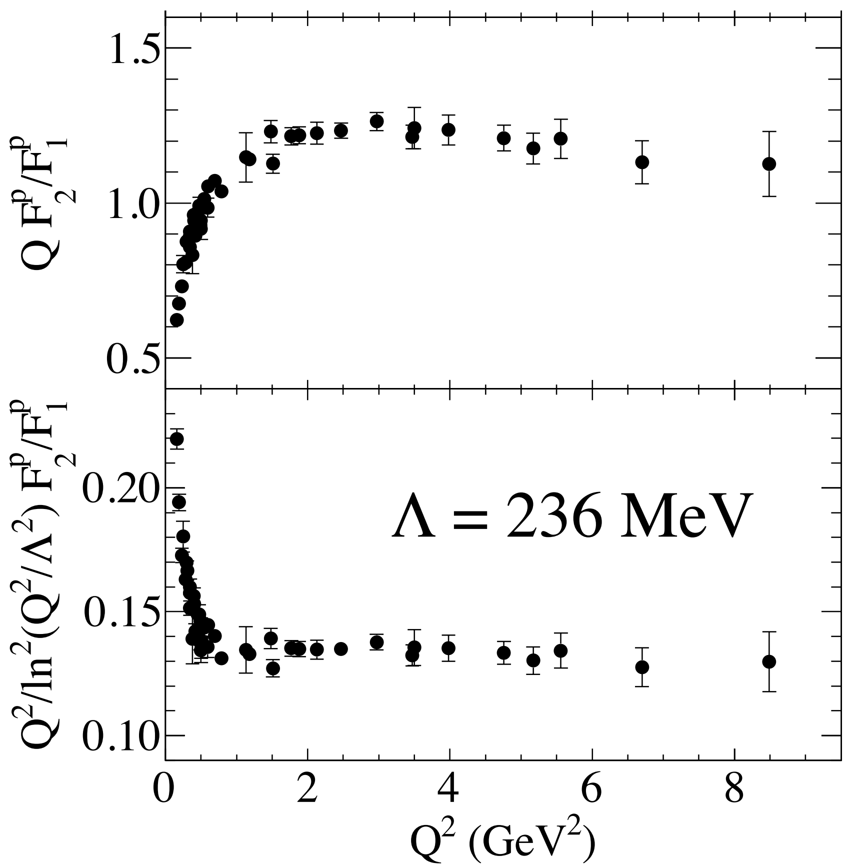


Nucleon form factors scaling

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

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

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



Discovery: It is rising and it looks like a higher F_2 can explain the data.

Jerry Miller suggested accounting for Orbital Angular Momentum!

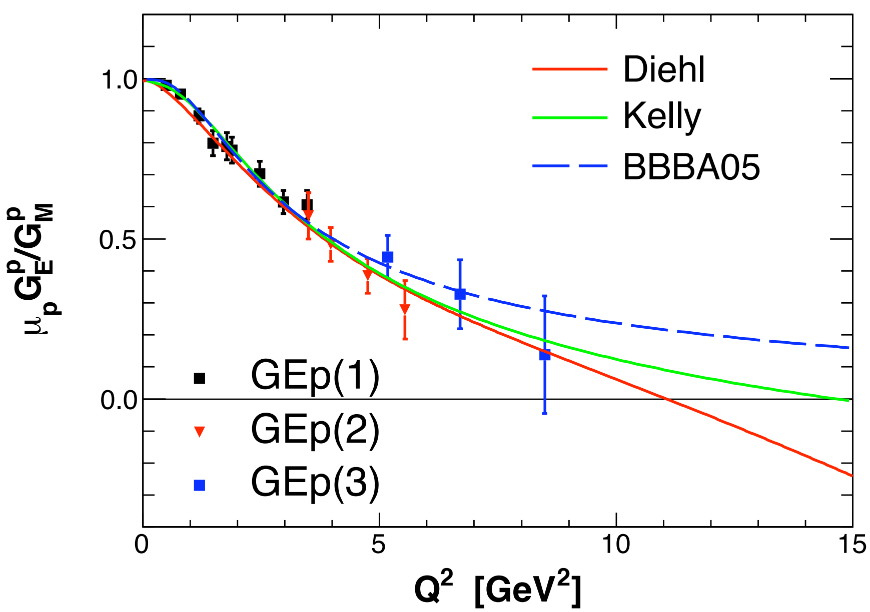
Balitsky-Ji-Yuan: Modified logarithmic scaling works from surprisingly low Q^2.

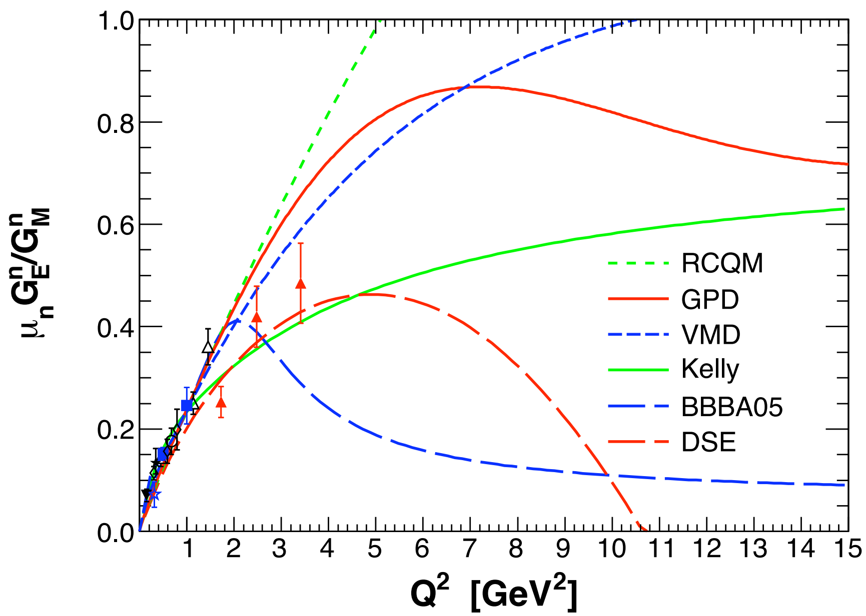
The goal is understanding of the nucleon

From the Sachs FFs to the contributions of the u- / d-quarks

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

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





The goal is understanding of the nucleon

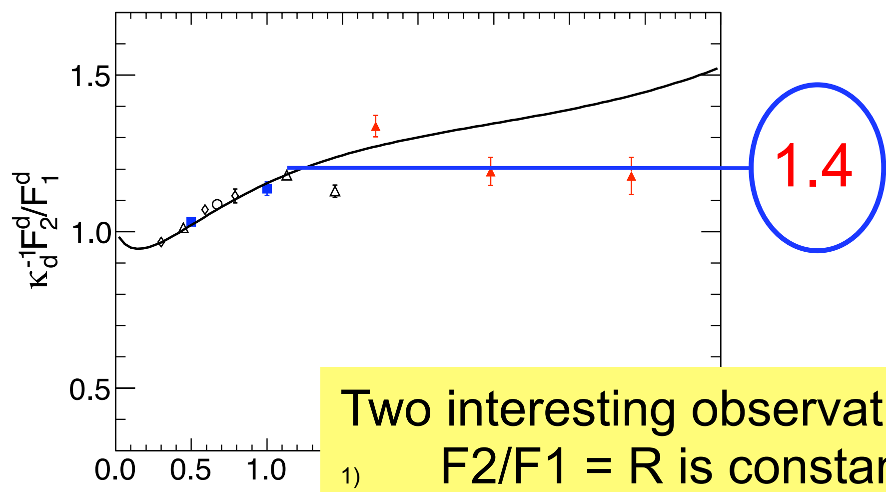
- A diquark configuration?
- An effect of orbital motion?

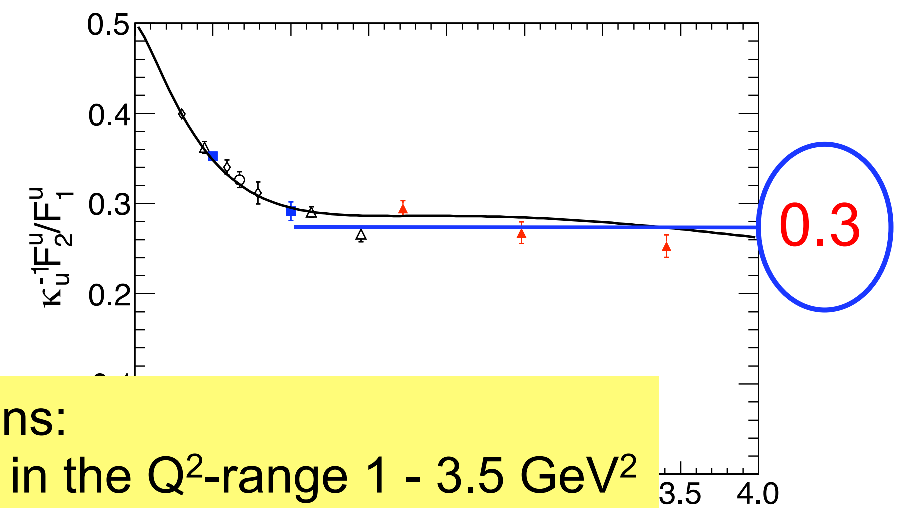
From Sachs FFs to the contributions of the u- / d-quarks

$$F_1 = \frac{G_E + \tau G_M}{1+\tau} \qquad F_1^u = 2\,F_{1p} + F_{1n}$$

$$F_2 = -\frac{G_E - G_M}{1+\tau} \qquad F_1^d = 2\,F_{1n} + F_{1p}$$

Results of E02-013 Hall A GEn

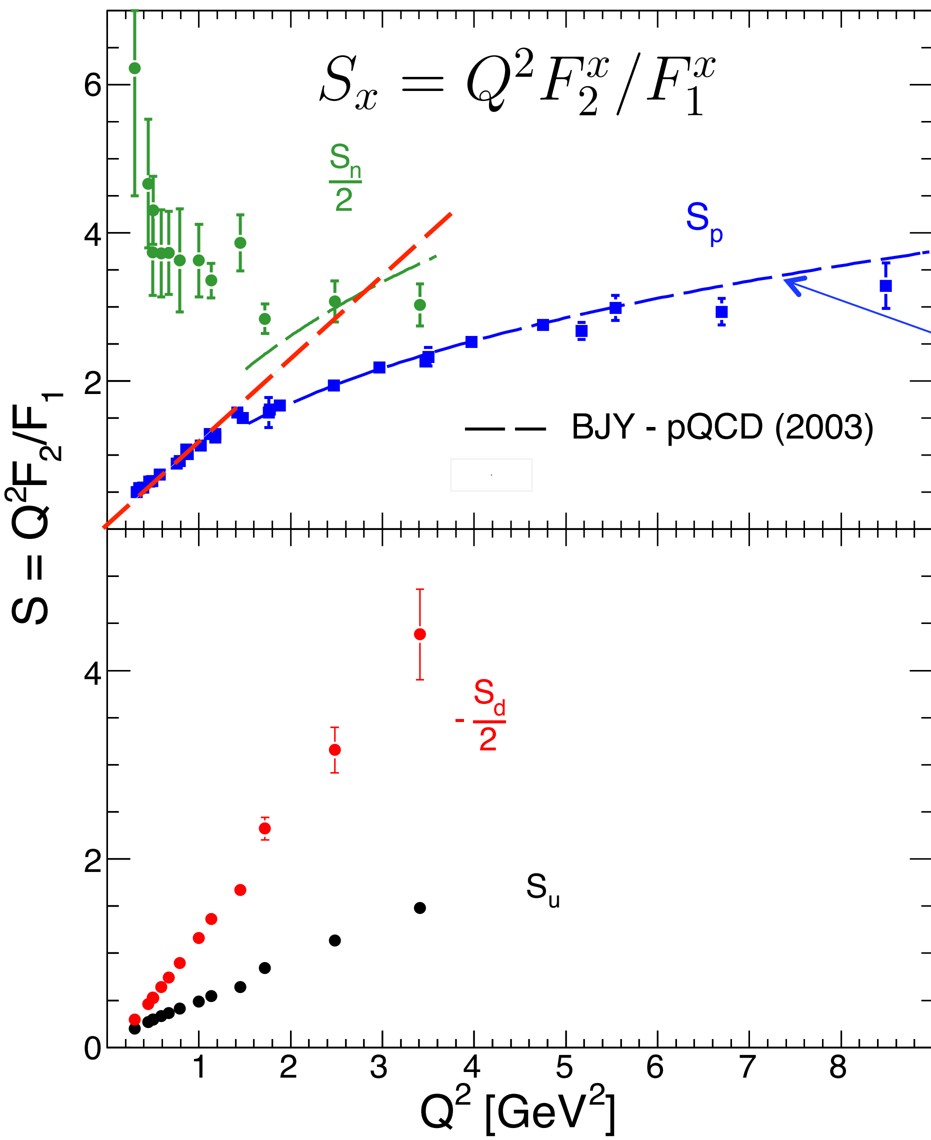




Two interesting observations:

1) F2/F1 = R is constant in the Q^2-range 1 - 3.5 GeV^2
2) The value of R for d-quark >> than R for u-quark

The goal is understanding of the nucleon



pQCD prediction for large Q^2:

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

pQCD updated prediction:

