Jefferson Lab
Thomas Jefferson National Accelerator Facility

Super Bigbite Spectrometer, Experimental Program

Bogdan Wojtsekhowski,

for SBS collaboration

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:

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

(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

Electron-nucleon elastic scattering –

Rosenbluth, 1950: hadron current structure

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

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

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

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

Method

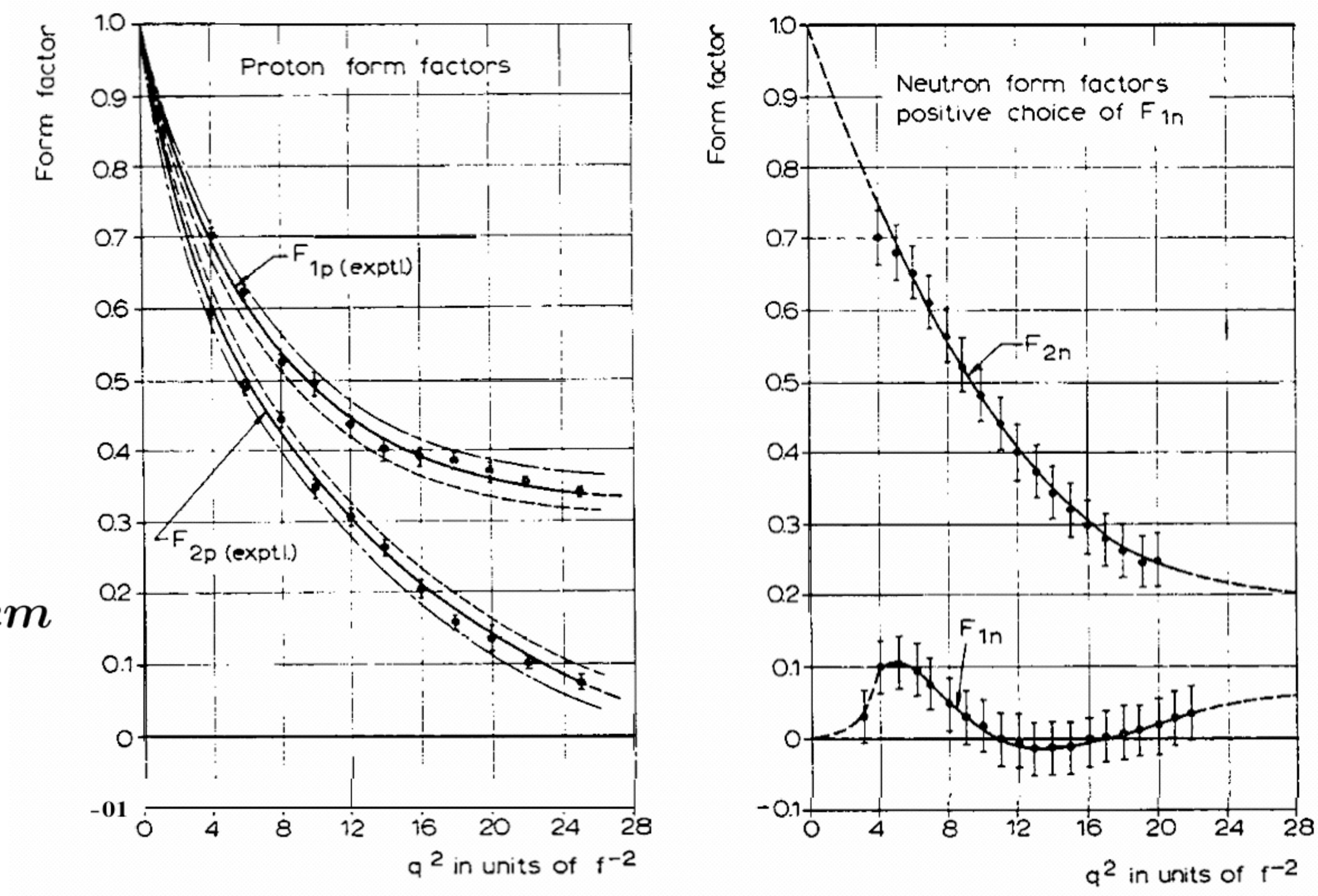
The first measurement of the Form Factors

R.Hofstadter,
1956

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

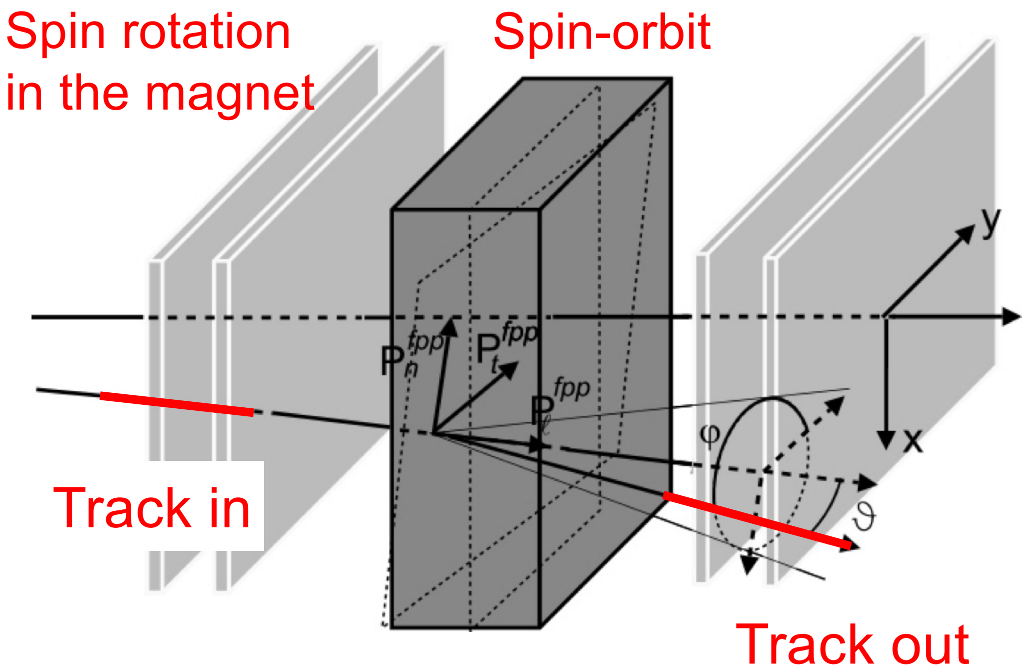
$$\rho = \rho_0 \times e^{-\sqrt{12}\, r/r_{e,m}}$$

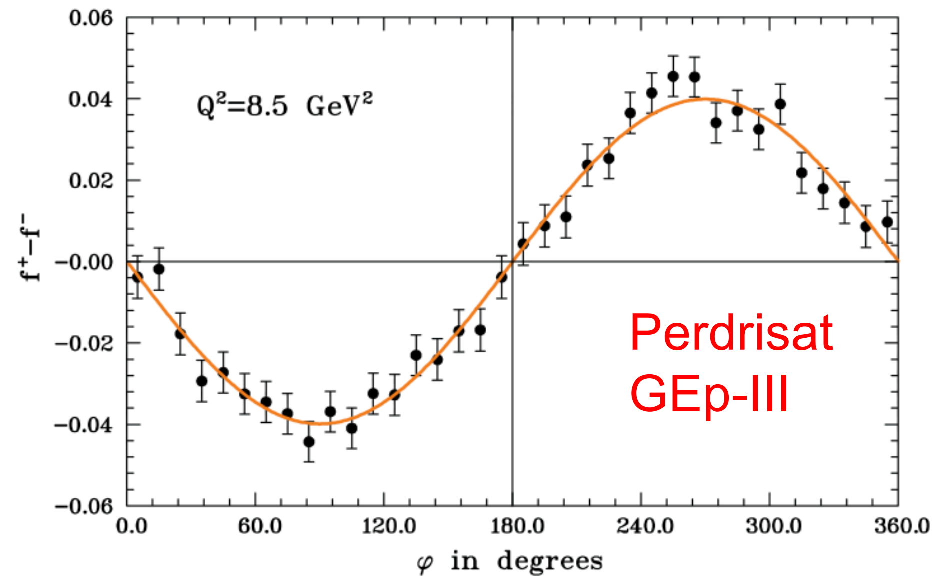
$$F(q) = \frac{1}{[1+(q\, r)^2/12]^2}$$



Electron-nucleon elastic scattering –

Akhiezer, 1958: double spin correlation





$$f^{\pm}(\vartheta,\varphi) = \frac{\epsilon(\vartheta,\varphi)}{2\pi}\left[1 \pm A_y(P_x^{fpp}\sin\varphi - P_y^{fpp}\cos\varphi)\right]$$

where $\pm$ refers to electron beam helicity

$$A = \frac{f^+ - f^-}{f^+ + f^-} = A_y\left(P_x^{fpp}\sin\varphi - P_y^{fpp}\cos\varphi\right)$$

$$\mu_p\frac{G_E^p}{G_M^p} = -\mu_p\frac{E_e + E_e'}{2M_p}\tan\frac{\theta_e}{2}\left(\frac{P_x^{fpp}}{P_y^{fpp}}\sin\chi_\theta + \gamma_p(\mu_p - 1)\Delta\phi\right)$$

Electron-nucleon elastic scattering –

Durand, 1959: neutron/proton ratio

1972 DESY, PL 39B. Q2 = 1.5 GeV2; δGMn/GMn ~ 5%
1994 CLAS6, Q2 up to 4.8 GeV2;
2007 SBS/GMn proposal

Volume 39B, number 3 PHYSICS LETTERS 1 May 1972

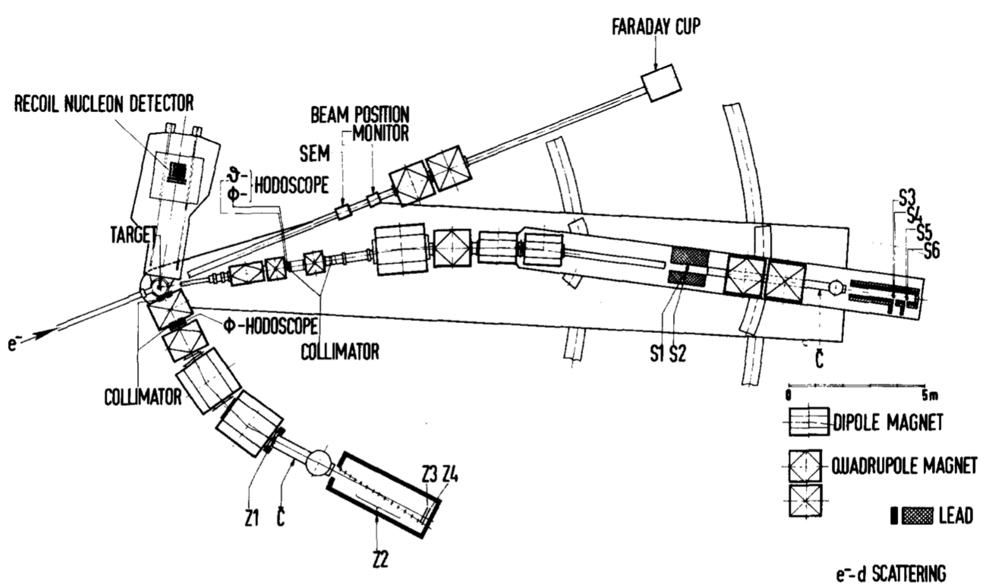
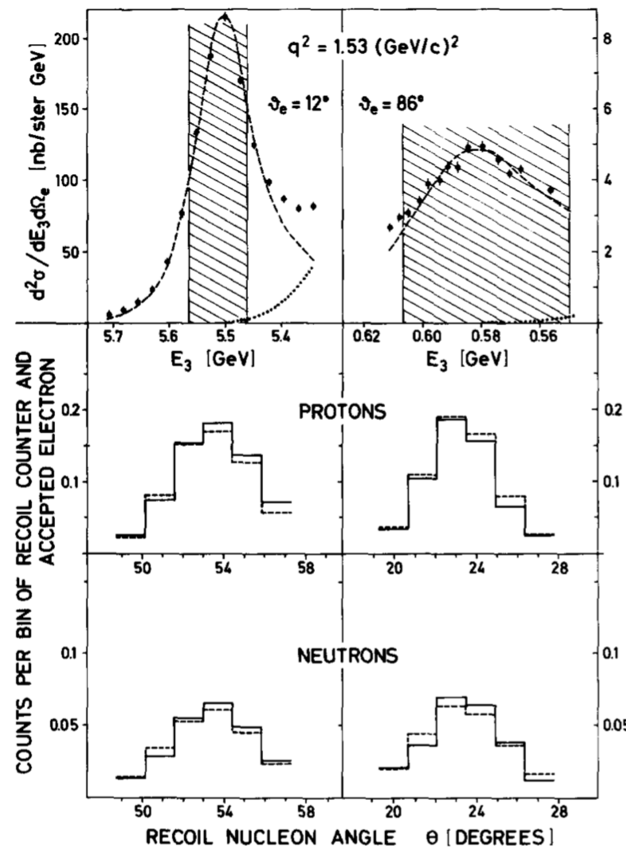


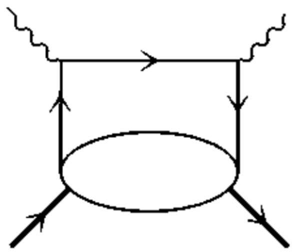
Fig. 1. Schematic view of the experimental set-up with the concrete shielding removed. S1 to S6 and Z1 to Z4 as well as the elements of the recoil nucleon detector are scintillation counters. S1 and Z2 are hodoscopes.



