Nucleon Form Factor Experiments with 12 GeV at Jefferson Lab

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Outline of this talk

Introduction

Current status of Nucleon Form factor data and theory (short)

The 12 GeV upgrade

The SBS project in Hall A

Three approved FF experiments

Conclusions

Prelude

It sometimes happens in scientific research that experimental results which were the basis of a consensus, suddenly are proven wrong.
This is what happened with experiments testing the structure of the proton by elastically scattering electrons at protons.
Such an experiment occurred twelve years ago with the then rather new CEBAF accelerator at JLab.
The relatively new technique of double polarization was used on an unprecedented scale.

$$\vec{e}p \to e\vec{p} \quad \vec{e}\vec{n} \to en \quad e\vec{p} \to e\vec{p}$$

$$\vec{e}\vec{p} \to ep \quad \vec{e}n \to e\vec{n}$$

For proton form factor studies, the first is best, for neutron studies the second is best; the third has never been attempted.
Single polarization asymmetry zero except for 2γ or PV effects.

Short History of Form Factors

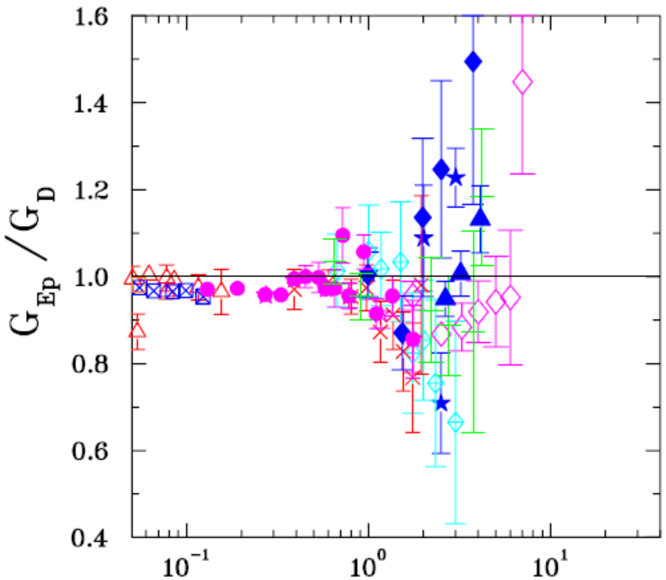
The results of this first experiment in 1998 surprised all involved, but were not necessarily recognized as "paradigm changing" by all. In all previous experiments in the 5 decades preceding this first CEBAF experiment, it had been found that the two form factors of the proton G_{Ep} and G_{Mp} (electric, magnetic), were in a ~ constant ratio, versus Q^2. G_E and G_M are related to F_1 and F_2 (Dirac, Pauli), as

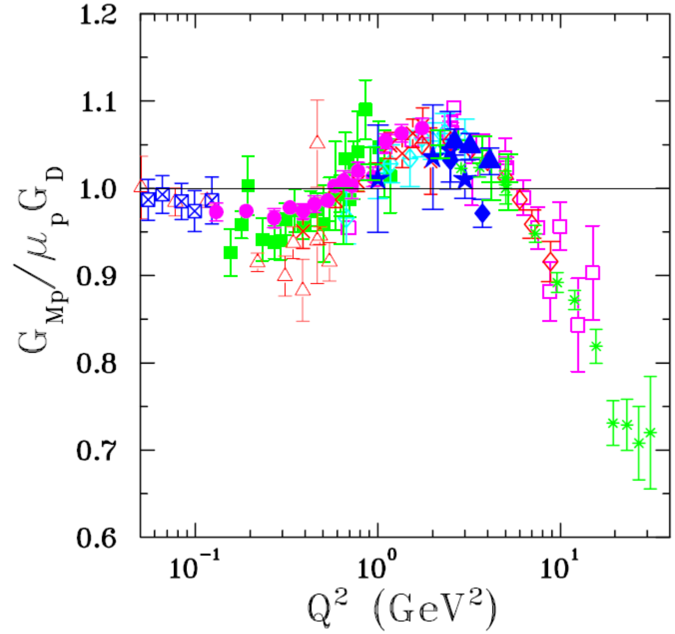
$$G_E = F_1 - \tau F_2, \quad G_M = F_1 + F_2, \quad \tau = \frac{Q^2}{4M^2}.$$