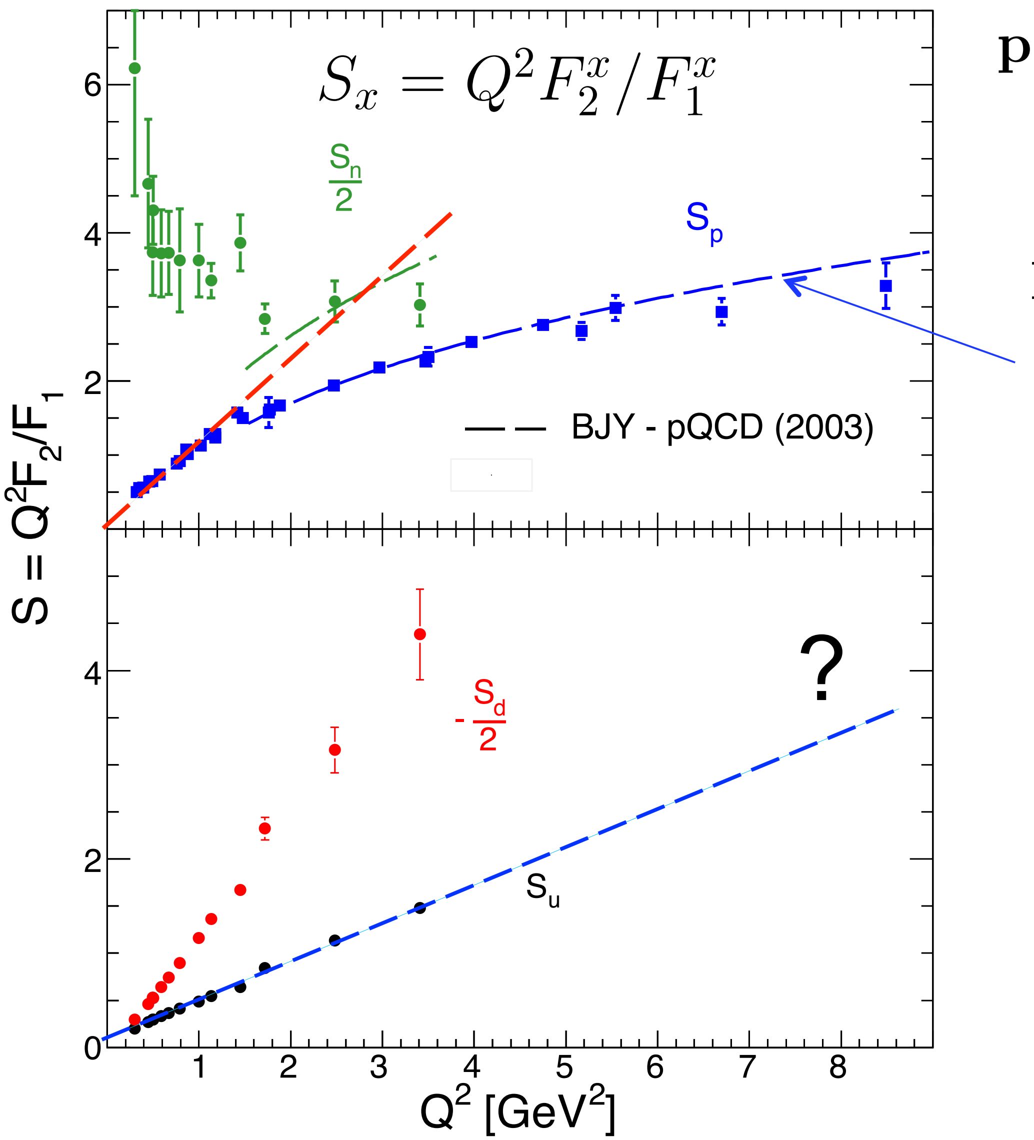
$$S \to \left[Q^2 / \ln^2(Q^2/\Lambda^2)\right] F_2/F_1$$

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

The lines for individual flavor are straight!

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

The goal is understanding of the nucleon



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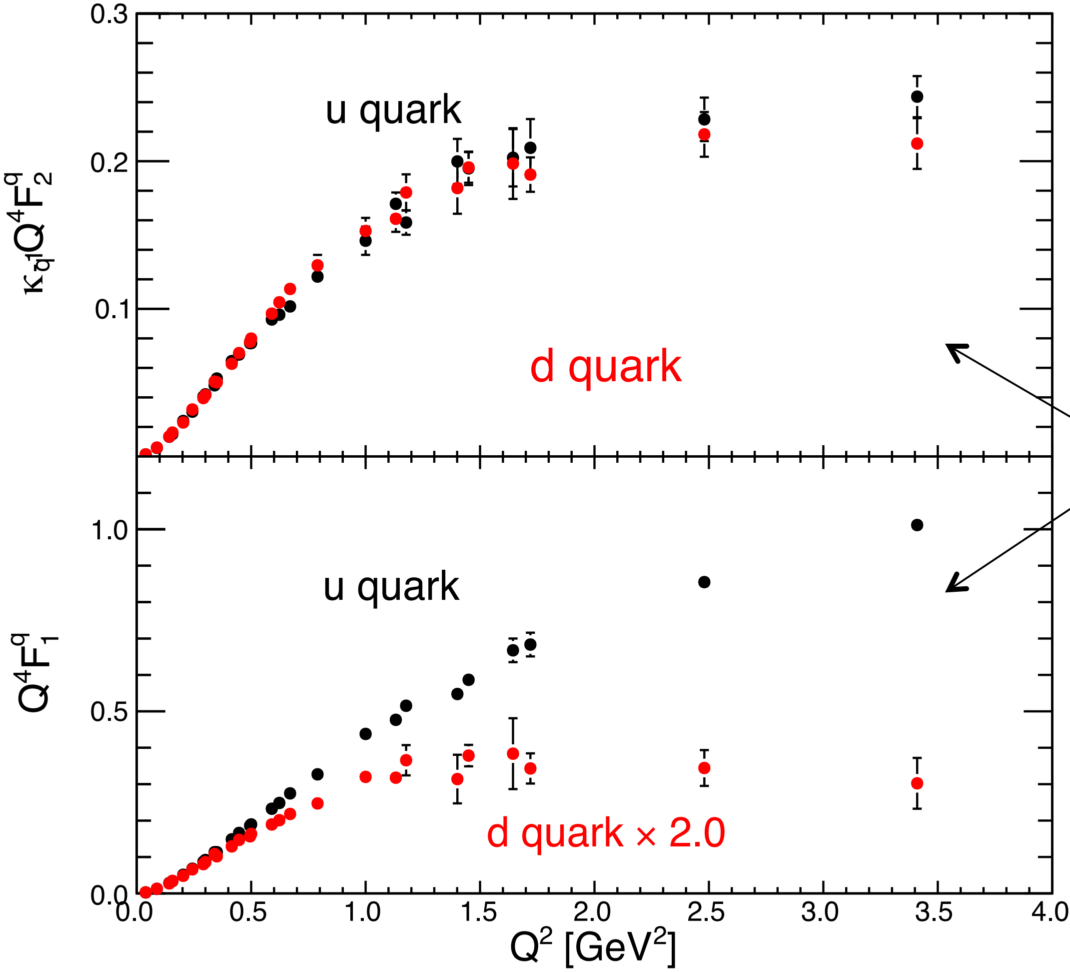
The flavor disparity in the nucleon



CJRW (u/d with new GEn data)
Phys. Rev. Lett. 106 (2011)
Qattan, Arrington (2-γ effects)
Phys.Rev. C86 (2012) 065210

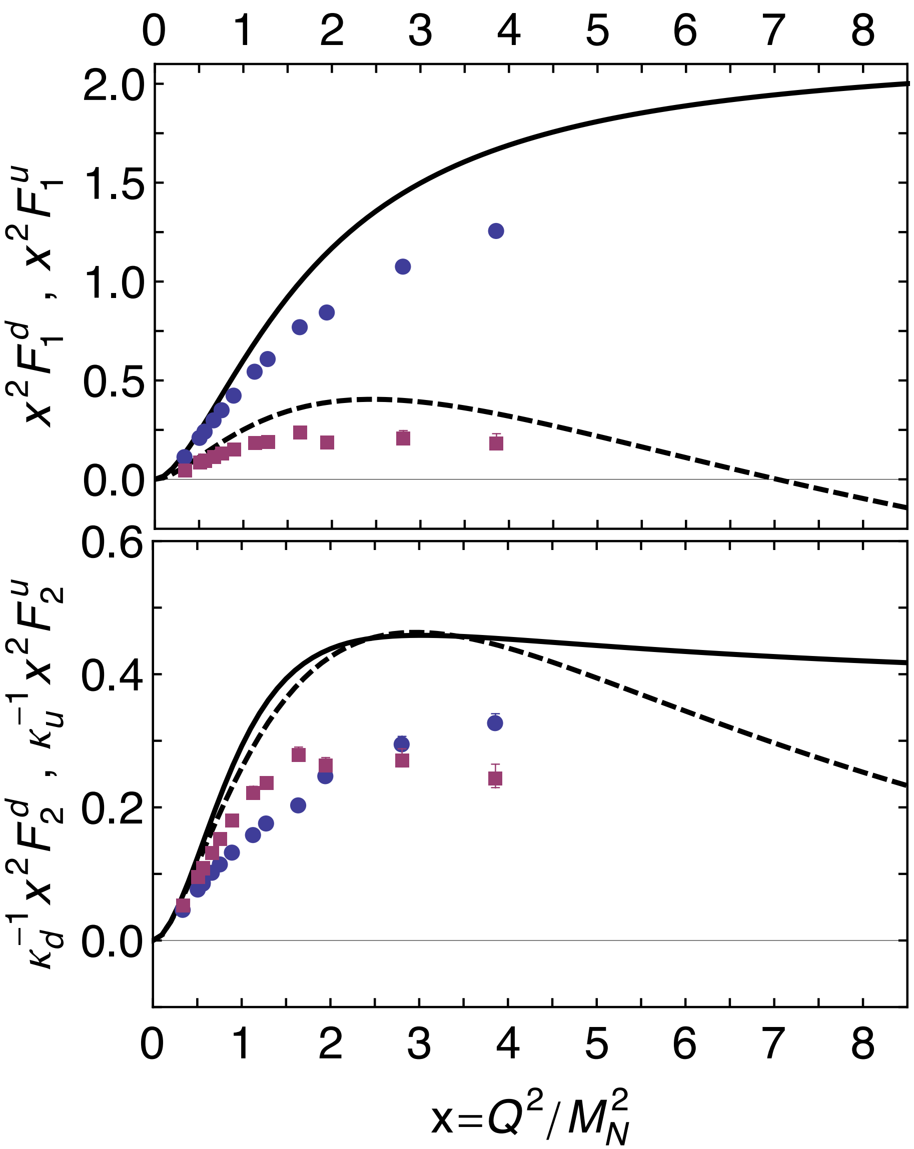
M.Diehl and P.Kroll (GPDs)
Eur.Phys.J. C73 (2013) 2397

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

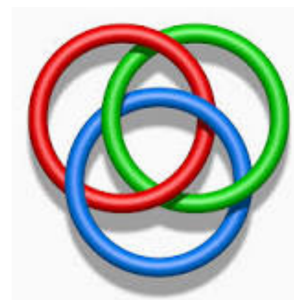
When the virtual photon of 3 GeV^2 interacts with the down quark the proton more likely falls apart than in the case of the up quark

Understanding of the nucleon



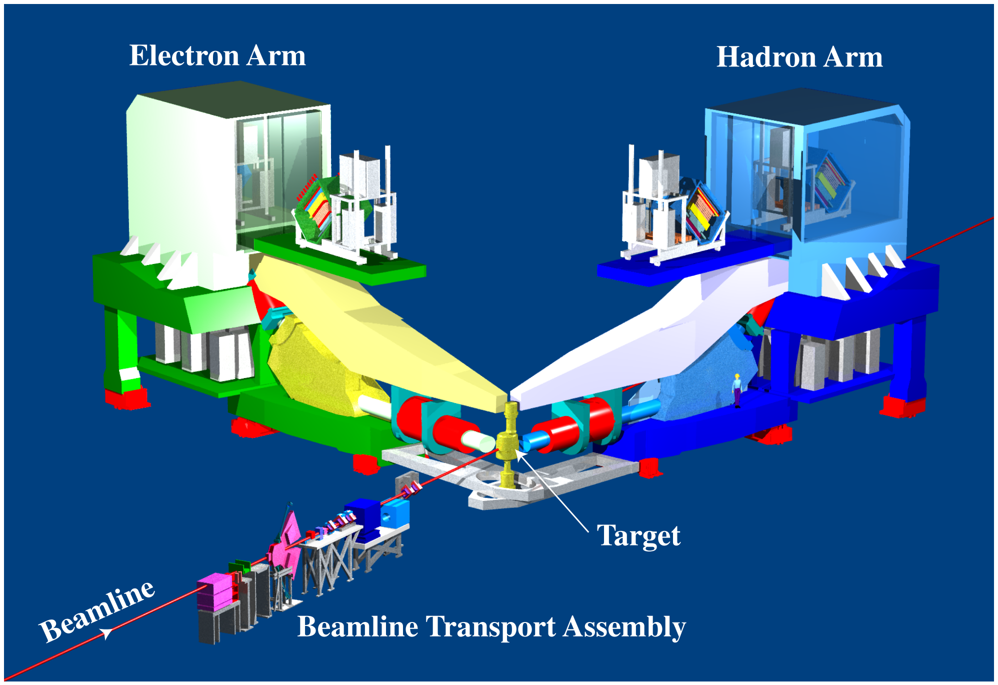
Segovia, Roberts, Schmidt,
"Understanding the nucleon as
a Borromean boundstate",
arXiv:nucl-th/ 1506.05112