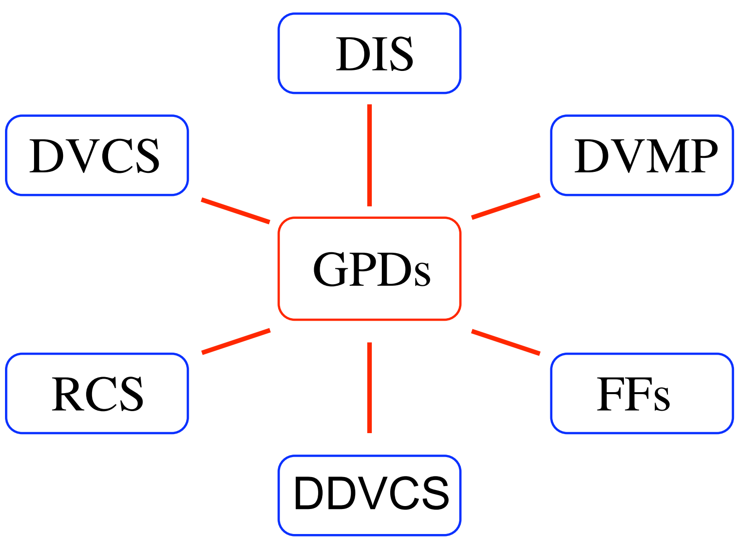
Method

The nucleon structure in terms of GPDs

Muller, Ji, Radyushkin



$+ \ldots$



Reduction formulas at $\xi = t = 0$
for DIS and $\xi = 0$ for FFs

$$H^q(x, \xi = 0, t = 0) \;=\; q(x)$$

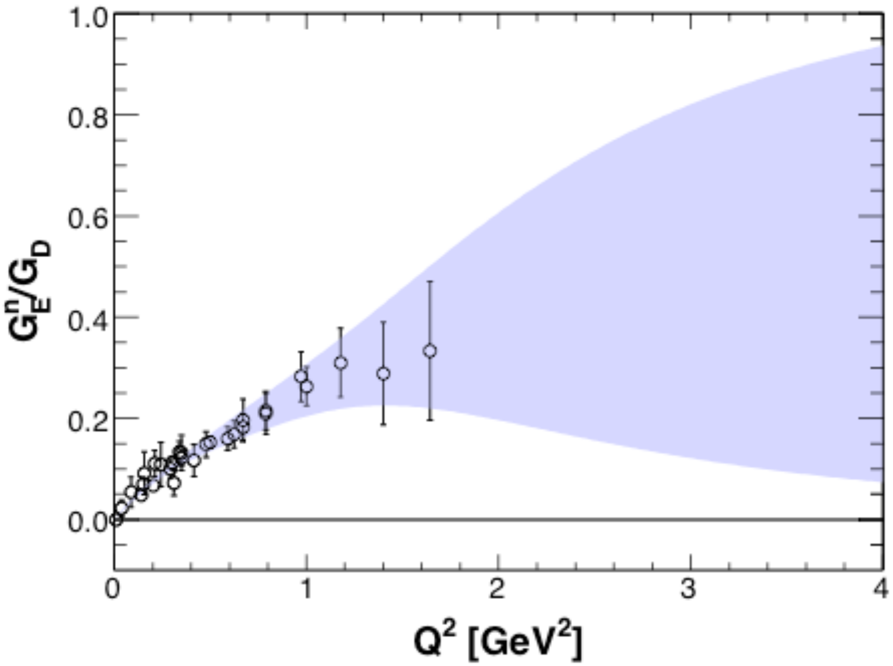
$$\tilde{H}^q(x, \xi = 0, t = 0) \;=\; \Delta q(x)$$

$$\int_{-1}^{+1} dx\, H^q(x, 0, Q^2) \;=\; F_1^q(Q^2)$$

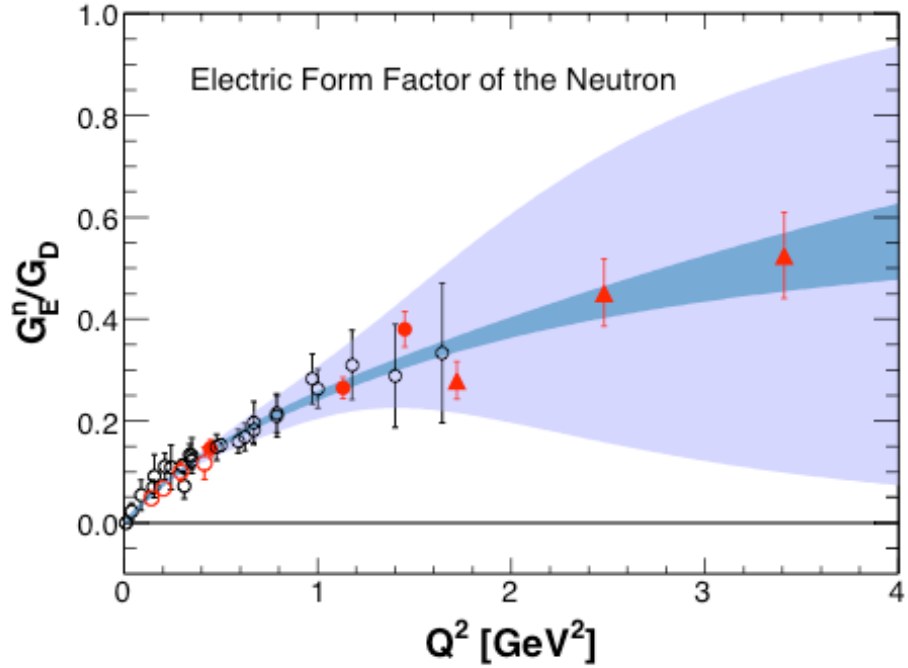
$$\int_{-1}^{+1} dx\, E^q(x, 0, Q^2) \;=\; F_2^q(Q^2)$$

The JLab G_E^n experiments

without JLab GEn experiments



significantly better accuracy and higher 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.

The goal is understanding of the nucleon

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

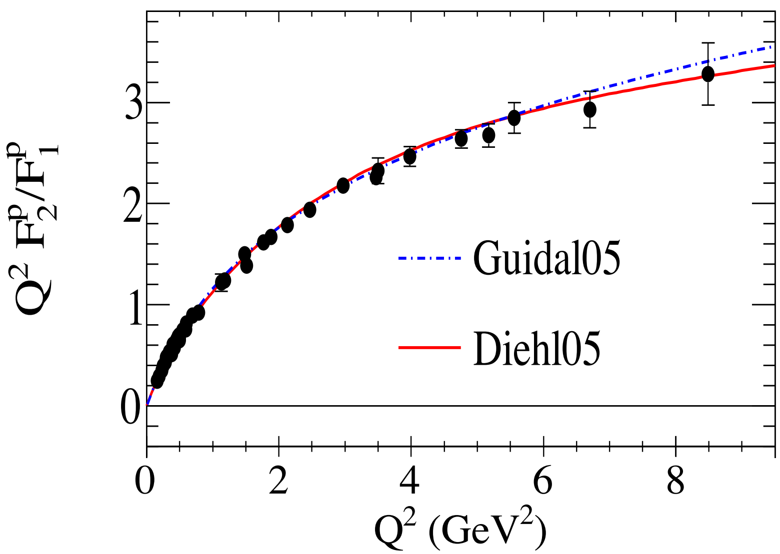
$$F_1 = \frac{G_E + \tau G_M}{1+\tau} \quad F_2 = -\frac{G_E - G_M}{1+\tau}$$

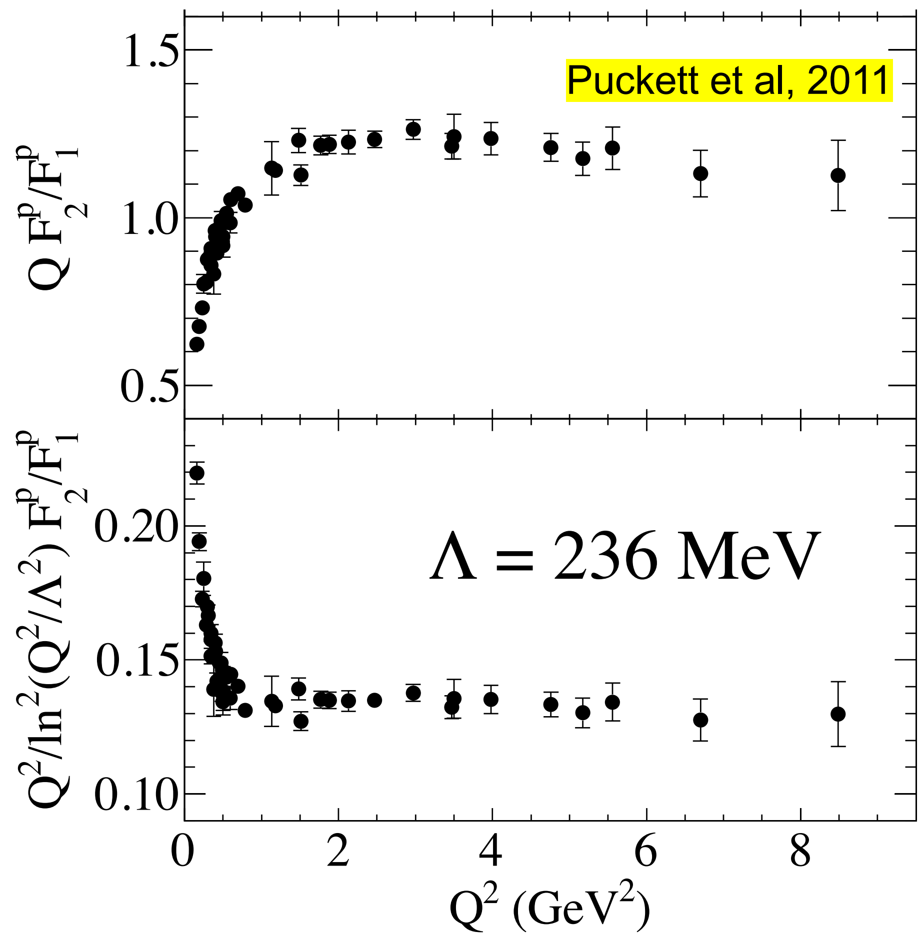
$$\tau = Q^2/4M^2$$

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

G.Miller: Orbital moment!