After the second G_{Ep} experiment in 2000, new results demonstrated beyond a doubt that it was not so: the ratio G_{Ep}/G_{Mp} decreases linearly with Q^2, at least up to ~5.6 GeV^2.

$$\frac{G_{Ep}}{G_{Mp}} = 1.0587 - 0.1426Q^2$$

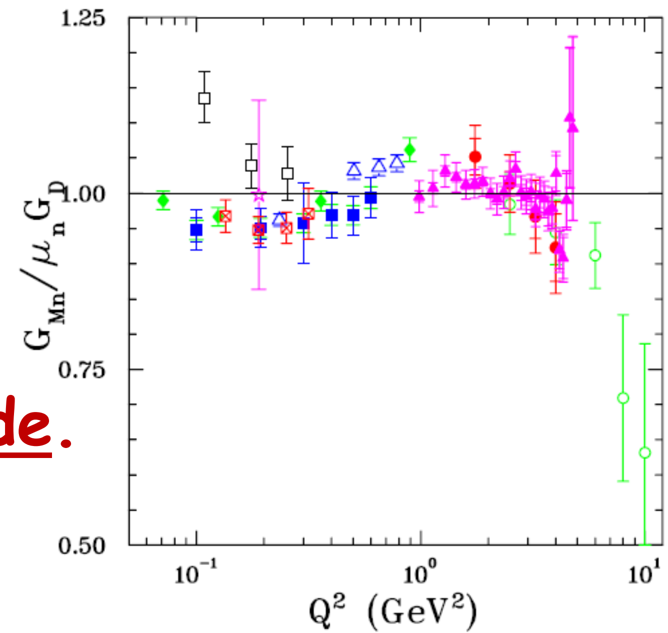
Results previous to Jlab Polarization Experiments





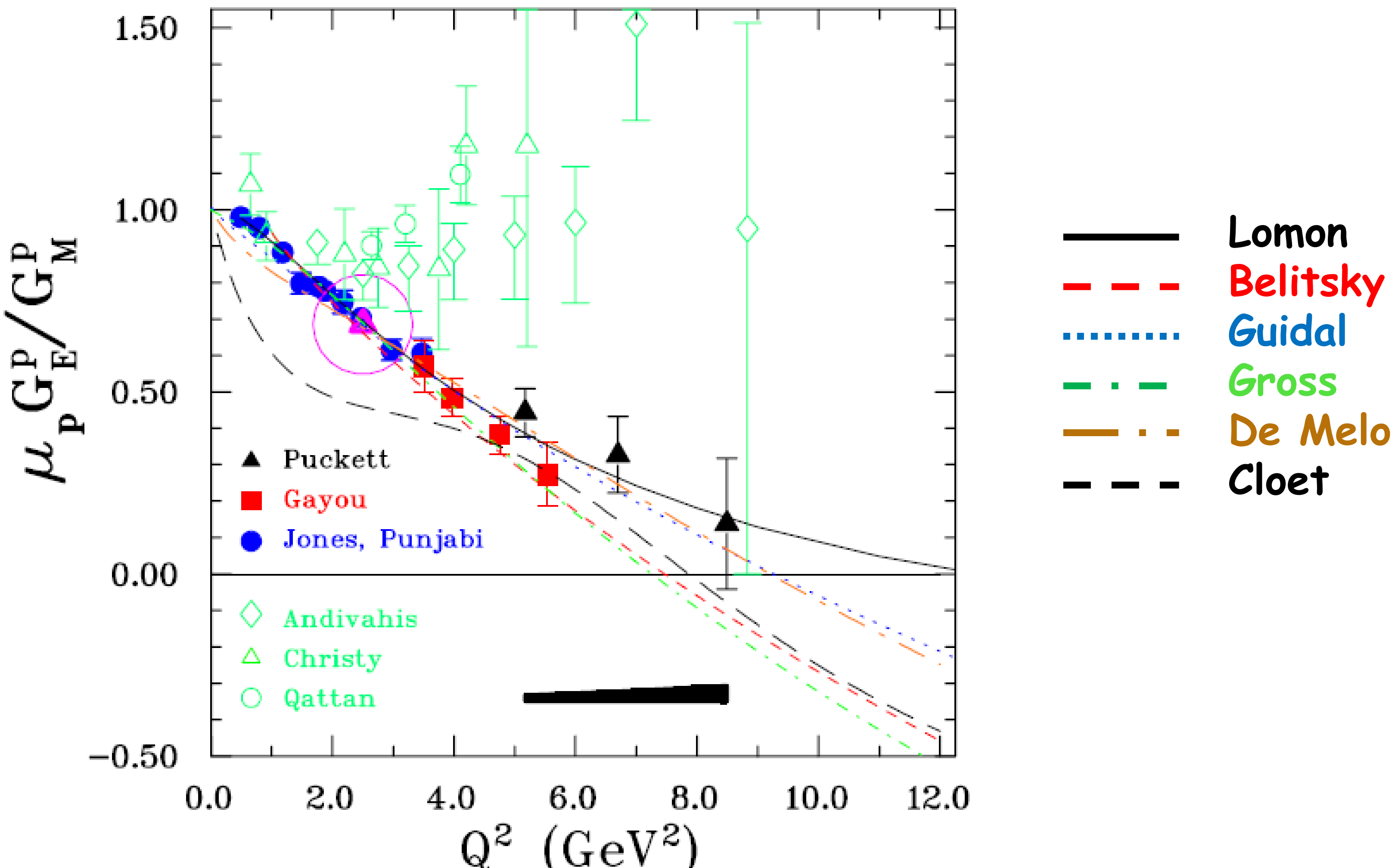
Divided by dipole FF G_D emphasizes similarity of behaviors of 3 FF:

$$G_D = \frac{1}{(1+Q^2/0.71)^2}$$



<u>That was then, now on next slide</u>.

Results of the 3 JLab G_{Ep} /G_{Mp} recoil polarization experiments, on a background of Rosenbluth data (in green)

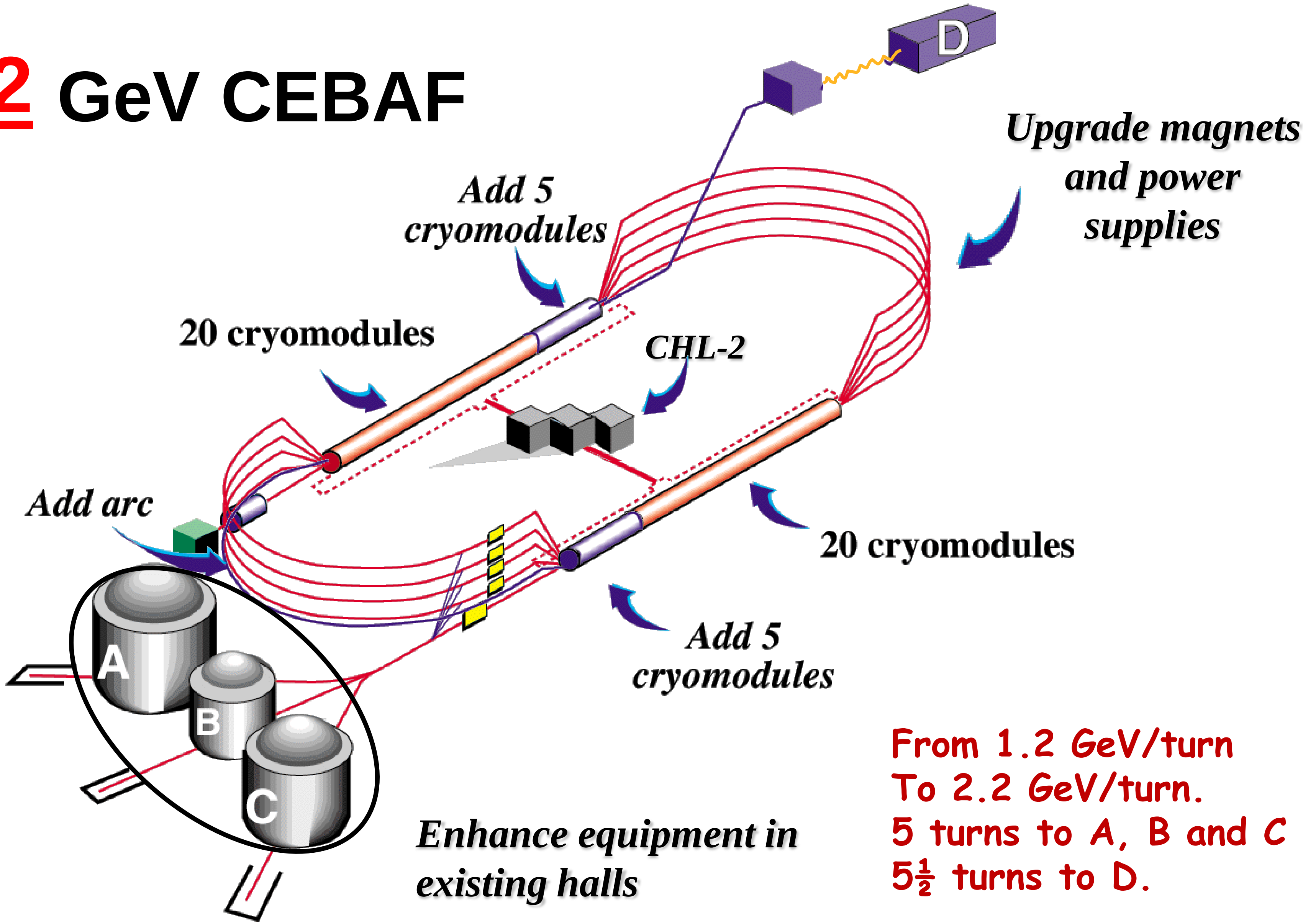


The Jlab 12 GeV upgrade project

When completed (in 2014?) will bring 12 GeV into a new experimental Hall (D),and 11 GeV in the 3 existing Halls (A, B and C). 80 μA and 85% polarization.

- Ten new superconducting radio-frequency (SRF) accelerating elements (five per Linac).
- Ten new RF stations to power the new cryomodules.
- Approximately double the refrigeration capacity.
- Modifications to the magnets in the recirculation arcs to keep the higher energy beam confined to the present beam path.