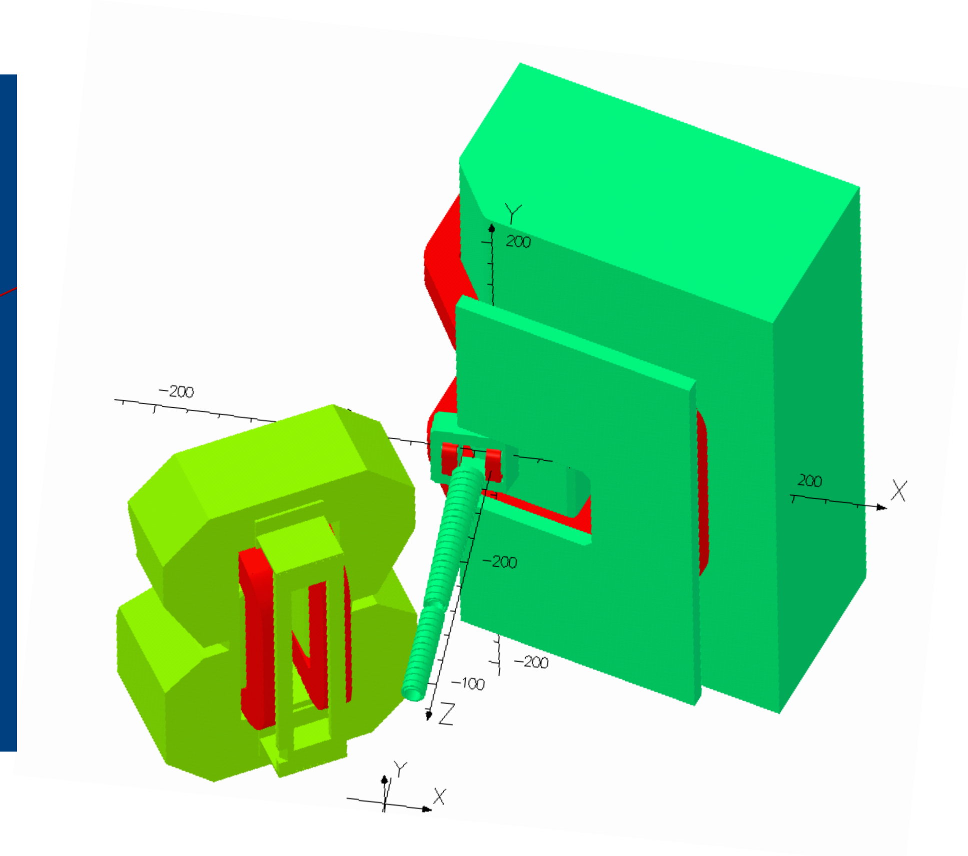
Craig Roberts,
Three Lectures on Hadron Physics
arXiv:nucl-th/ 1509.02925



The diquarks in the nucleon
combined provide a key to
understanding of the structure of
the three-quark bound system

Hall A at JLab





The Hall is equipped with several magnetic spectrometers

Optimization of the experimental setup

Energy, Solid angle, Efficiency

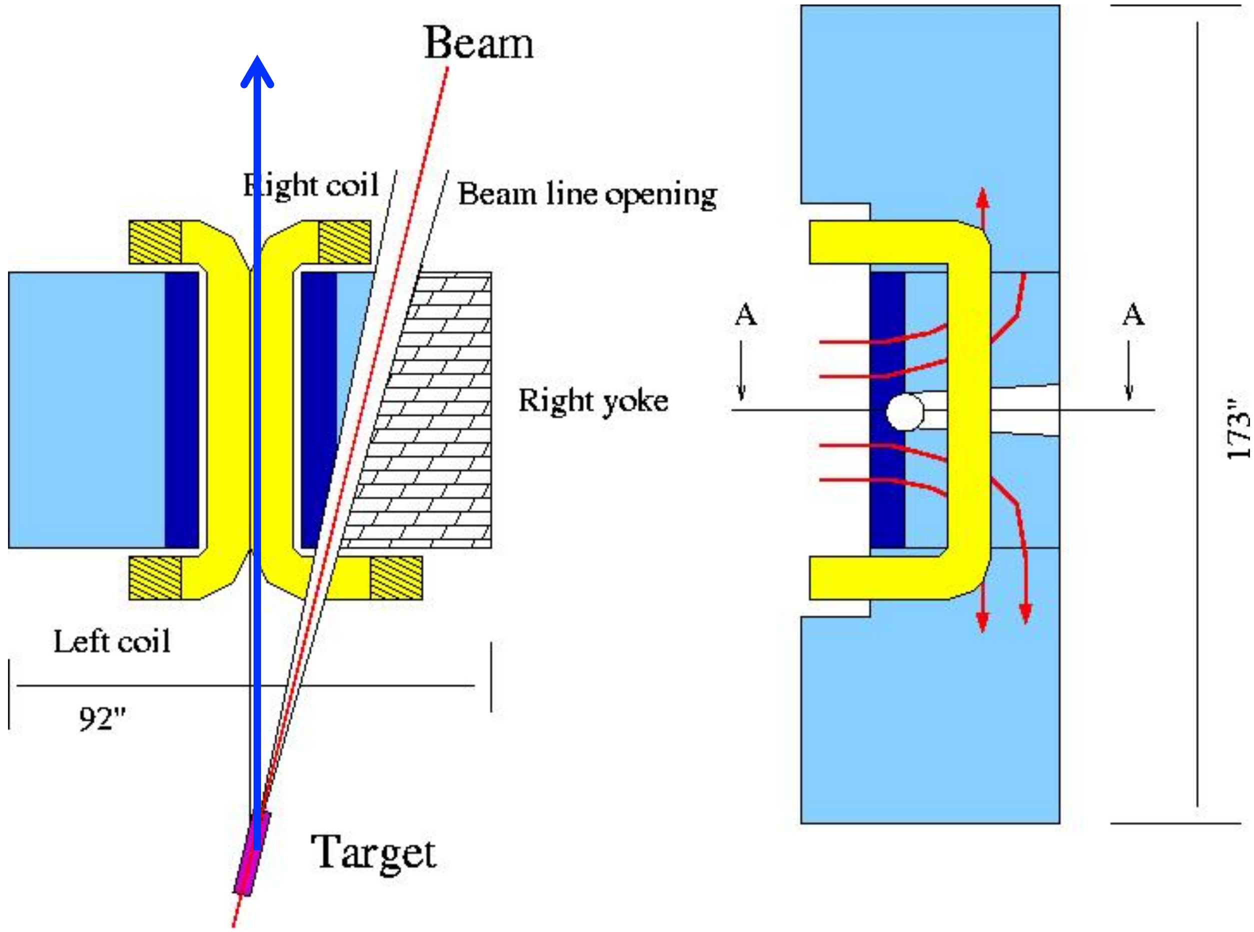
$$\text{Form factor} \propto Q^{-4}$$

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

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

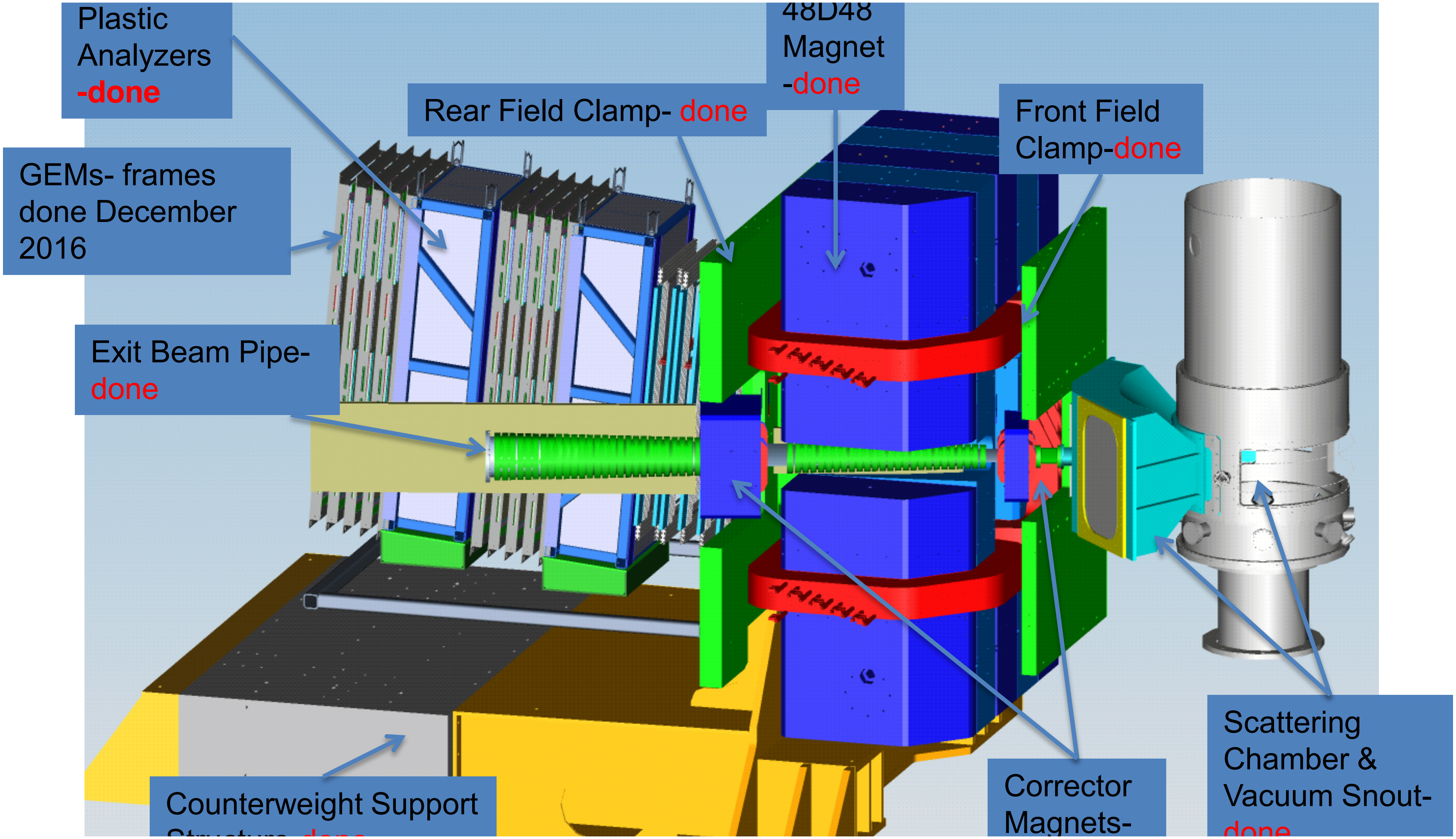
$$\propto E^2/Q^{16}$$

The concept of Super Bigbite



presented to PAC32 on Aug. 7, 2007

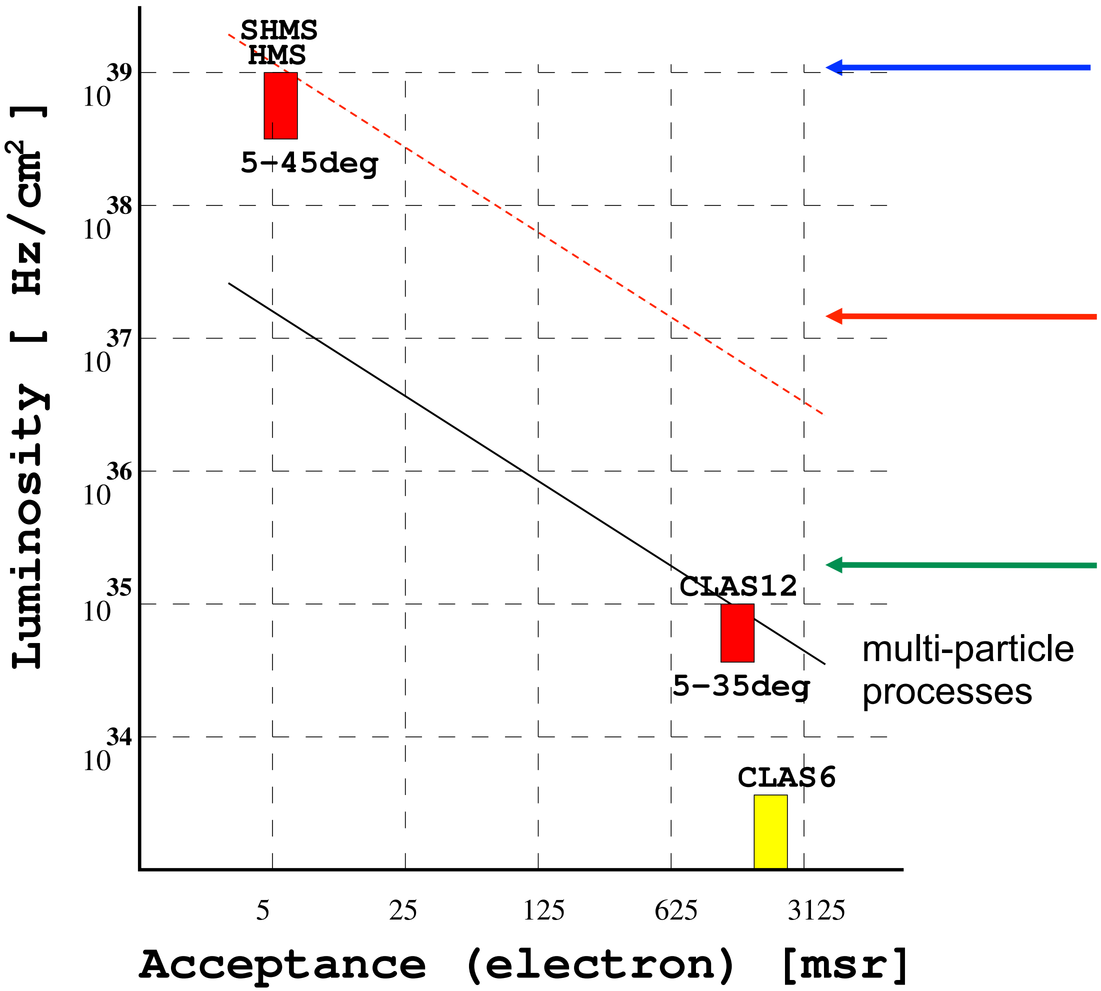
Super Bigbite Spectrometer in 2017



Solid angle 70 msr for the central angle > 15^o

JLab detector landscape

A range of 10^4 in luminosity.