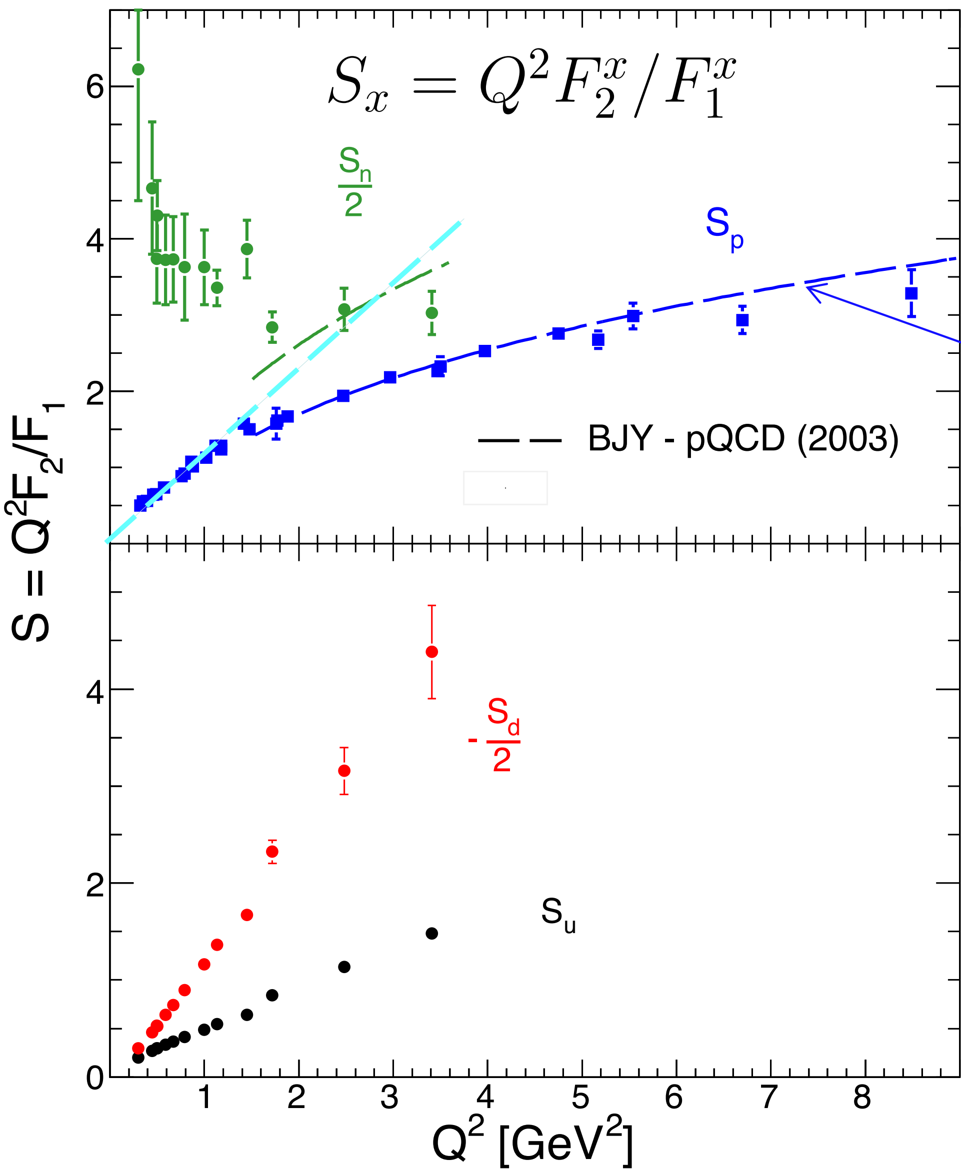
Balitsky-Ji-Yuan: modified scaling due to the orbital moment w.f.





Motivation

The goal is understanding of the nucleon



pQCD prediction for large Q^2:

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

pQCD updated prediction:

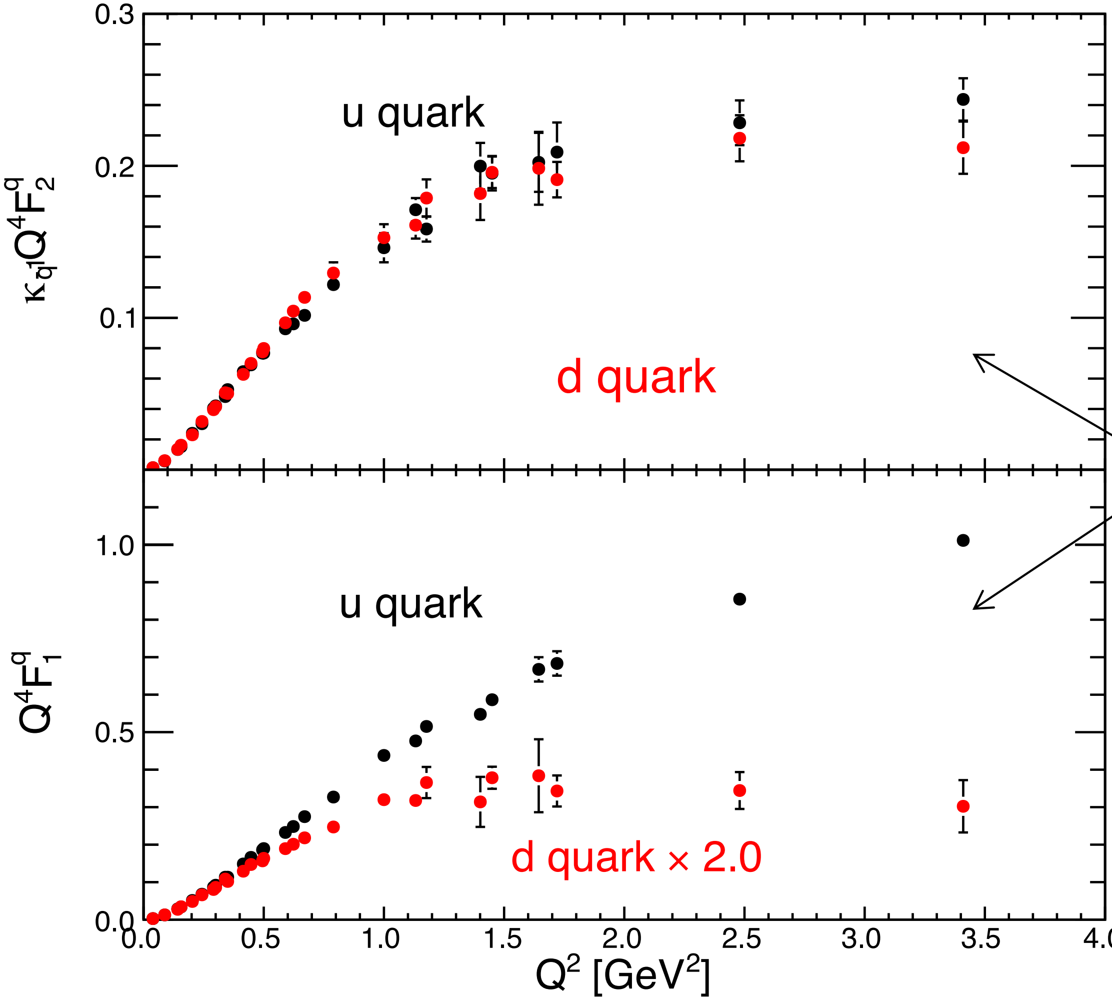
$$S \to \left[Q^2/\ln^2(Q^2/\Lambda^2)\right] F_2/F_1$$

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)

Flavor 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

Electromagnetic form factors

in proton

$$F_i^p = e_u F_i^u + e_d F_i^d$$
$$F_i^n = e_u F_i^d + e_d F_i^u$$

The experiment suggests that the probability of proton survival after absorption of a massive virtual photon is much higher when the photon interacts with an up quark, which is doubly represented in the proton.
This may be interpreted as an indication of the up-up correlation. At high Q^2 a correlation usually enhances the high momentum component and the interaction cross section.
The relatively weak down quark contribution to the F_{1p} indicates a suppression of the up-down correlation or a mutual cancellation of different types of up-down correlations.

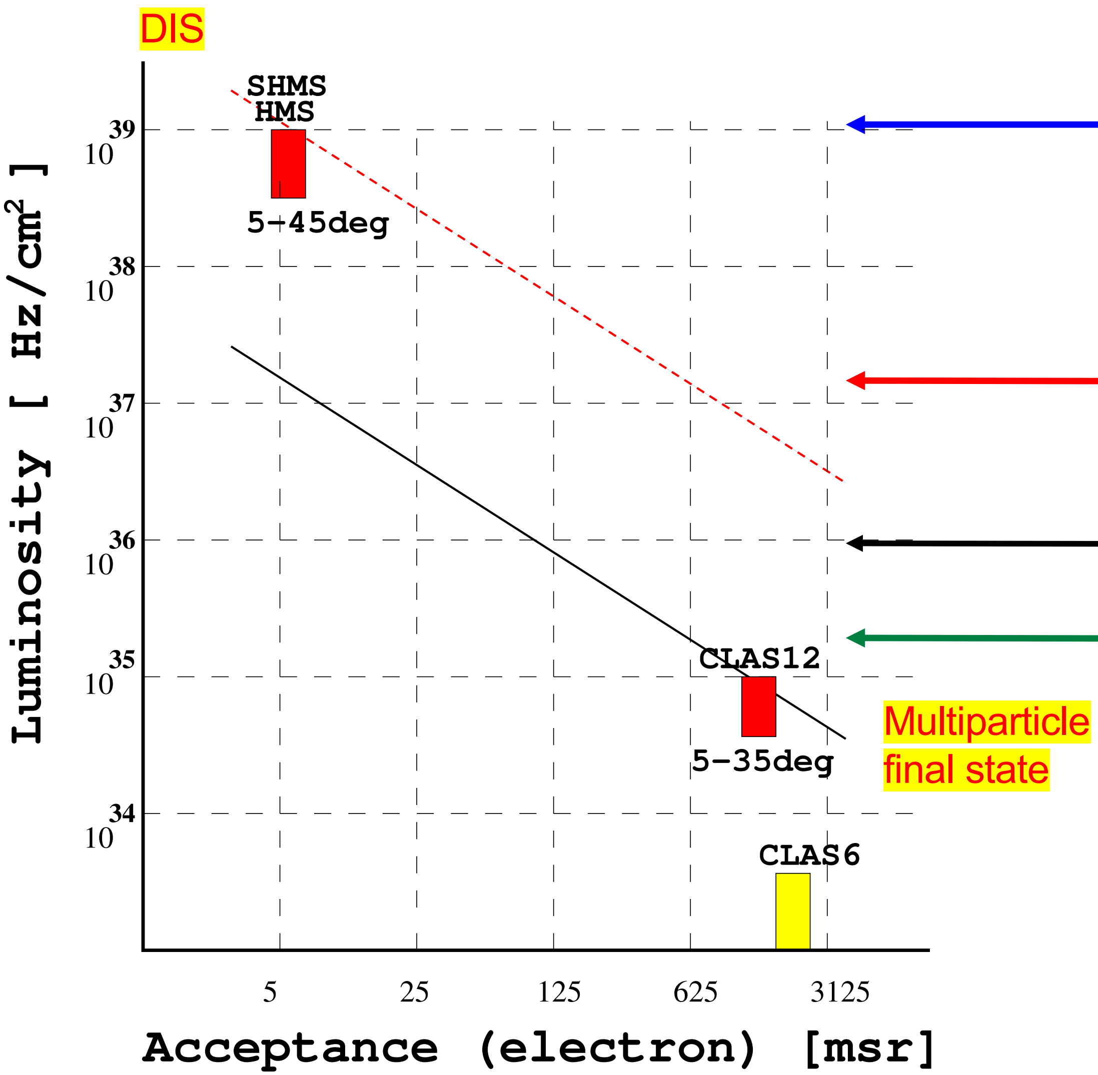
Diquark workshop – ECT-2019

Diquark correlations in hadron physics: Origin, impact and evidence

M.Yu. Barabanov [1], M.A. Bedolla [2], W.K. Brooks [3], G.D. Cates [4], C. Chen [5], Y. Chen [6,7], E. Cisbani [8], M. Ding [9], G. Eichmann [10,11], R. Ent [12], J. Ferretti [13], R.W. Gothe [14], T. Horn [15,12], S. Liuti [4], C. Mezrag [16], A. Pilloni [9], A.J.R. Puckett [17], C.D. Roberts [18,19,*], P. Rossi [12,20], G. Salmé [21], E. Santopinto [22], J. Segovia [23,19], S.N. Syritsyn [24,25], M. Takizawa [26,27,28], E. Tomasi-Gustafsson [16], P. Wein [29], B.B. Wojtsekhowski [12]

Progress in Particle and Nuclear Physics 116 (2021) 103835

JLab detector landscape



A range of 10^5 in luminosity.