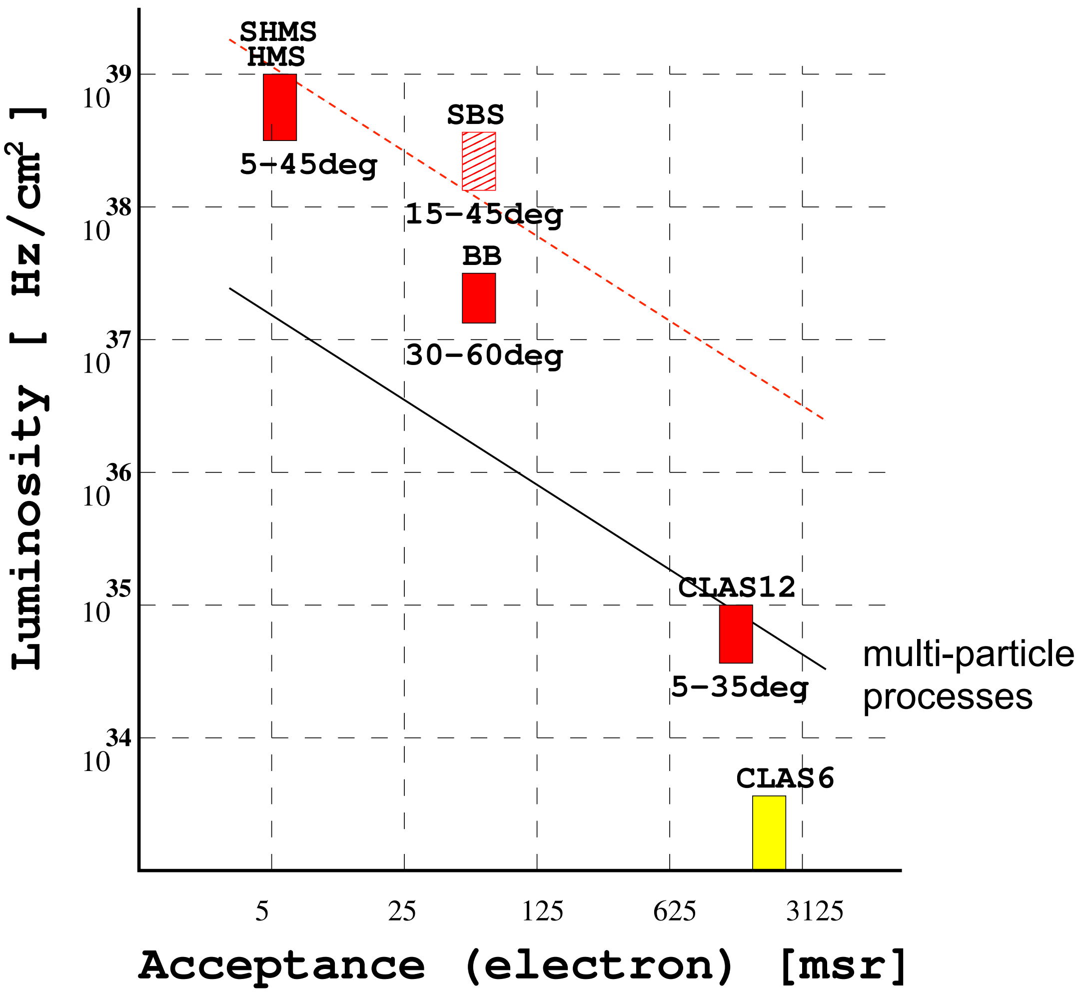


The LH_2 target can be used up to L ~ 10^{39}

The polarized ^{3}He at L ~ 10^{37}

The polarized NH_3 at L ~ 10^{35}

JLab detector landscape



A range of 10^4 in luminosity.

A big range in solid angle:
from 5 msr (SHMS)
to about 1000 msr (CLAS12).
========================

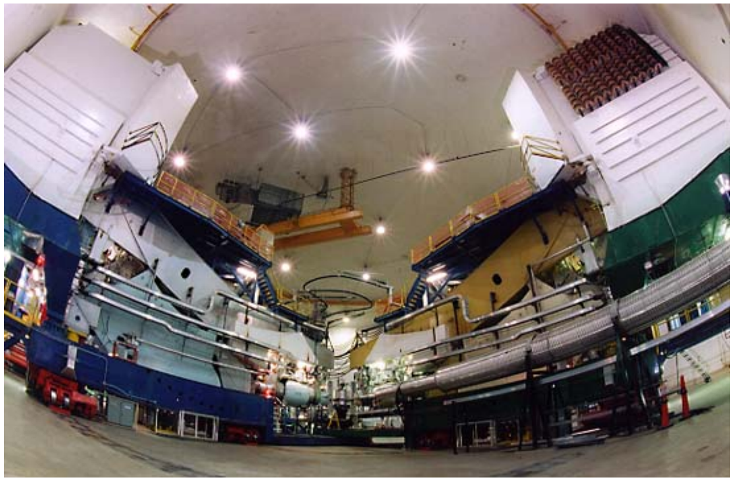
The SBS is in the middle:
for solid angle (up to 70 msr)
and high luminosity capability.

In several A-rated experiments SBS was found to be the best match to the physics.

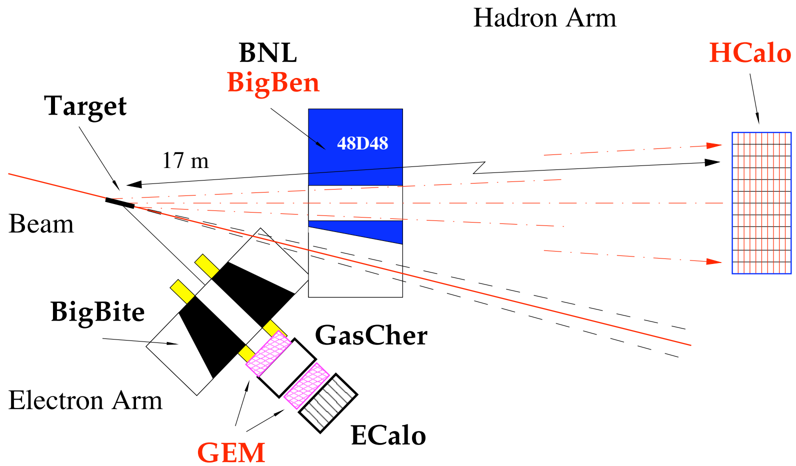
GEM allows a spectrometer with open geometry (->large acceptance) at high L.

Optimization of the experimental setup

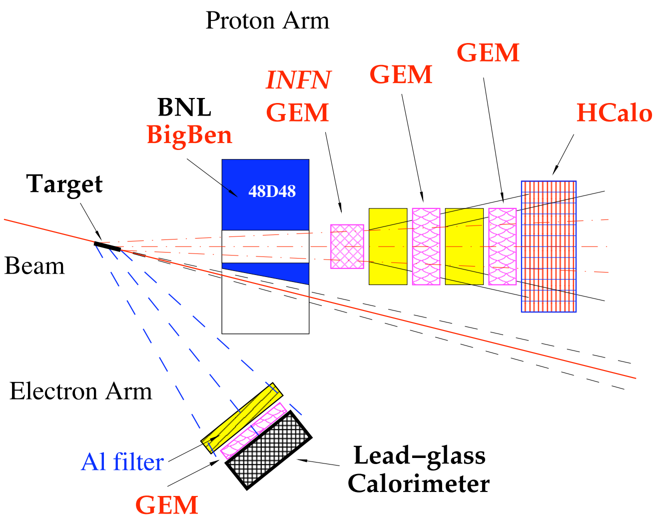
Proton magnetic form factor: E12-07-108



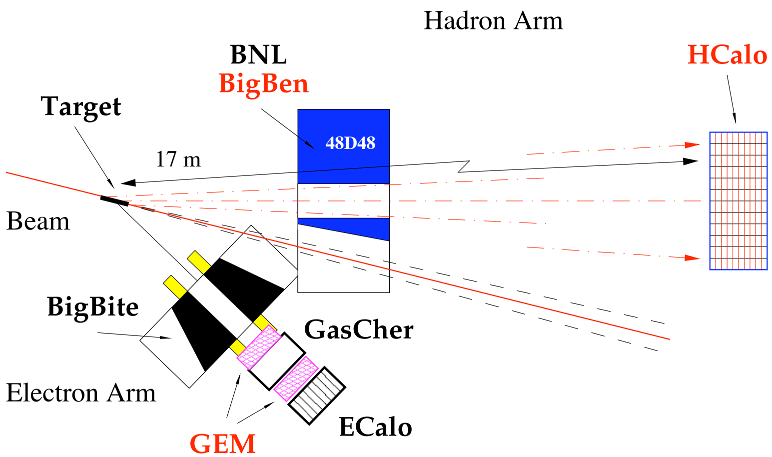
Neutron/proton form factors ratio: E12-09-019



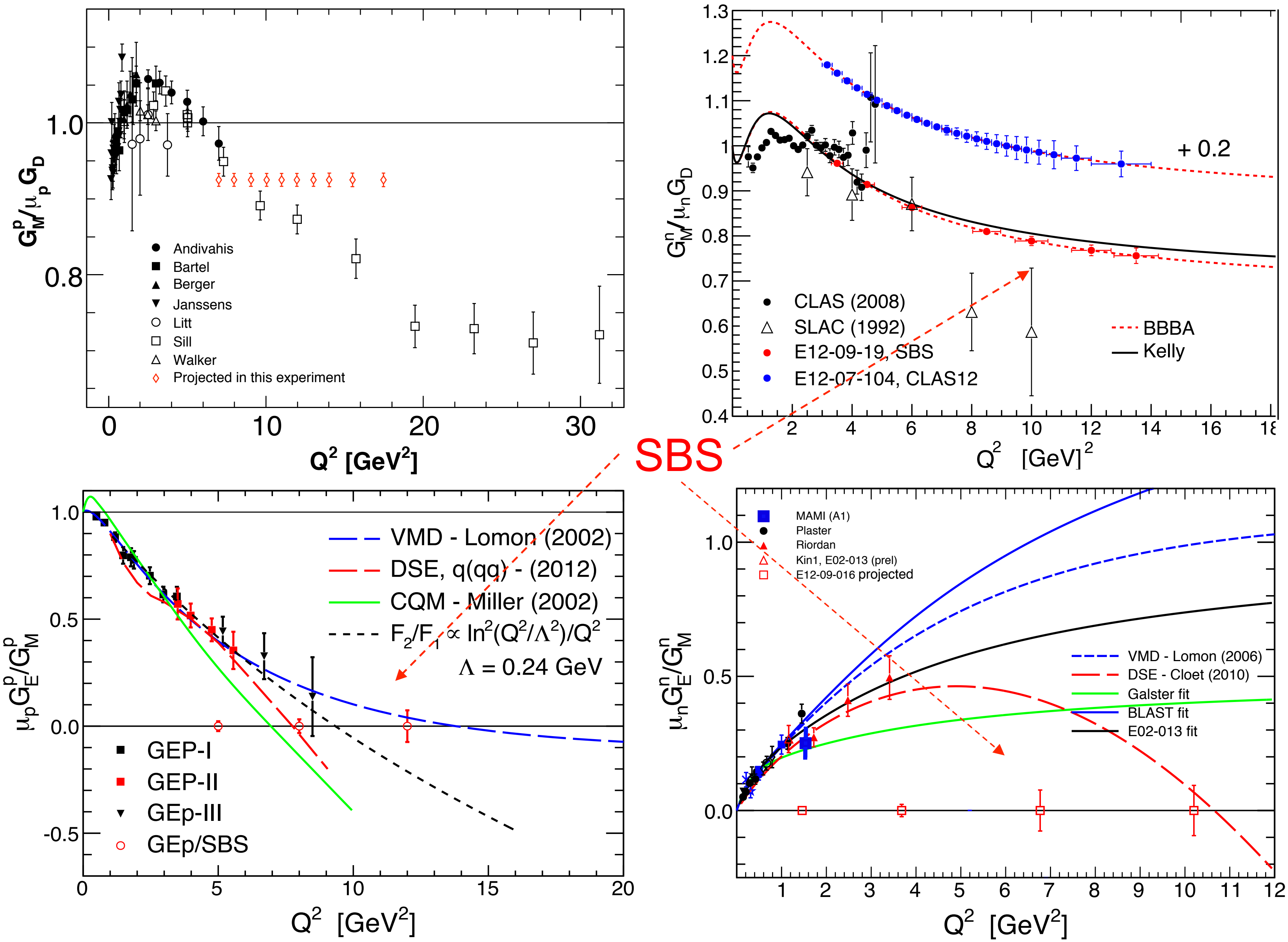
Proton form factors ratio, GEp(5): E12–07–109



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



The nucleon FFs

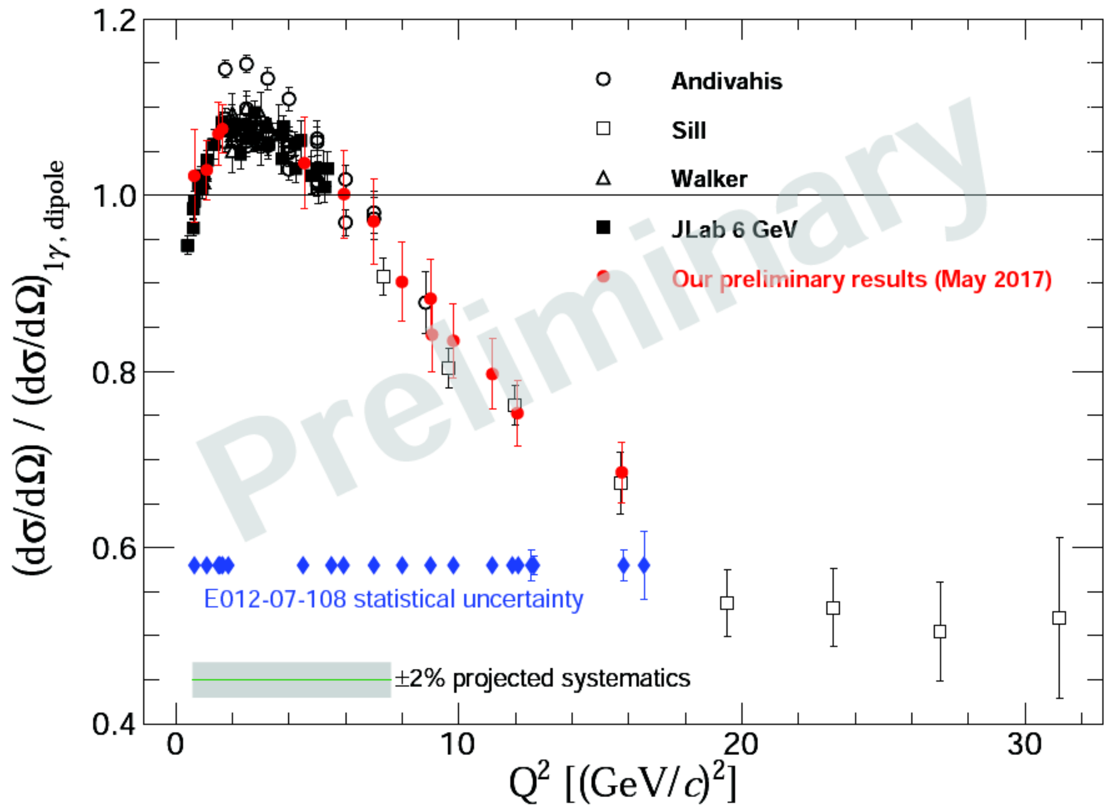


E012-07-108 Experiment

Precision Measurement of the Proton Elastic Cross-Section at High Q^2

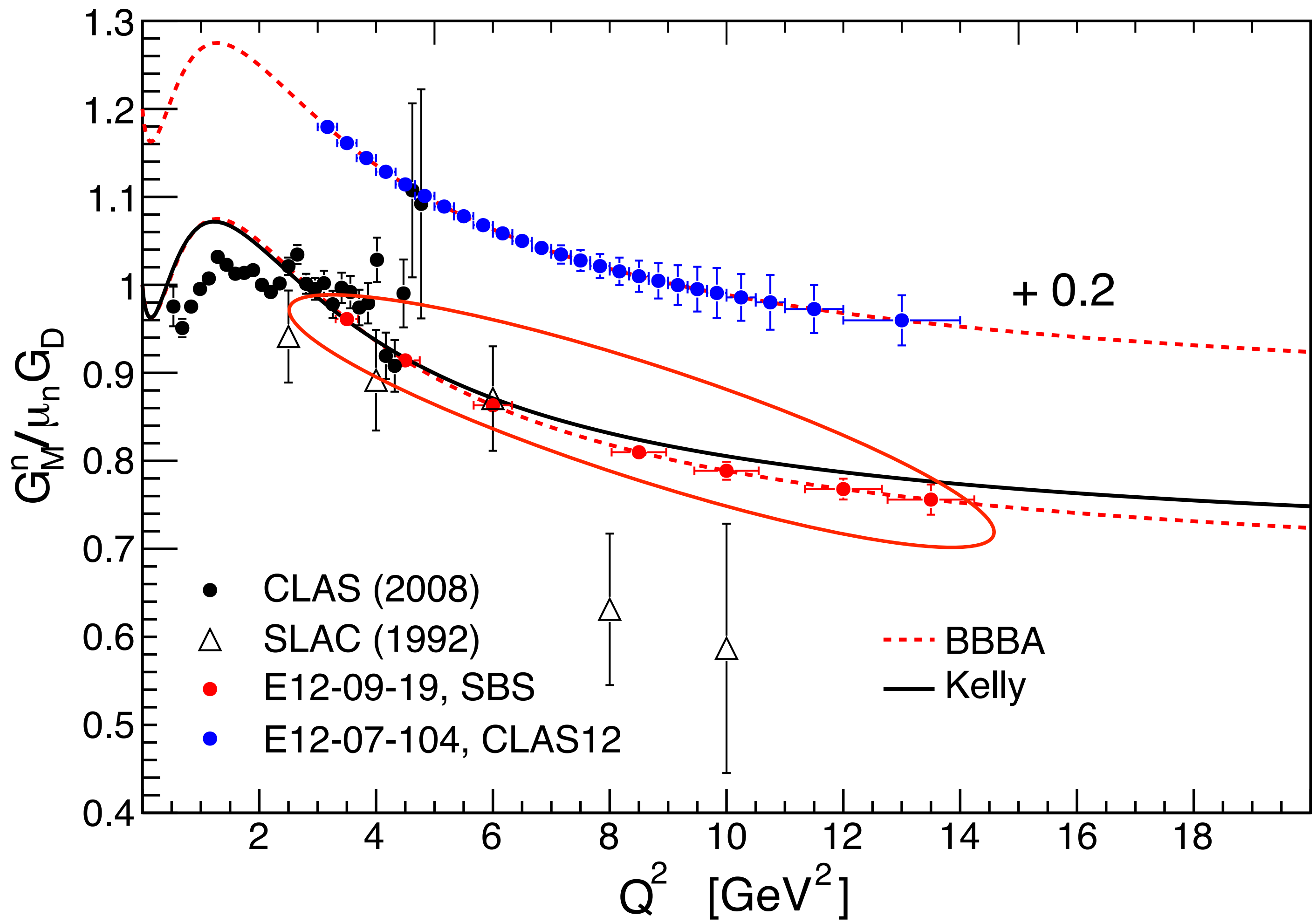
- Precision e-p elastic cross-section is necessary to:
  - Constrain two-photon exchange (TPE) contribution through global analysis
  - Determine GEp, GMp and TPE contributions at high Q^2, in combination with polarization measurements
  - Find absolute form factor values from 12-GeV era JLab experiments
- Preliminary cross-section results are presented below with 5% uncertainty (total)
- Final results will be available very soon (fall 2018), 2% systematic uncertainty

JLab E012-07-108, *e-p* elastic cross section

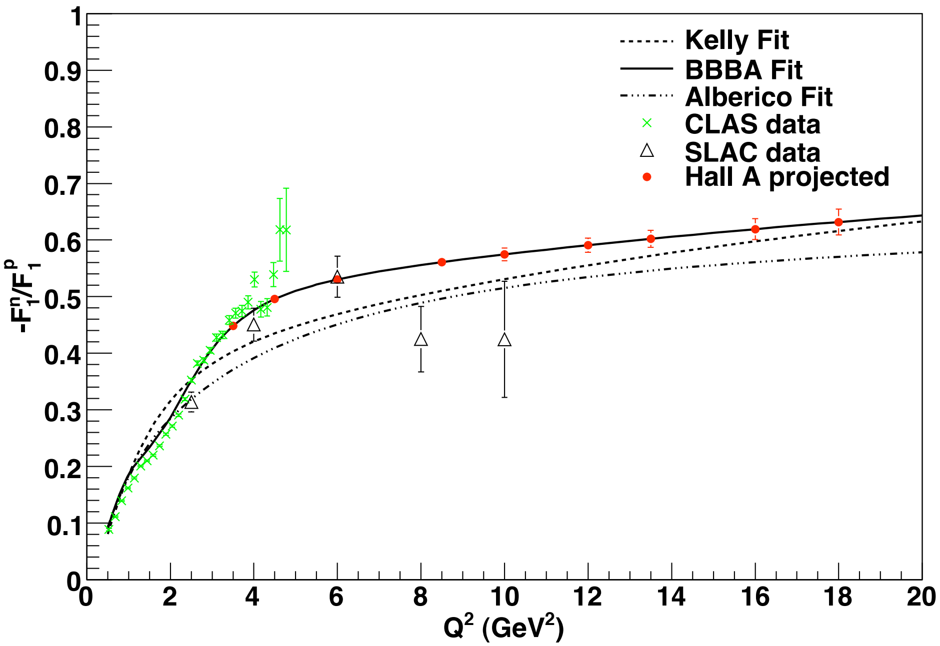


12 GeV GMn experiment

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



GMn/GMp and GPDs

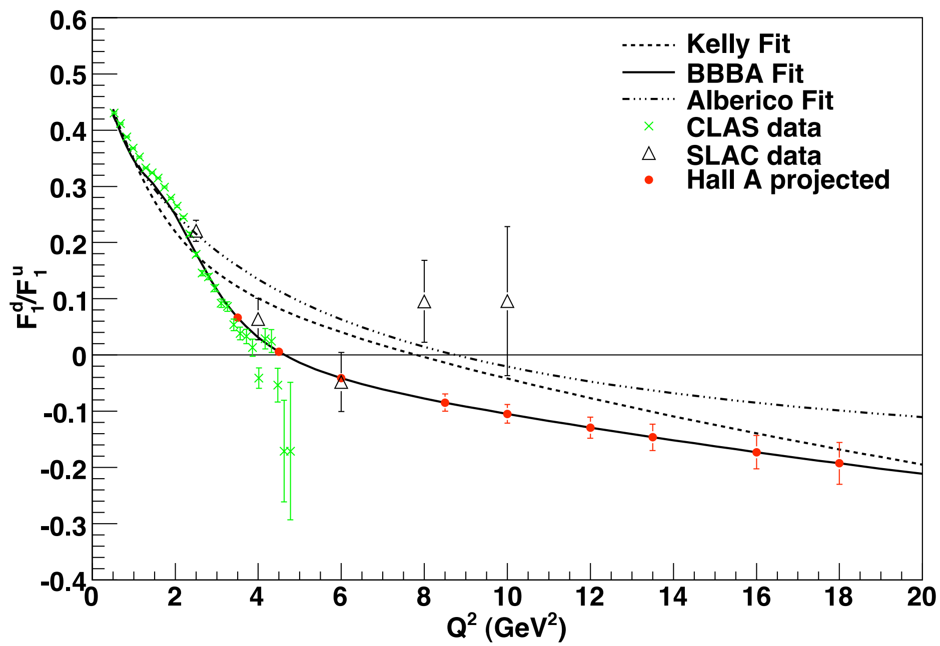


GPD model (Guidal et al):