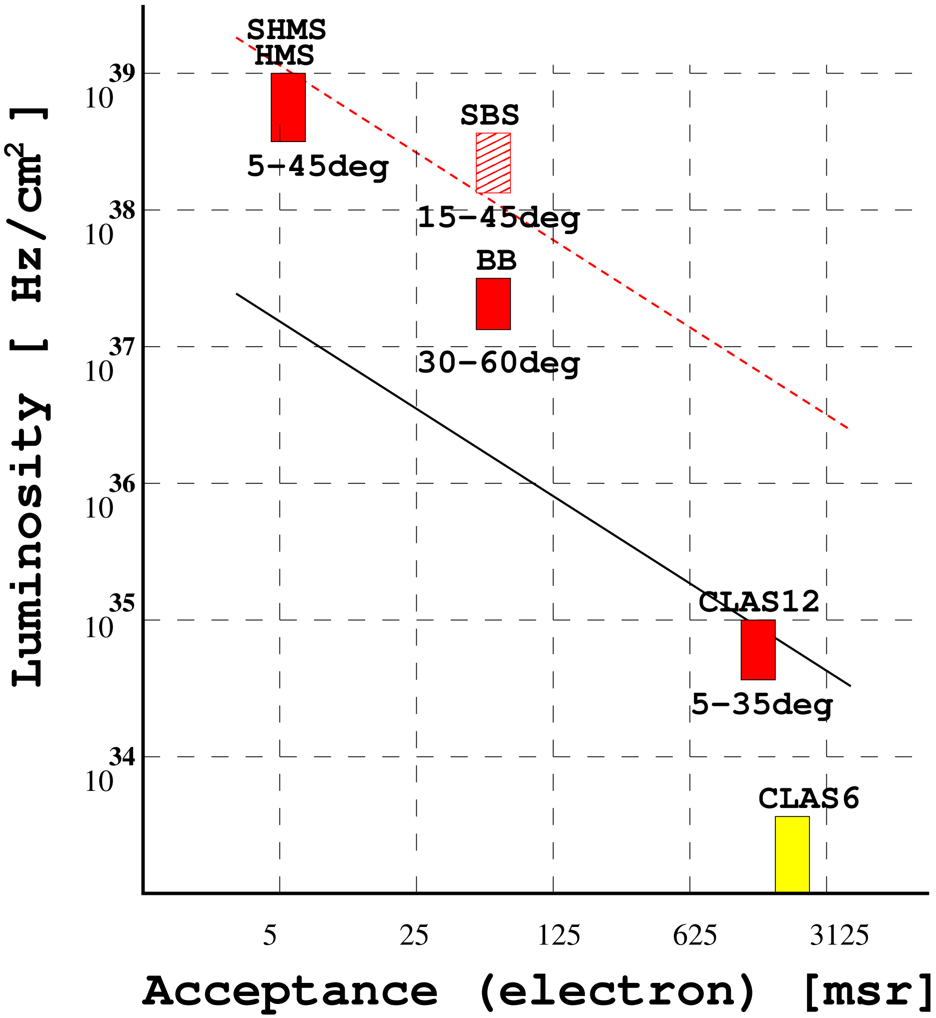
The LH_2 target can be used up to L ~ 10^{39}

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

Sullivan - tagging on soft proton

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.

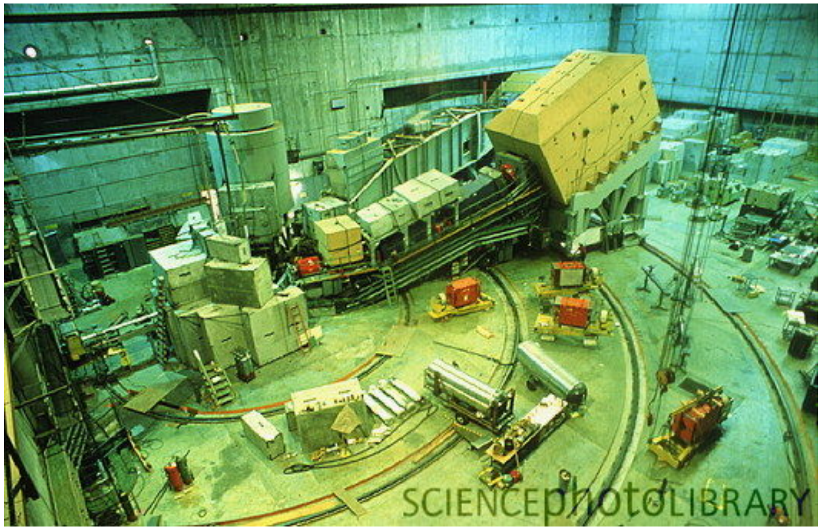
In several A-rated experiments SBS was found to be the best match to the physics.