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

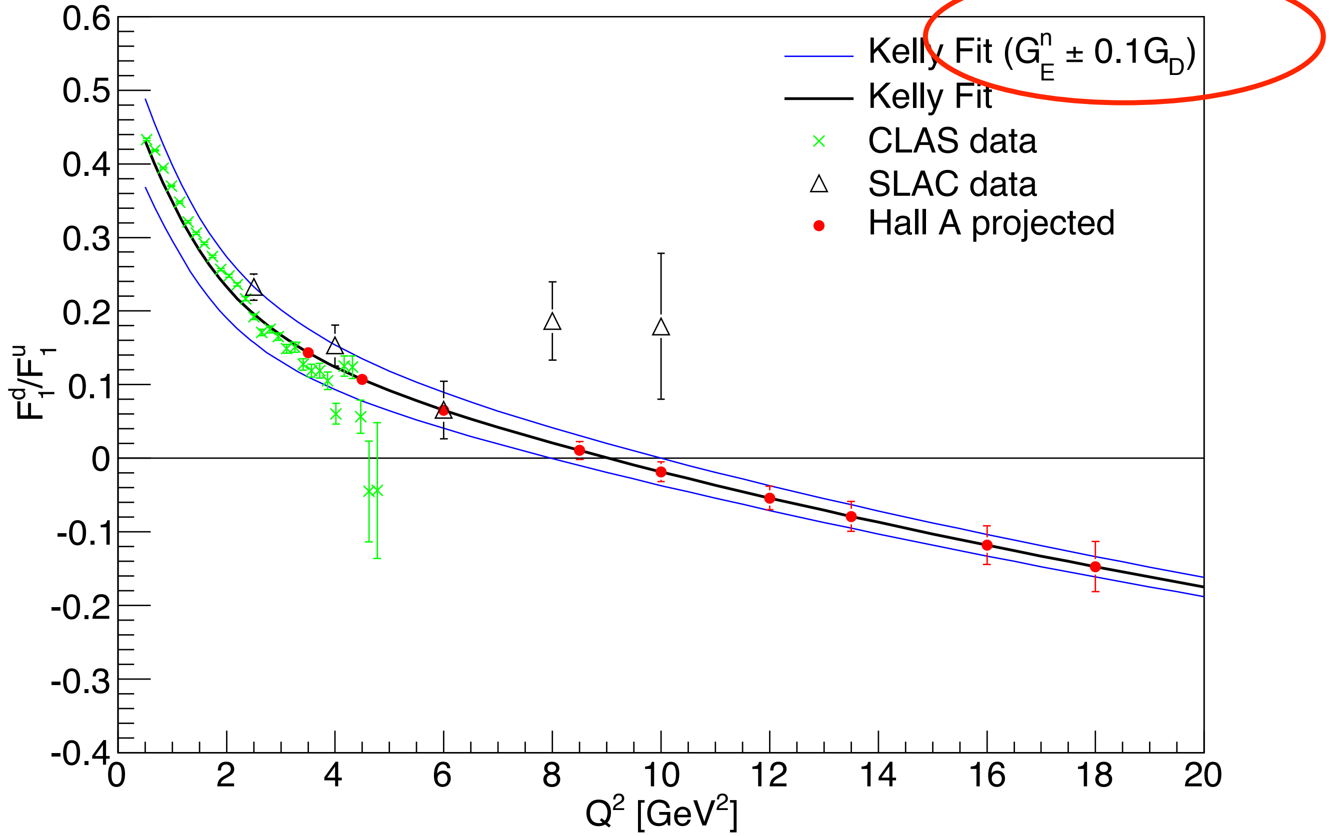
$$F_1^d(t) = \int_0^1 dx d_v(x) e^{-t\alpha' \ln x}.$$

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



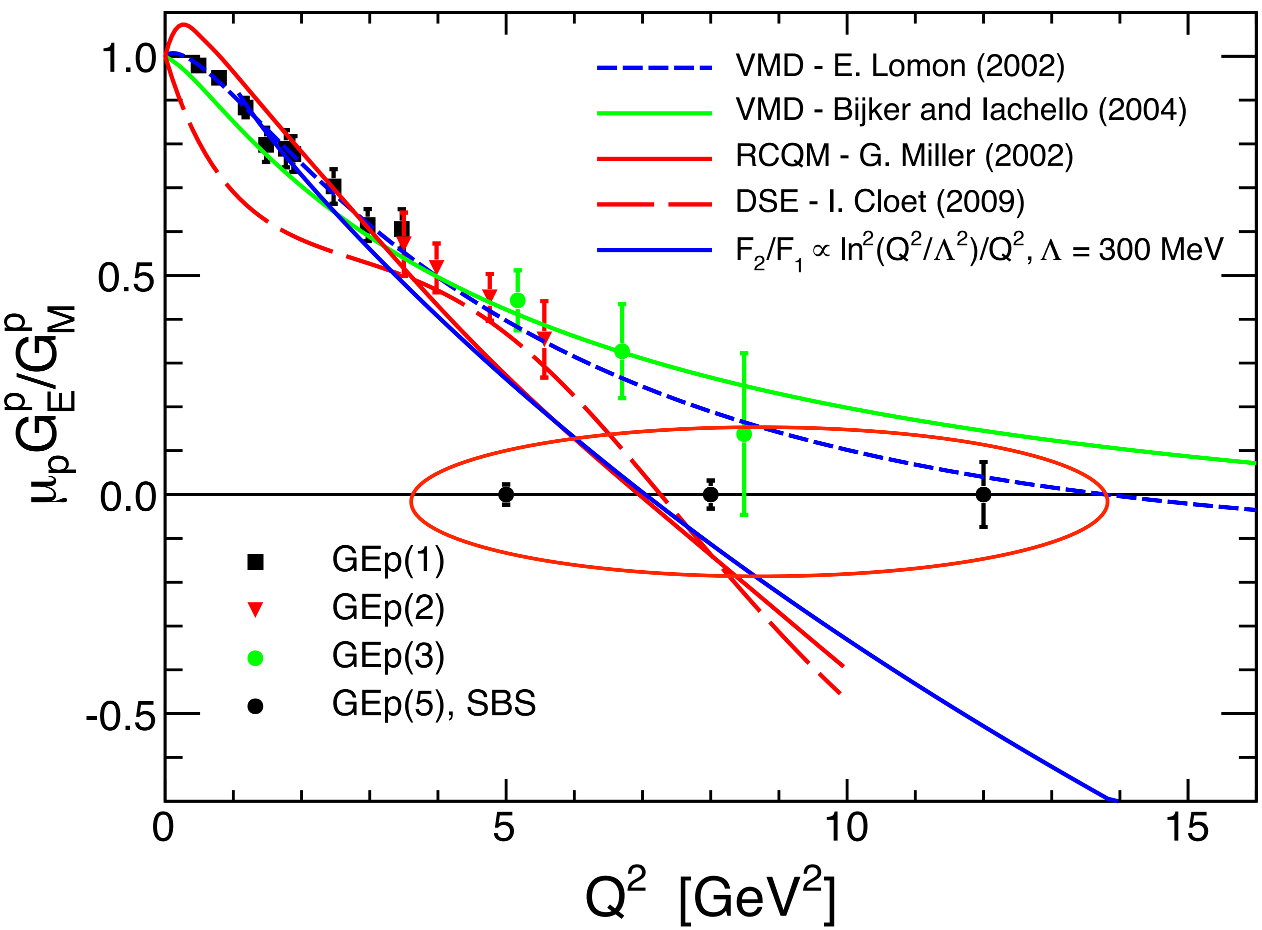
F_1 decomposition at very large Q^2

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

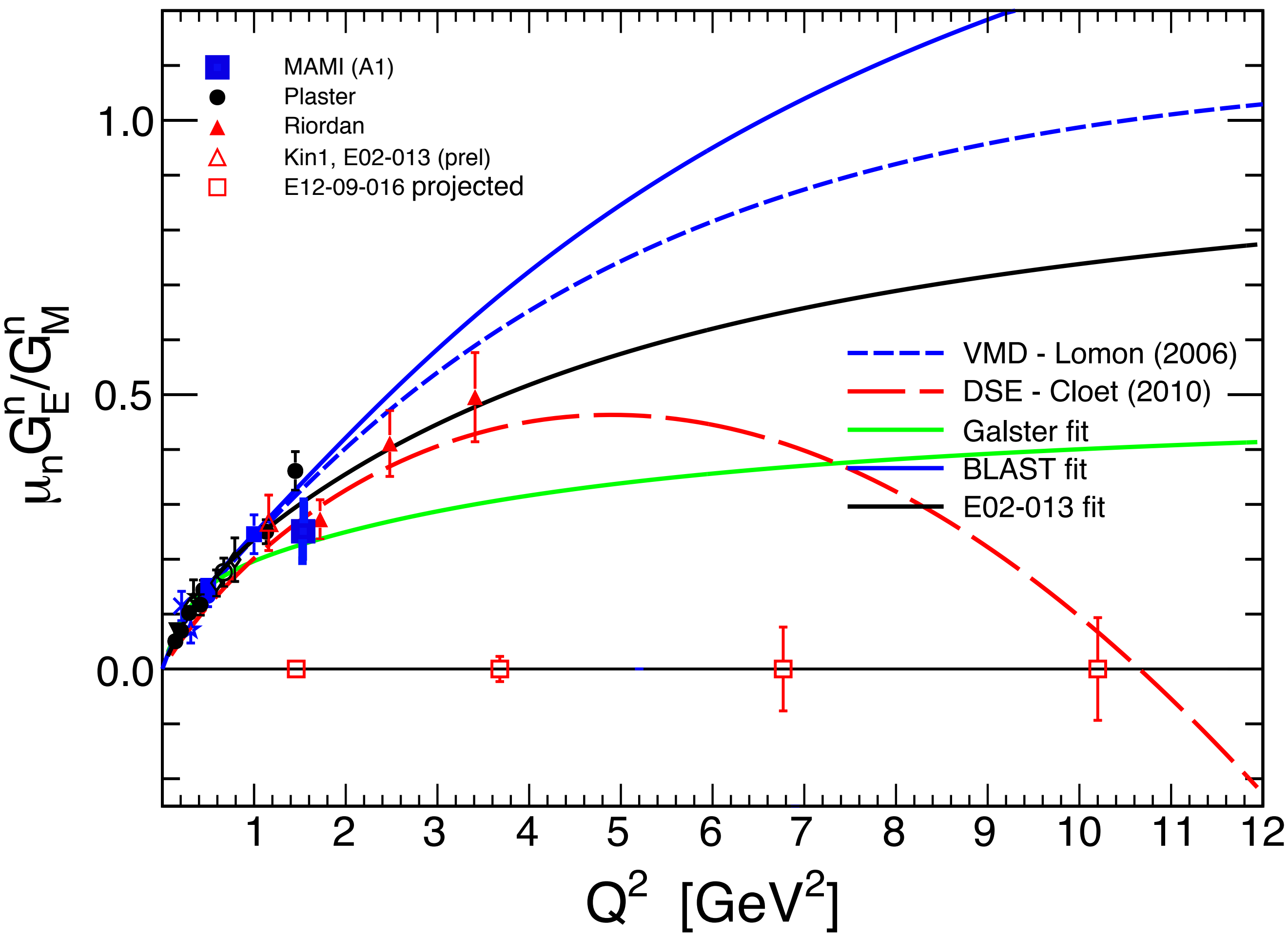


12 GeV GEp experiment

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



12 GeV GEn experiment



A diquark component of the nucleon

Correlations: q-qbar and q-q

Mesons are diquarks: Scalar and Vector

Strangeness FFs: F^s_E and F^s_M

A number of experiments were performed on FF_s

The signal was found to be consistent with zero

Electromagnetic form factors

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

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

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

Strangeness form factors

Method from D.Beck and R.McKeown

Polarized electron beam elastic e-p scattering

$$A = \left[\frac{-G_F Q^2}{4\sqrt{2}\pi\alpha}\right] \frac{\varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1 - 4\sin^2\theta_W)\varepsilon' G_M^\gamma G_A^e}{\varepsilon (G_E^\gamma)^2 + \tau (G_M)^2}$$

Strangeness form factors

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

G^s_E is 0 at Q^2=0 and G^s_M is also very small

Small G^s_M is consistent with the vector s-$\bar{s}$

In fact, the ϕ-meson magnetic moment is ~0 and the meson has a very small size ~ 0.26 fm