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

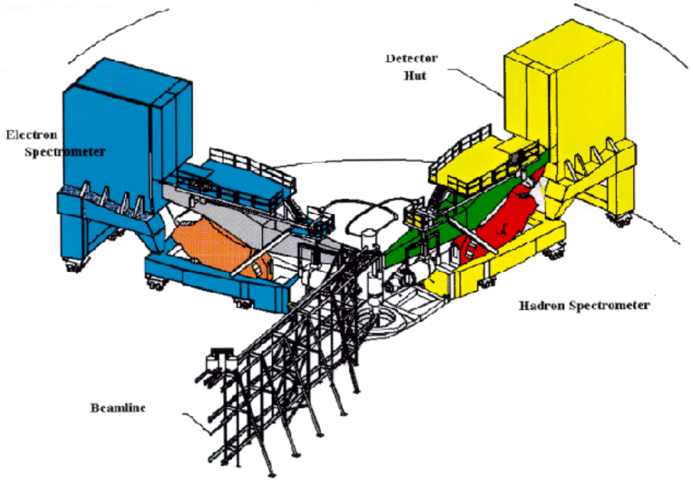
Focusing spectrometers

- Stanford
- SLAC
- DESY
- Bonn
- Bates
- NIKHEF
- Mainz
- JLab

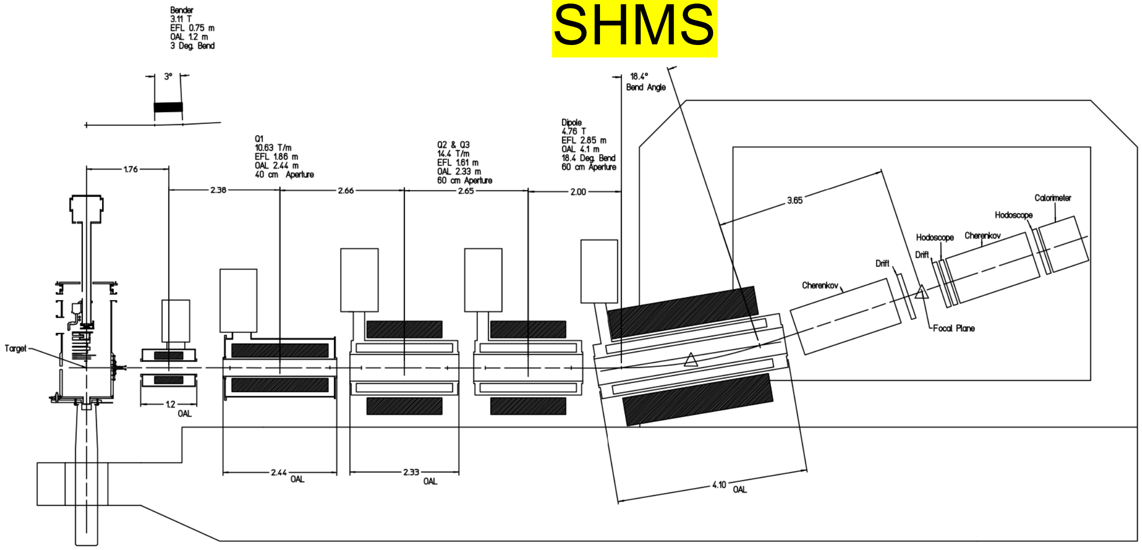
ESA



HRS



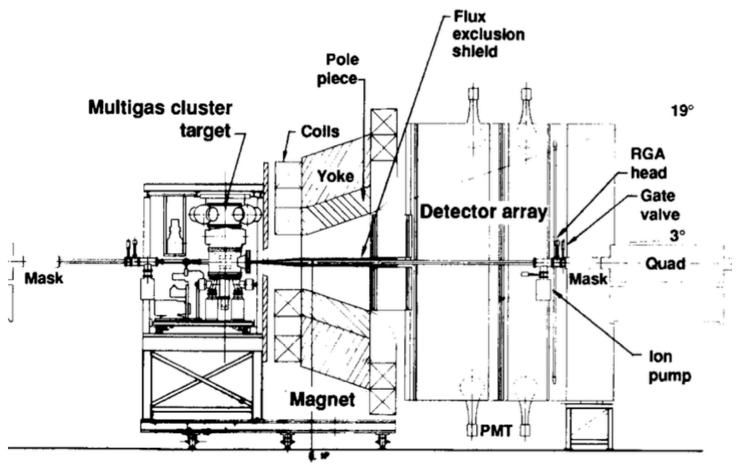
SHMS



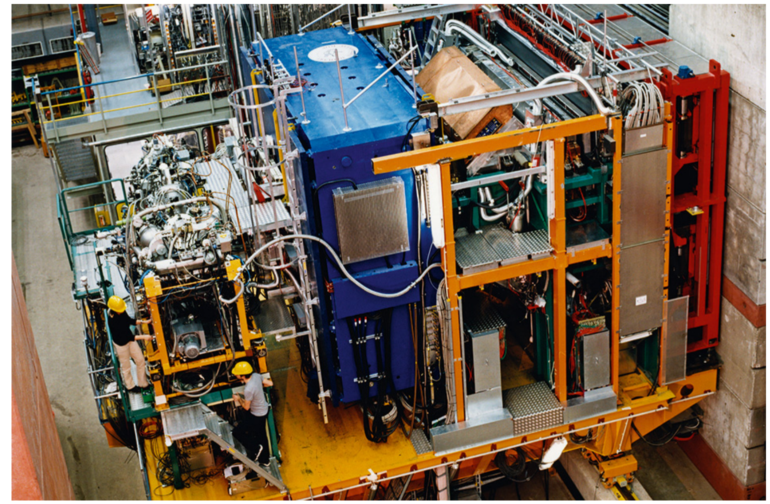
Large acceptance spectrometers

Stanford
SLAC
DESY
Bonn
Bates
NIKHEF
Mainz
JLab

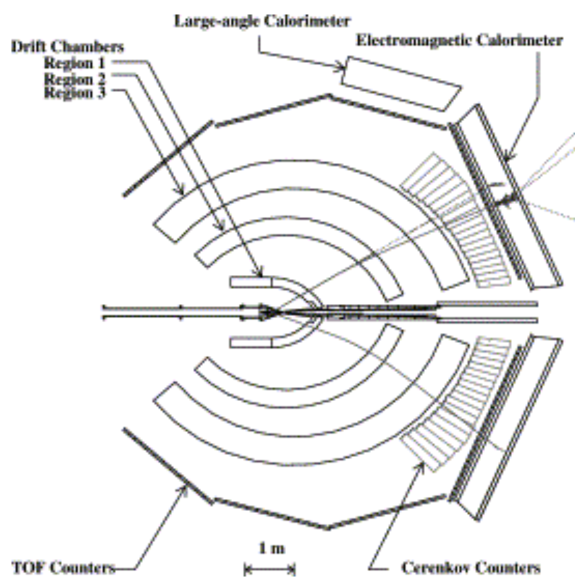
PEGASYS-1989



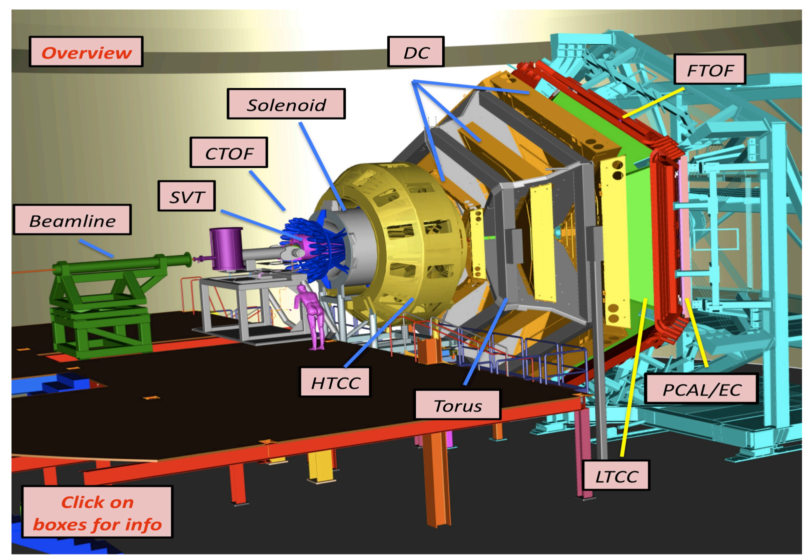
HERMES-1995



CLAS6



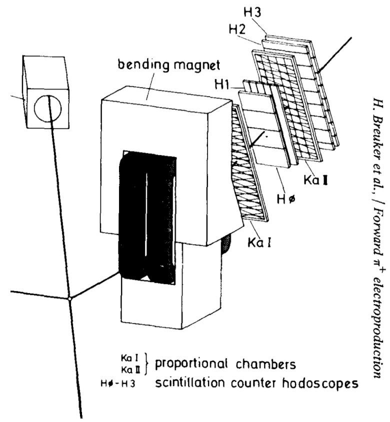
CLAS12



Medium acceptance spectrometers

Stanford
SLAC
DESY
Bonn
Bates
NIKHEF
Mainz
JLab

Bonn pion arm



CEBAF-1986

F. Gross / CEBAF:

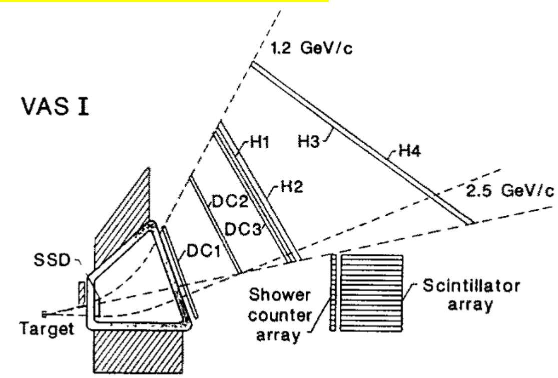
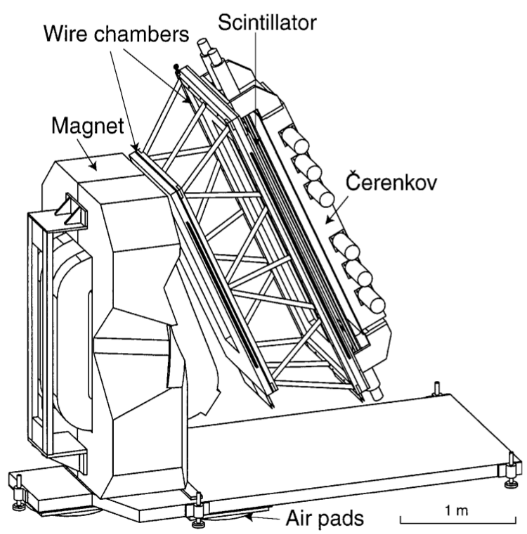
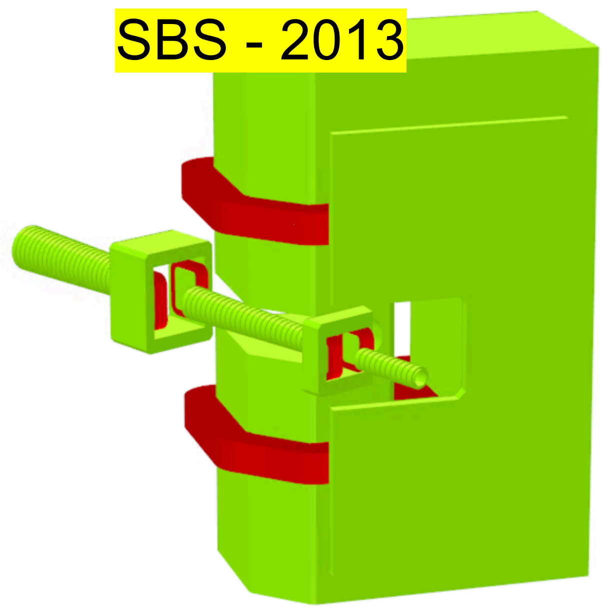


Fig. 7. Schematic of one possible design for a hadron spectrometer for Hall C, known as VAS I. It consists of a large dipole and planes of drift chambers, with a shower counter and scintillator array to detect neutrals. The whole assembly is about 10 m long.

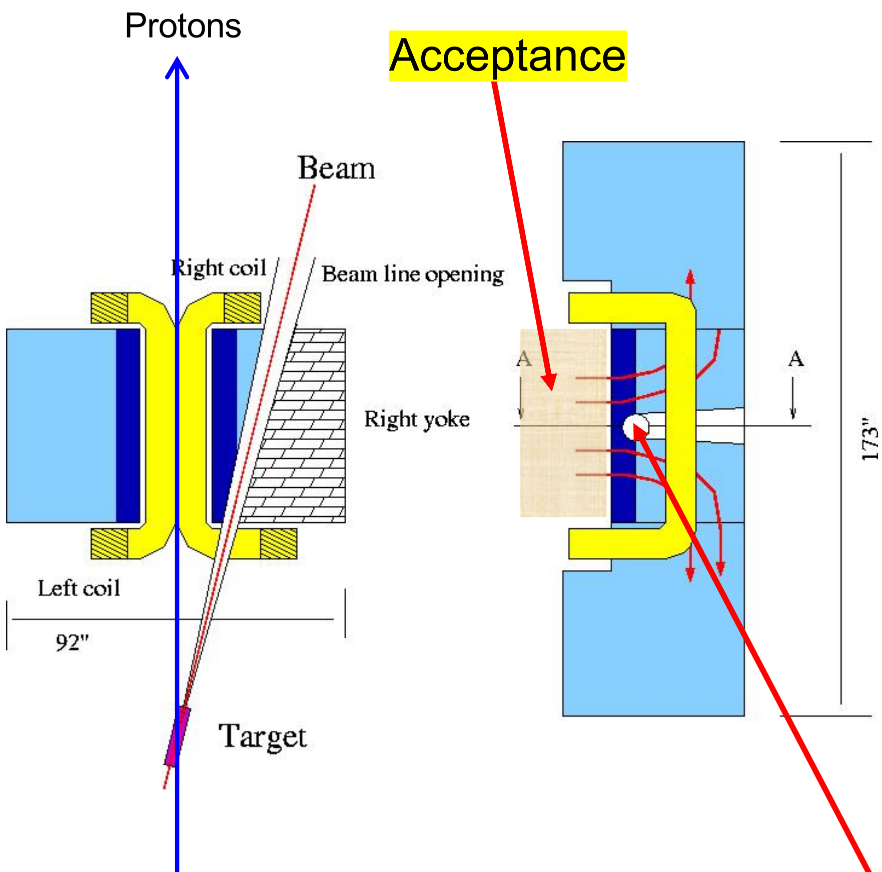
NIKHEF-1999



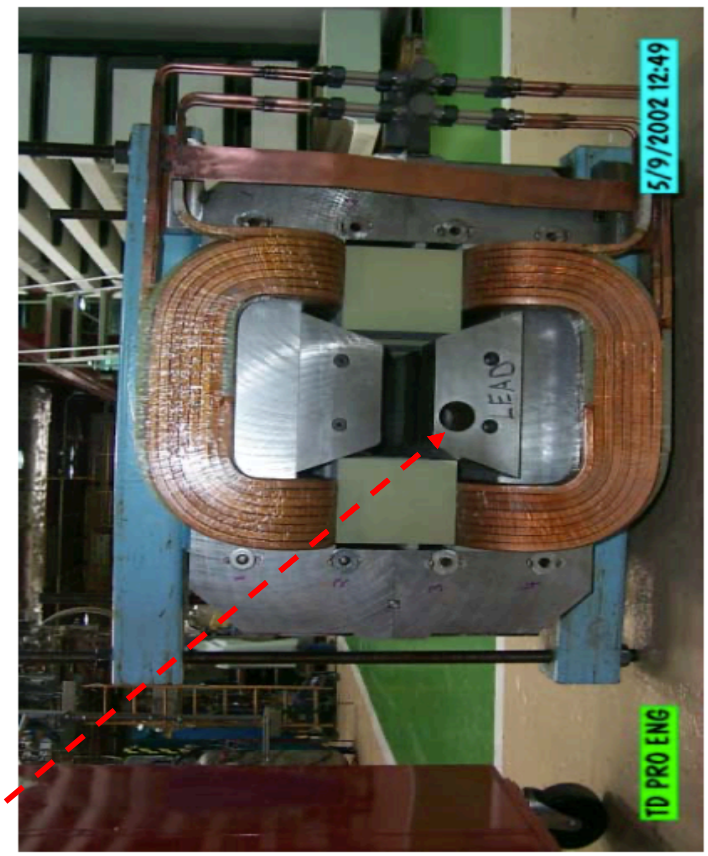
SBS - 2013



Concept of the SBS



Lambertson magnet in accelerator

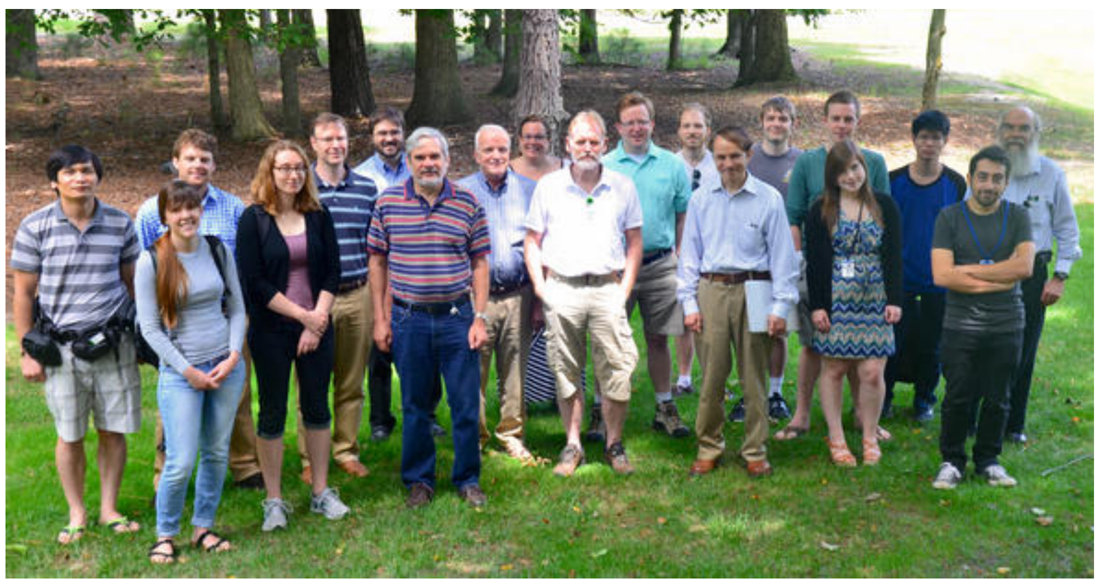


Beam

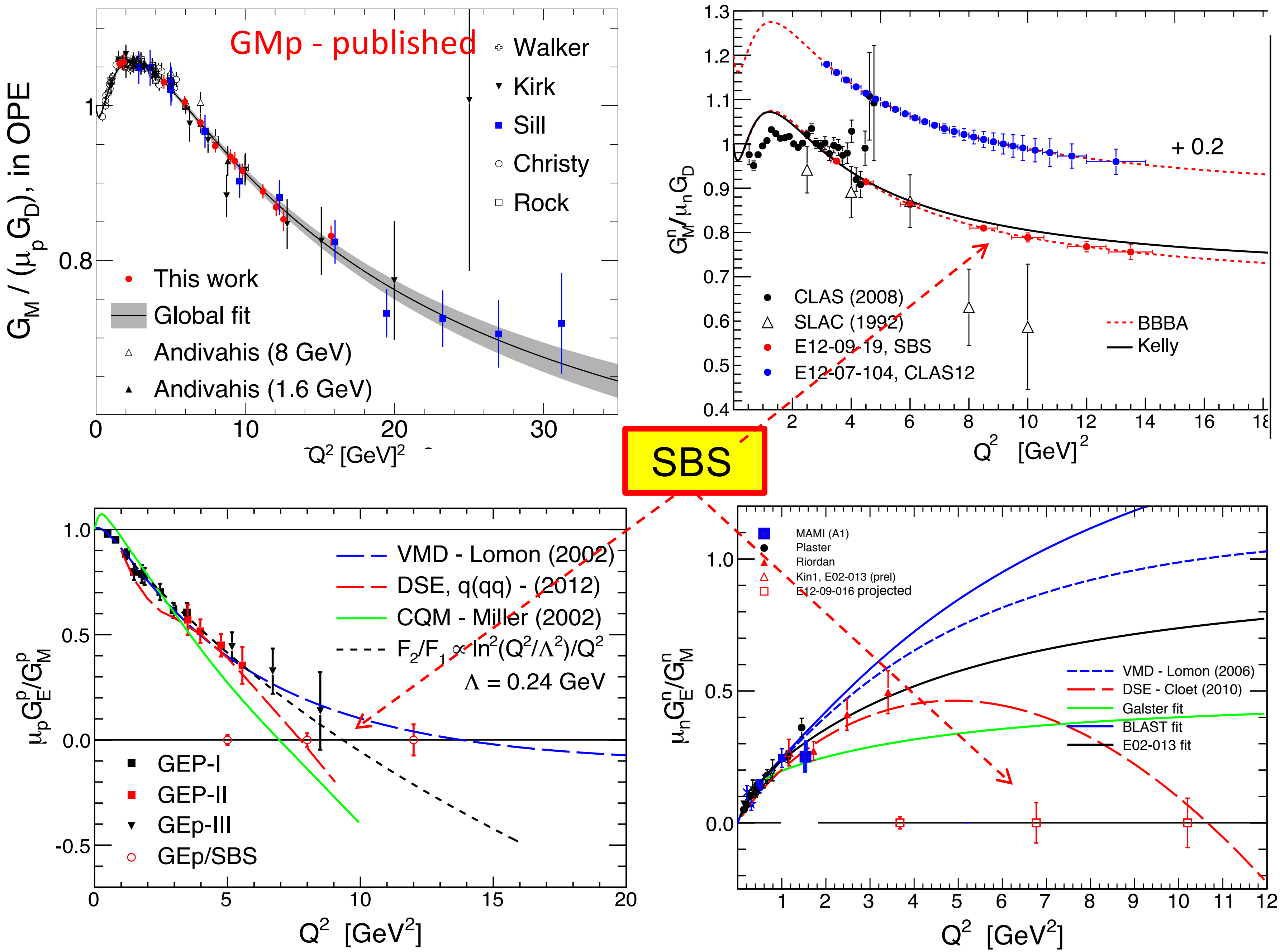
Magnet: 48D48 - 46 cm gap, 2-3 Tesla*m
Solid angle is 70 msr at angle 15 deg.
GEM chambers with 70 μm resolution
momentum resolution is 0.5% for 5 GeV/c
angular resolution is 0.5 mr

SBS collaboration

JLab, INFN, UVa, CMU, AANL, UoG, StMU, W&M, ODU, NCCU, NCAT, CSLA, VT, …

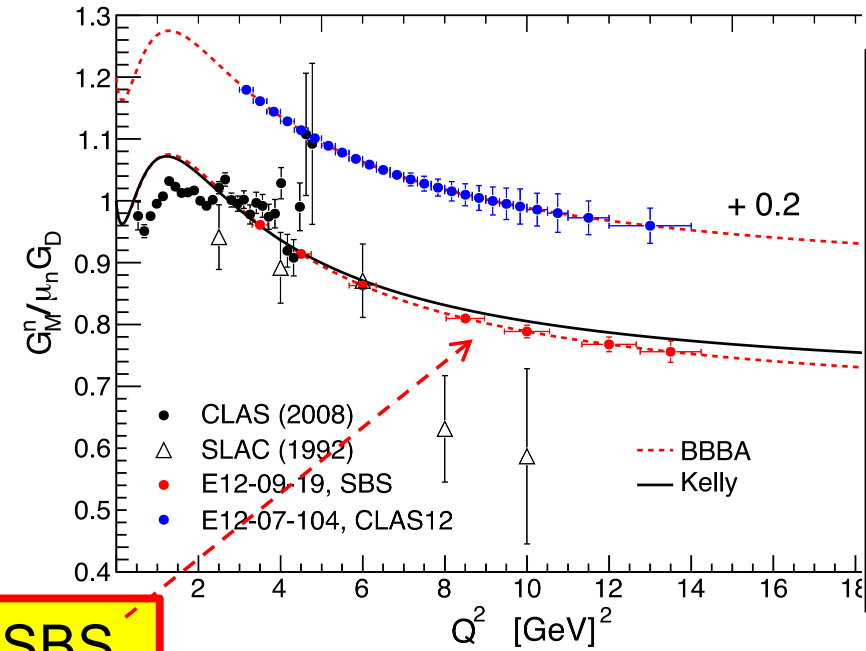


The nucleon FFs



Experimental Program

The nucleon FFs



Challenges:

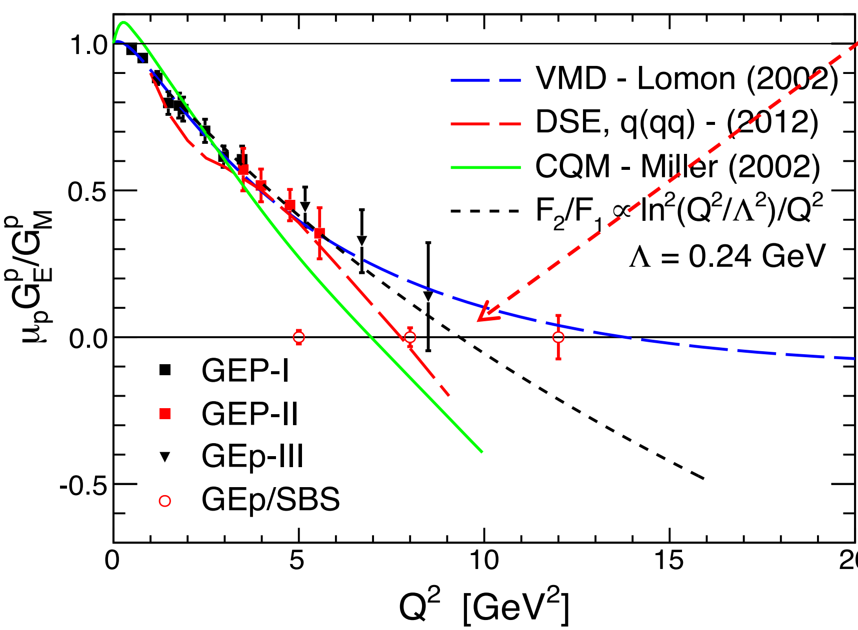
Form factor $\propto Q^{-4}$

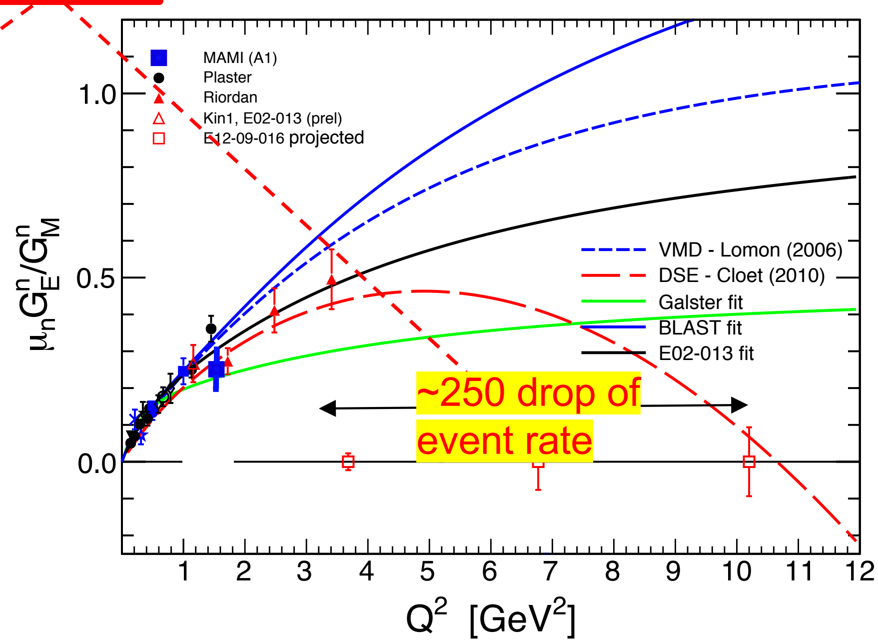
Cross section $\propto E^2/Q^4 \times Q^{-8}$