Strangeness form factors

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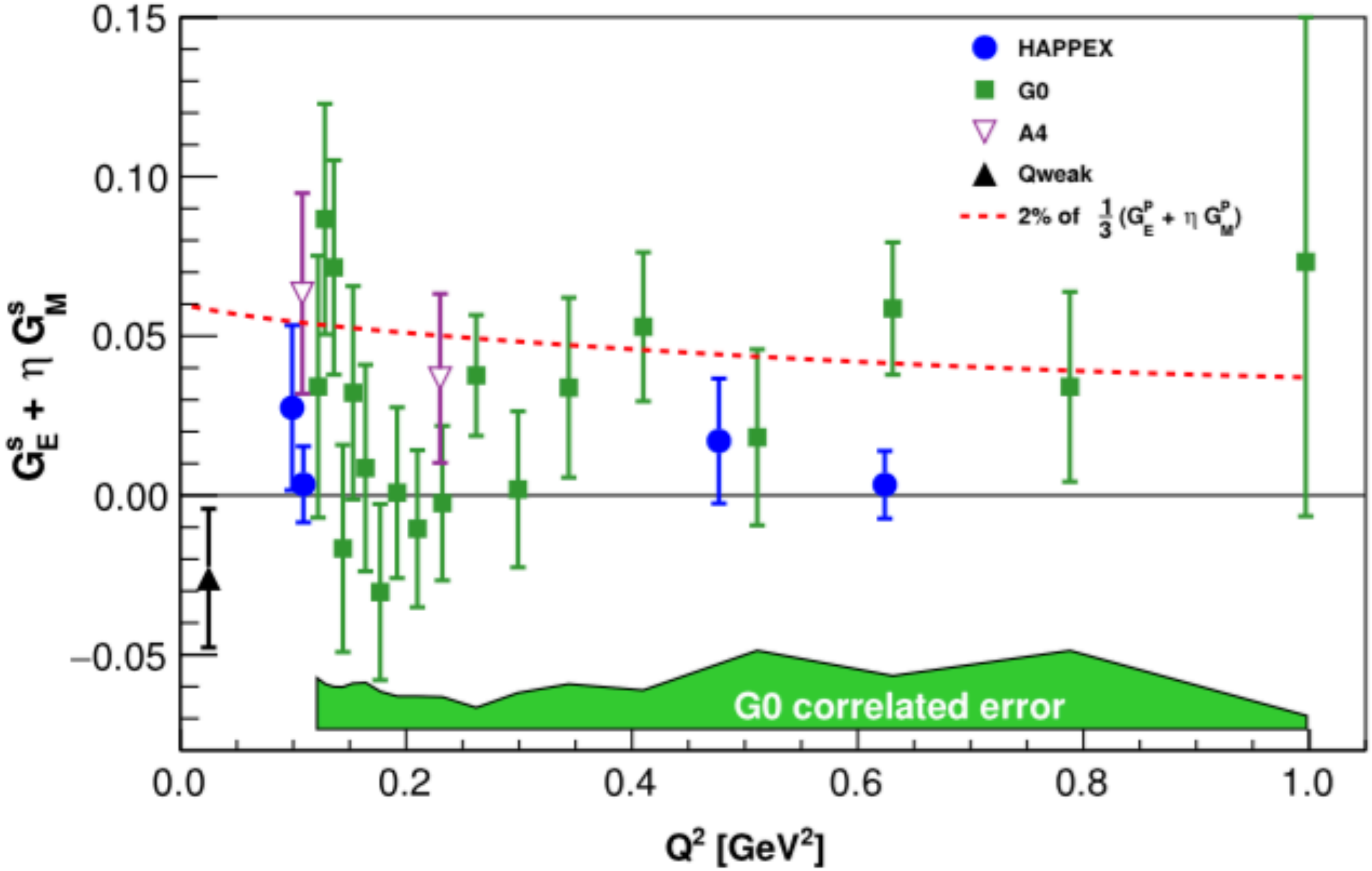
In fact, the ϕ-meson magnetic moment is ~0
and the meson has a very small size ~ 0.26 fm

$$A = \left[\frac{-G_F Q^2}{4\sqrt{2}\pi\alpha}\right] \frac{\varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1 - 4\sin^2\theta_W)\varepsilon' G_M^\gamma G_A^e}{\varepsilon (G_E^\gamma)^2 + \tau (G_M)^2}$$

We propose to look for G^s at large Q^2 ~ a few GeV^2

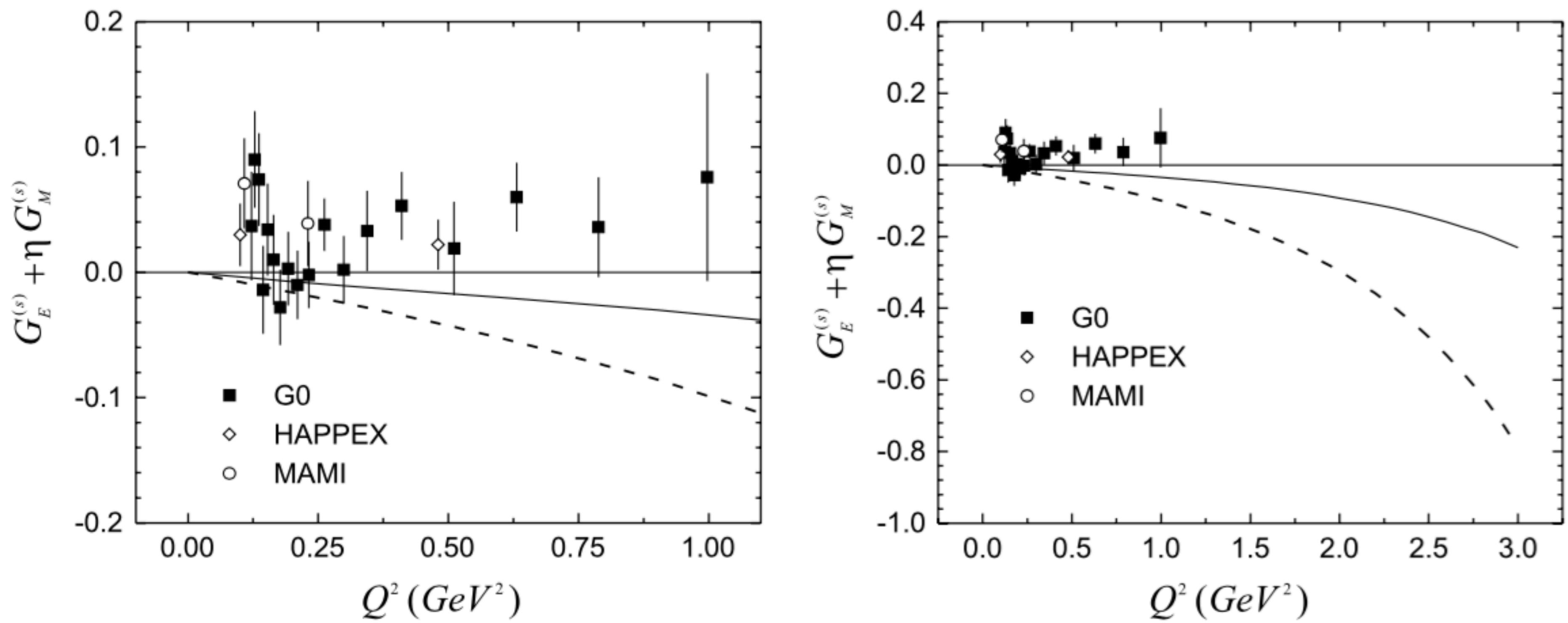
Strangeness form factors



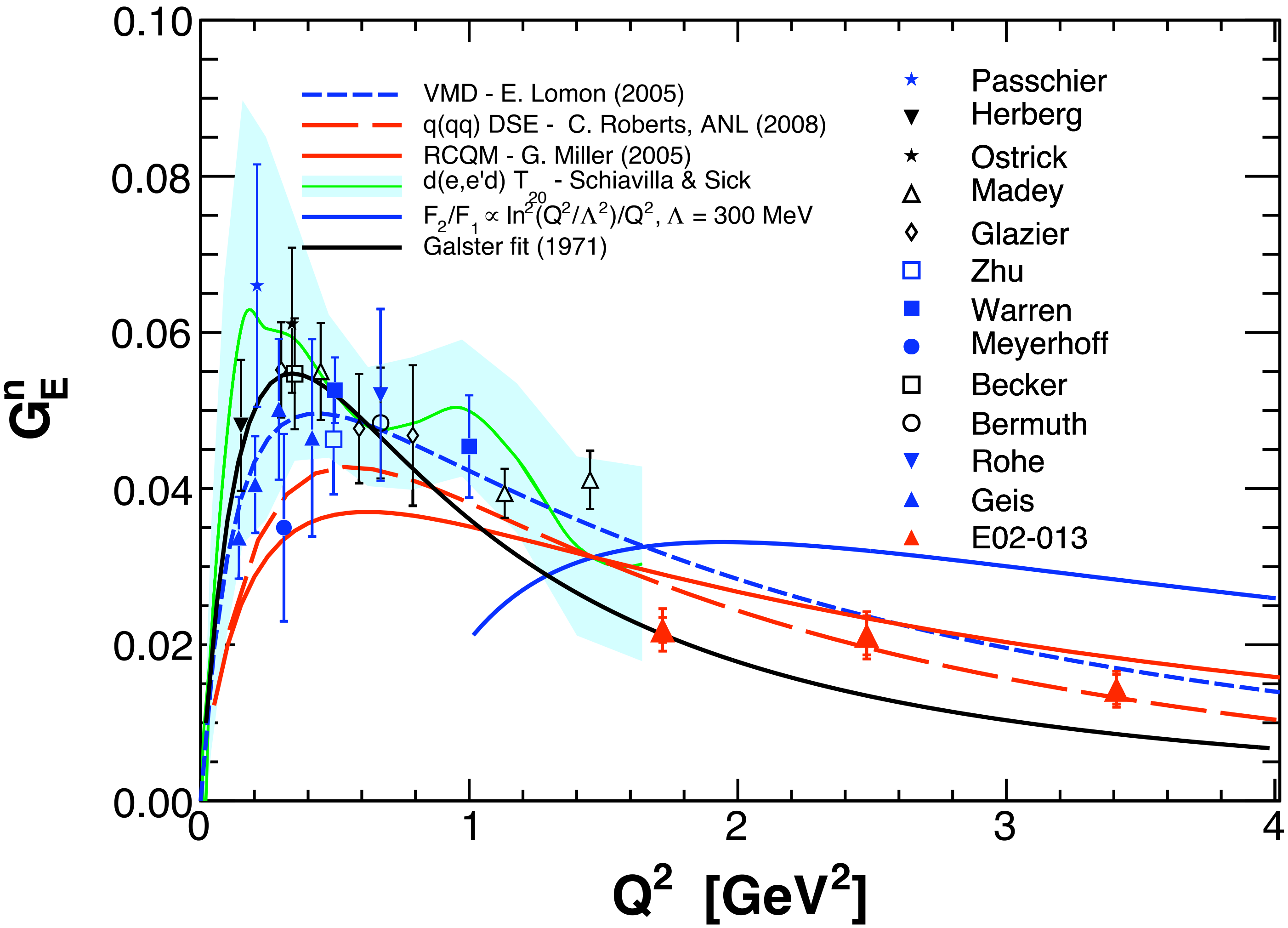
Strangeness form factors

Fabiana Carvalho, Fernando S. Navarra, and Marina Nielsen

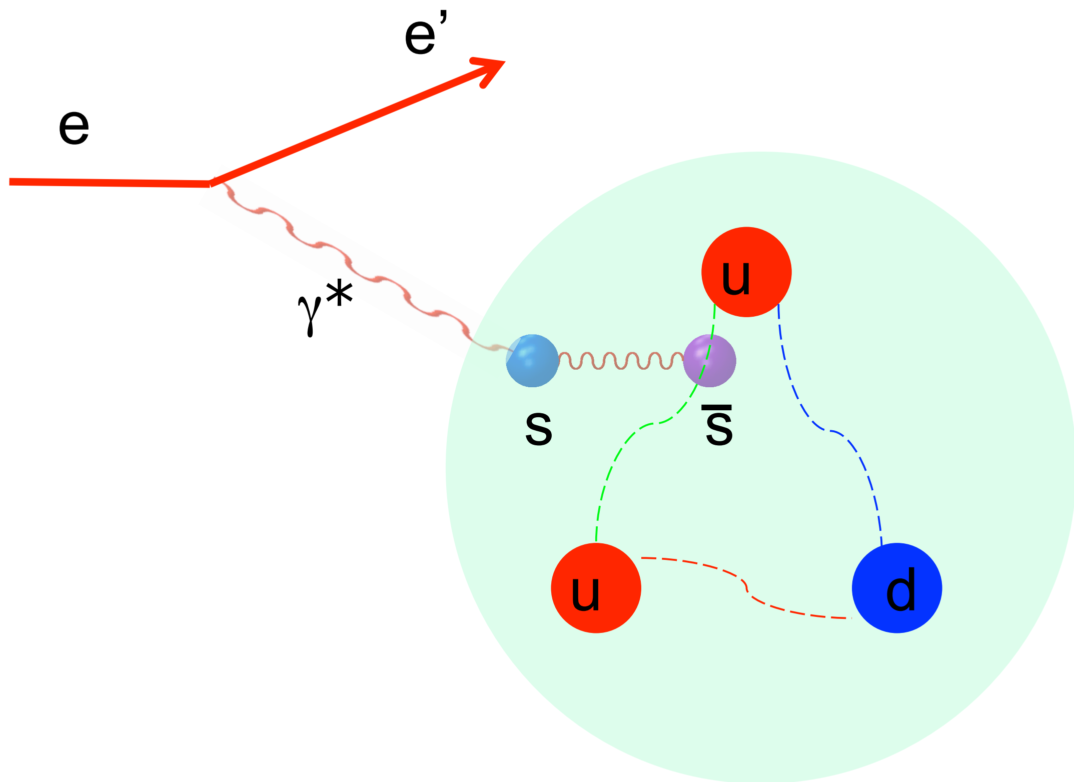
PHYSICAL REVIEW C **72**, 068202 (2005)



Neutron electrical form factor



Strangeness form factors



If the relevant s-s̄ correlation is a vector
then the phi-meson is a good model

ϕ-meson form factor

PARAMETER β IN $\phi \to Pe^+e^-$ DECAYS

In the one-pole approximation the electromagnetic transition form factor for $\phi \to Pe^+e^-$ ($P = \pi,\eta$) is given as a function of the e^+e^- invariant mass squared, q^2, by the expression:

$$|F(q^2)|^2 = (1 - q^2/\Lambda^2)^{-2},$$

where vector meson dominance predicts parameter $\Lambda \approx 0.770$ GeV ($\Lambda^{-2} \approx 1.687$ GeV^{-2}). The slope of this form factor, $\beta = dF/dq^2(q^2{=}0)$, equals Λ^{-2} in this approximation.

The measurements below obtain β in the one-pole approximation.