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

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

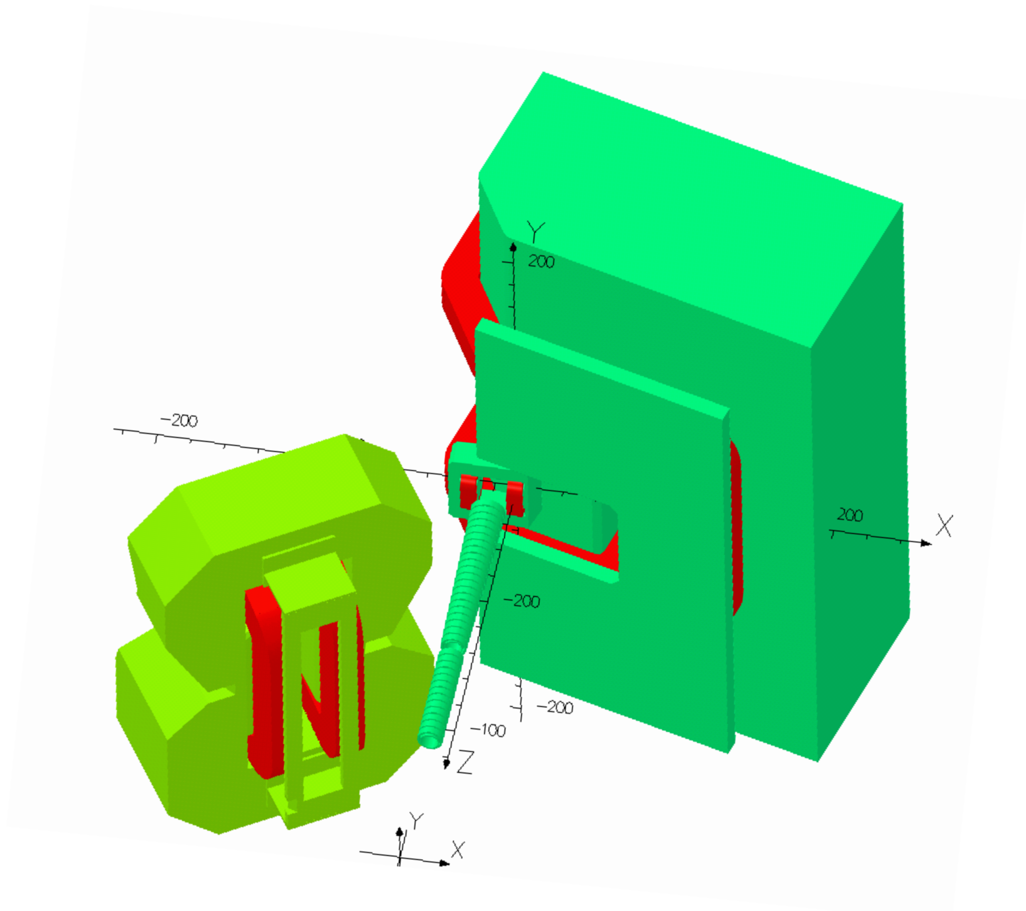
SBS





Experimental Program

Two-arm setup in the FF experiments



$\sigma_p/p = 0.08 + 0.004 \times p[\mathrm{GeV}]$

$\sigma_\theta = 1 - 2$, mrad

$\Omega = 70 - 90$ msr, for $\theta \geq 30°$

$\sigma_p/p = 0.0029 + 0.0003 \times p[\mathrm{GeV}]$

$\sigma_\theta = 0.14 + 1.3/p[\mathrm{GeV}]$, mrad

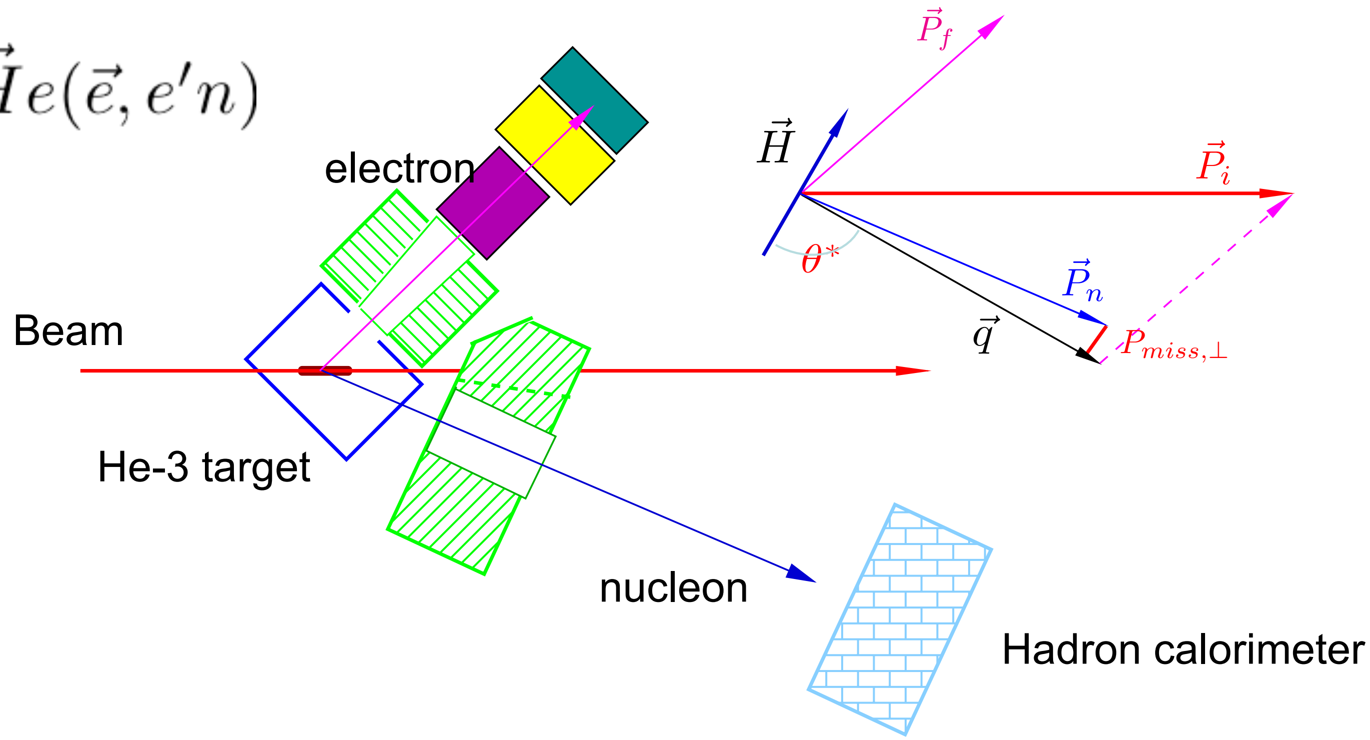
$\Omega = 72$ msr, for $\theta \geq 15°$

$\Omega = 30$ msr, for $\theta = 7.5°$

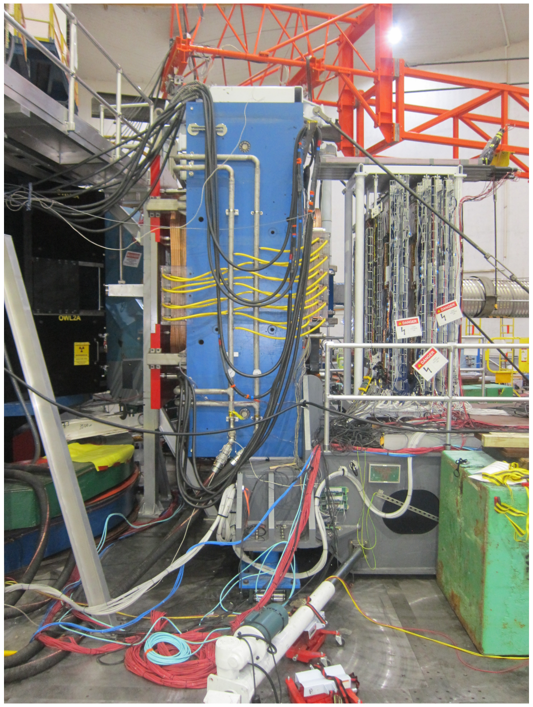
GEn-II: E12-09-016

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

$^3\vec{H}e(\vec{e}, e'n)$

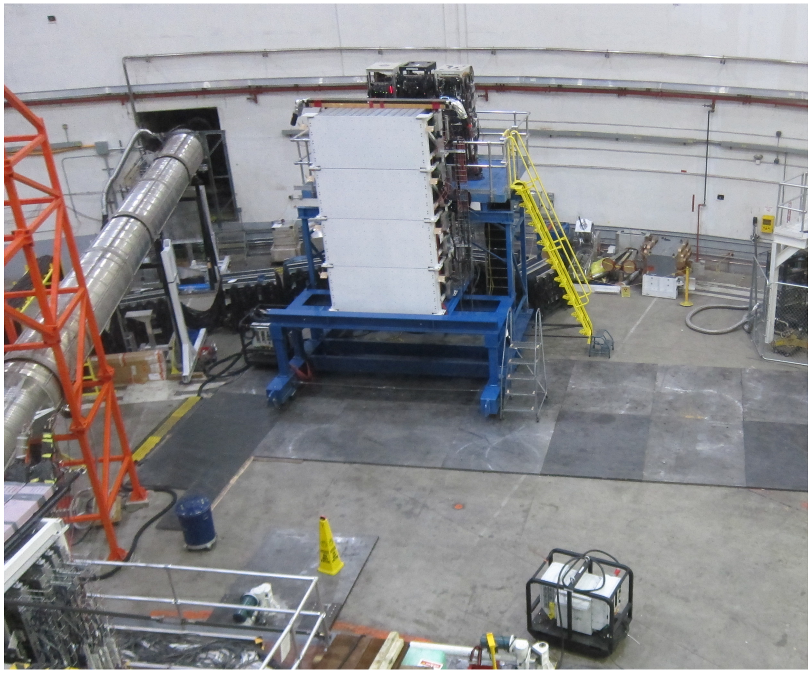


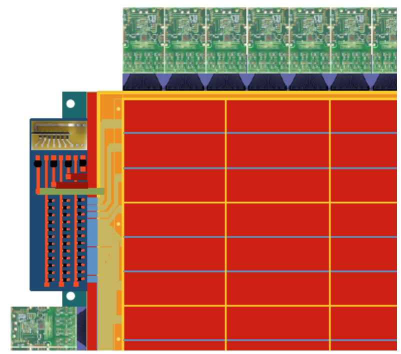
SBS is constructed

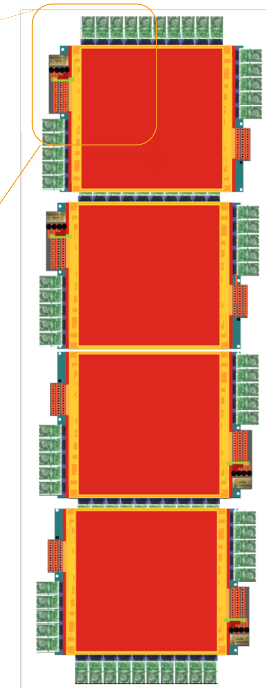


SBS magnet parameters and operation confirmed in GMn and GEn runs

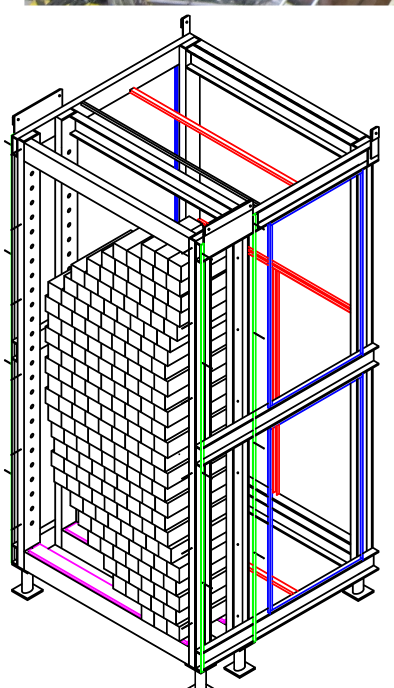
SBS detectors

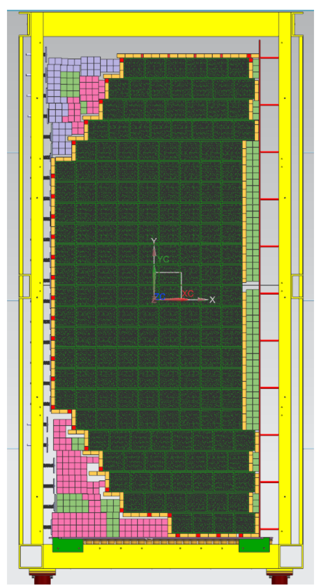






- Protection resistors are outside the chamber: reliable, easy access.
- Large alignment pins, away from the active area
- Wide frames on the two sides not in active area: better mechanical rigidity and more room for gas inlets, HV traces etc.
- Electronics arranged to minimize the material within active area.