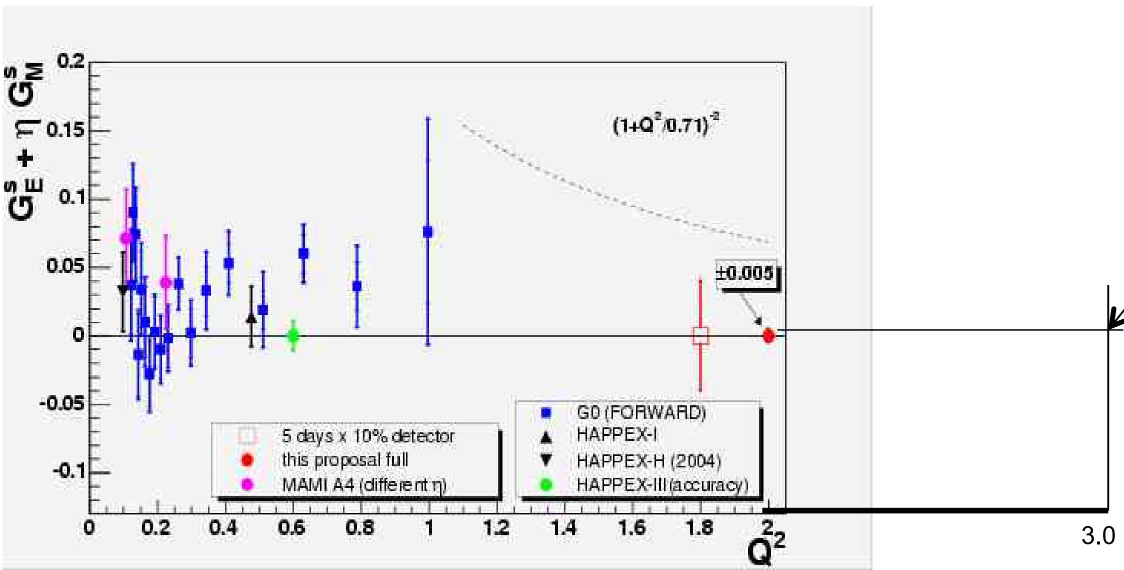
PARAMETER β IN $\phi \to \pi^0 e^+e^-$ DECAY

VALUE (GeV^{-2})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2.02±0.11	9.5k	[1] ANASTASI 16B	KLOE	1.02 $e^+e^- \to \pi^0 e^+e^-$

This combined phi-pi radius ~ 0.69 fm
with a pi-0 radius of ~ 0.64 fm and
a ϕ-meson radius of ~ 0.26 fm

Coincidence parity experiment

Strangeness Form factor



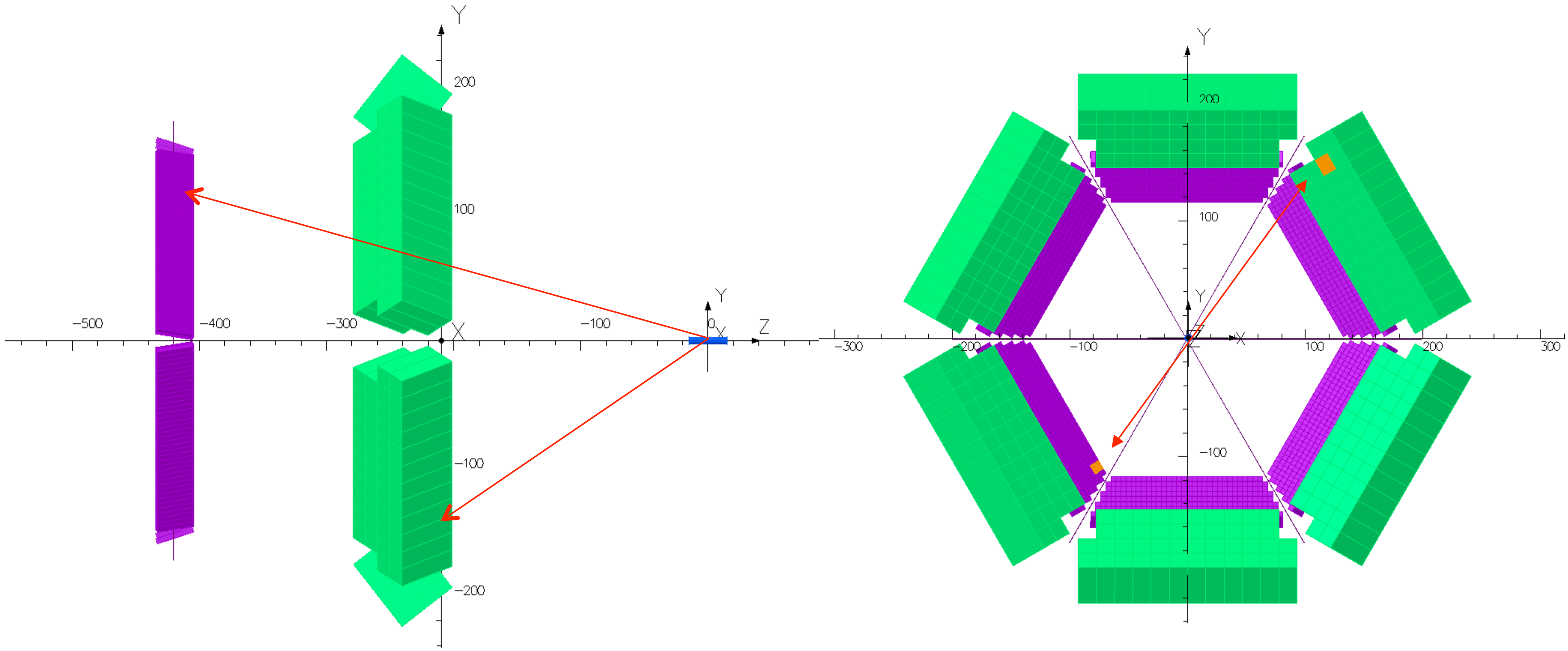
projected precision
at Q^2 = 3 GeV^2

$\Delta G^s/G_D = 0.05$

PAC29, January 12, 2006

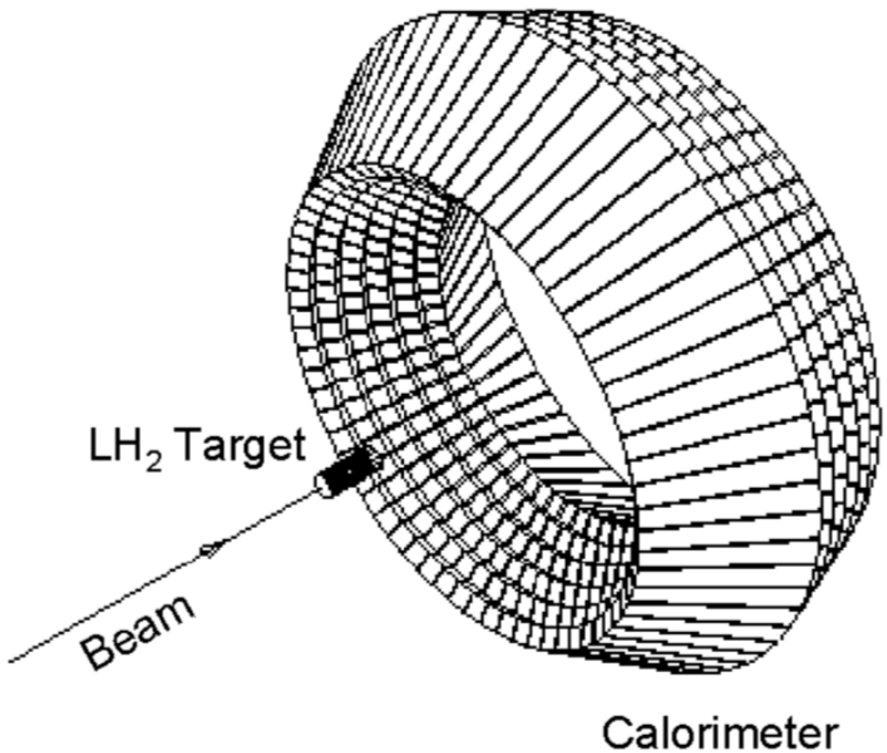
Coincidence is needed for selecting of the elastic scattering process

Coincidence parity experiment



The apparatus can re-use two calorimeters from the GEp/SBS experiment

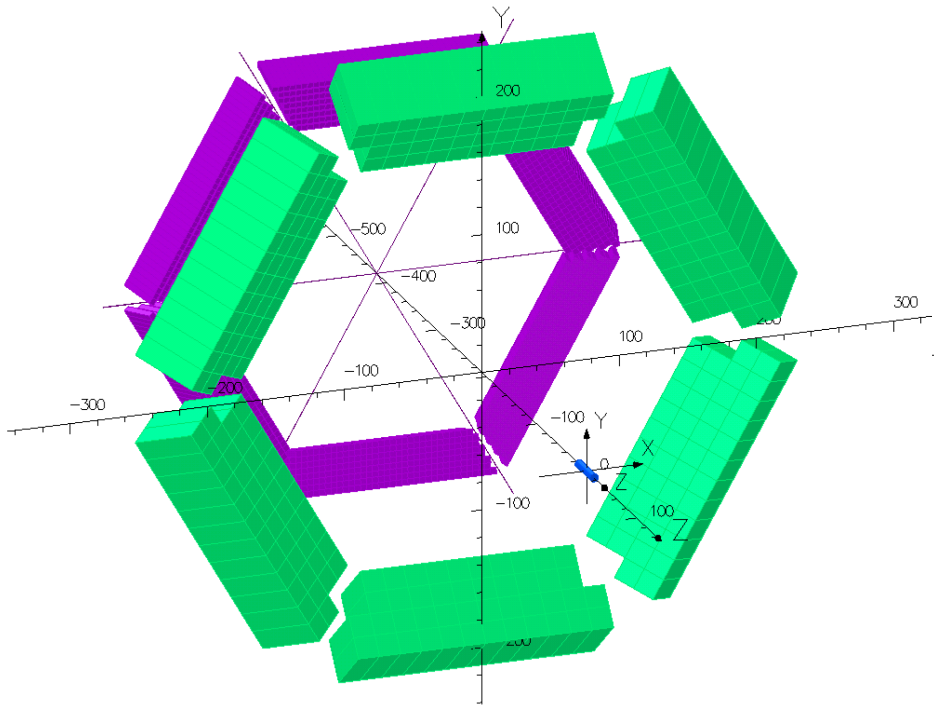
Calorimeter for parity experiment

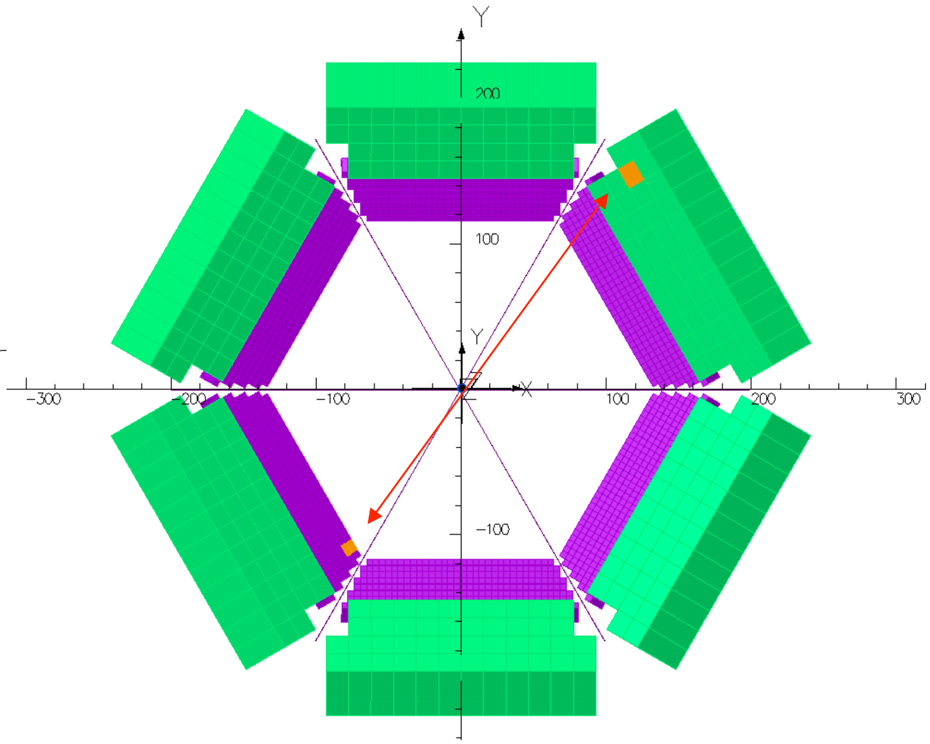


Schematic of the parity-violating electron scattering experimenta PVA4

Success with a low energy electron beam

Coincidence parity experiment





The projected rate of elastic e-p events is 50 kHz
Statistical accuracy is ~ 6 ppm in a 30 day run
Standard asymmetry is expected to be ~ 200 ppm

Summary

- Flavor decomposition of the nucleon Form Factors revealed significant change in the up and down quarks' contributions to the F_1 form factor at Q^2 above 1-1.5 GeV^2.
- Nucleon Form Factors, first investigated 60 years ago, is an active field which has many questions to be answered.
- 12-GeV JLab with the Super Bigbite spectrometer will be an ideal tool for the experiments in Nucleon Form Factor physics at large Q^2.
- Strangeness FF likely has a peak at a high Q^2 and could be discovered in a 3 GeV^2 JLab experiment.