HCAL – hadron calorimeter

GEM – multi layer tracker largest in the world

ECAL – high temperature lead-glass calorimeter

Figure-of-Merit in One- & Two-Arm 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 $p_h \sim 2\text{-}8$ 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

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

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

Experimental Program

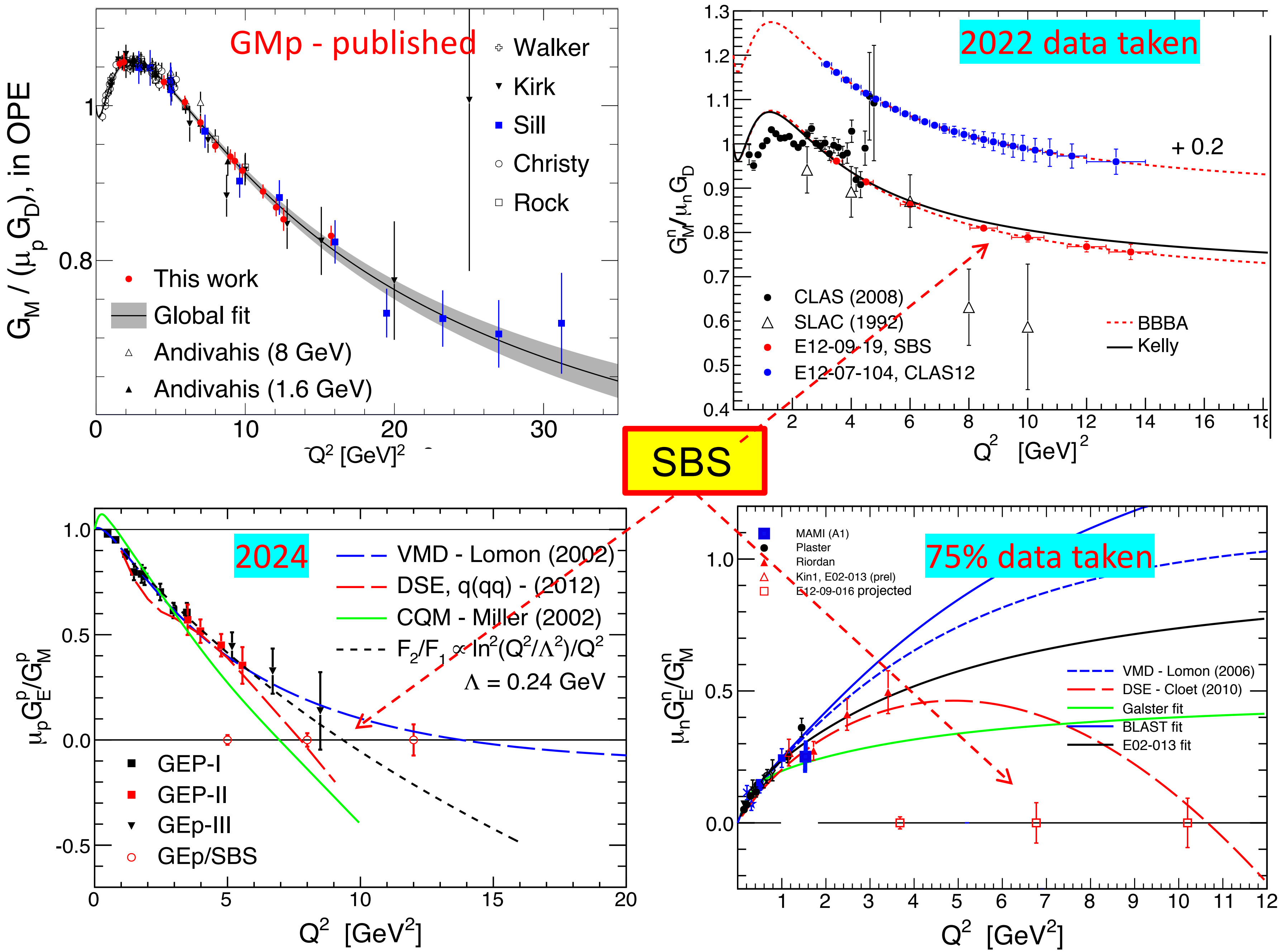
- SBS Nucleon FF program will provide precision results up to:

  G^p_E @ 12 GeV^2 (FOM up due to SBS Ω x10 and GEM)

  G^n_E @ 10 GeV^2 (FOM up due to 3He x10 - convection)

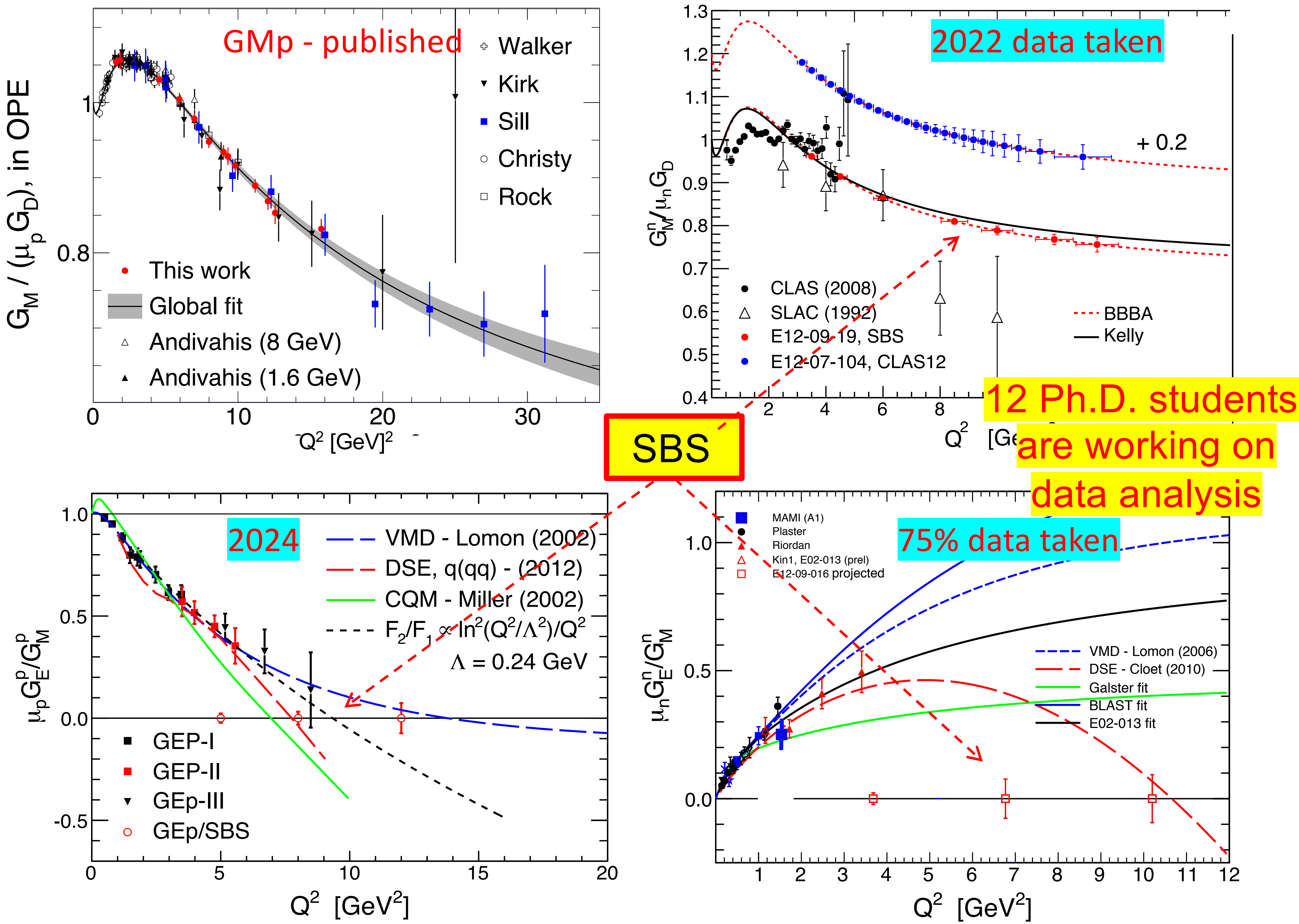
  G^n_M @ 13.5 GeV^2 (p/n with SBS magnet and HCAL)

The nucleon FFs



Experimental Program

The nucleon FFs



Experimental Program

Experimental Program

- SBS Nucleon FF program will provide precision results up to:

  G^p_E @ 12 GeV^2 - there is perspective to 15 GeV^2

  ✓ G^n_E @ 10 GeV^2 - on the limit

  ✓ G^n_M @ 13.5 GeV^2 - there is perspective to 18 GeV^2

done | in the provisional schedule

- Experimental program includes: nTPE; Pion ALL/KLL; GEn-RP;

  neutron/proton

approved | new ideas for

after move to Hall C => SIDIS; TDIS; DVCS; g2p/d2p; γDVCS

Ω_e x10 dp/p gluonGPD

approved | under study

reuse of the detectors: WACS, polWACS, TCS, sFF

Electromagnetic form factors strange quarks contribution

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

Current assumption is sFF = 0

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

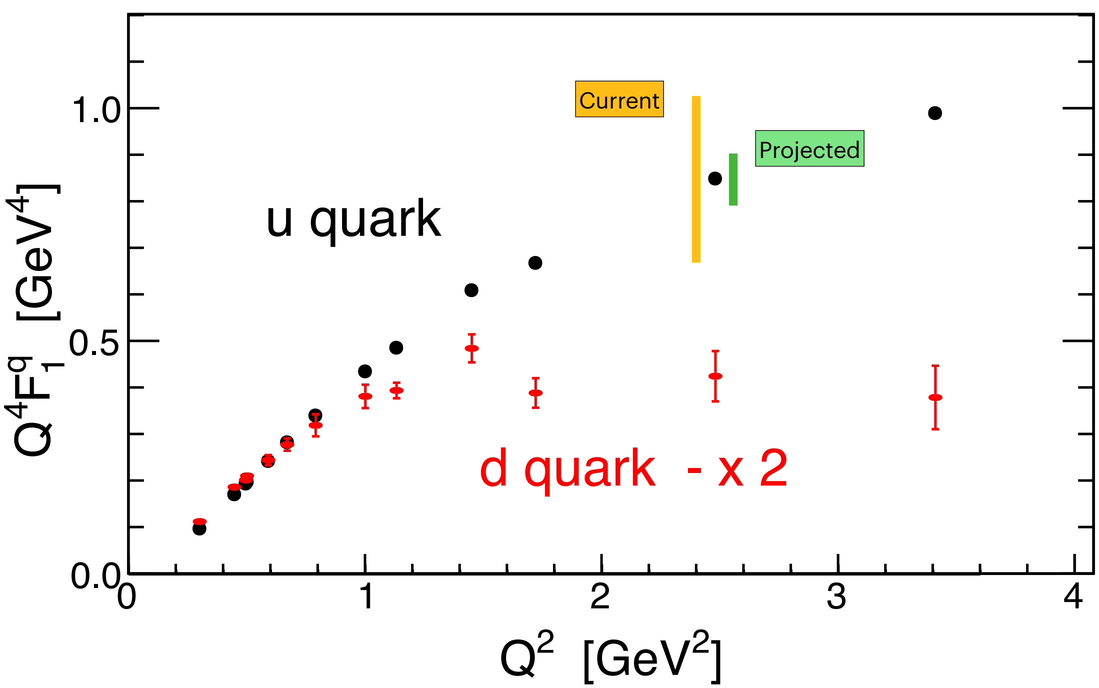
$$F_1^s(0) = 0 \qquad F_2^s(0) = \mu_s$$

Impact of sFF on flavor decomposition

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

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

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



Summary

- Accurate measurements of the Nucleon Form Factors at high Q^2 will significantly boost understanding of the nucleon.
- 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 be completed in 2023, in 2024 will be a SBS/GEp experiment.

Experiments are diamonds

Form Factors are forever