- Modifications to the extraction system to support the higher energy beams.
- A tenth arc-beamline to provide an extra pass through the North Linac.
- A new beamline connecting Hall D to the baseline accelerator.

12 GeV CEBAF



From 1.2 GeV/turn
To 2.2 GeV/turn.
5 turns to A, B and C
5½ turns to D.

Form Factors with 11 GeV beam

The higher energy of 12 GeV CEBAF will give access to higher momentum transfers in all Form Factor measurements.

One new facility to be implanted from day one will be the Super Bigbite Spectrometer (SBS) in Hall A.

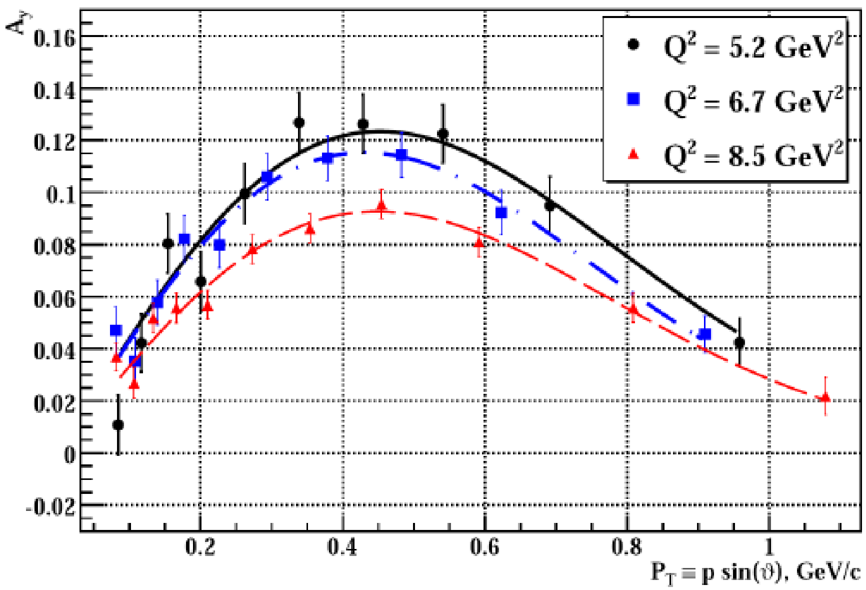
First developed for G_{Ep}/G_{Mp} measurements to 15 GeV^2; re-designed so it can be re-configurated for G_{En} and G_{Mn} exp.

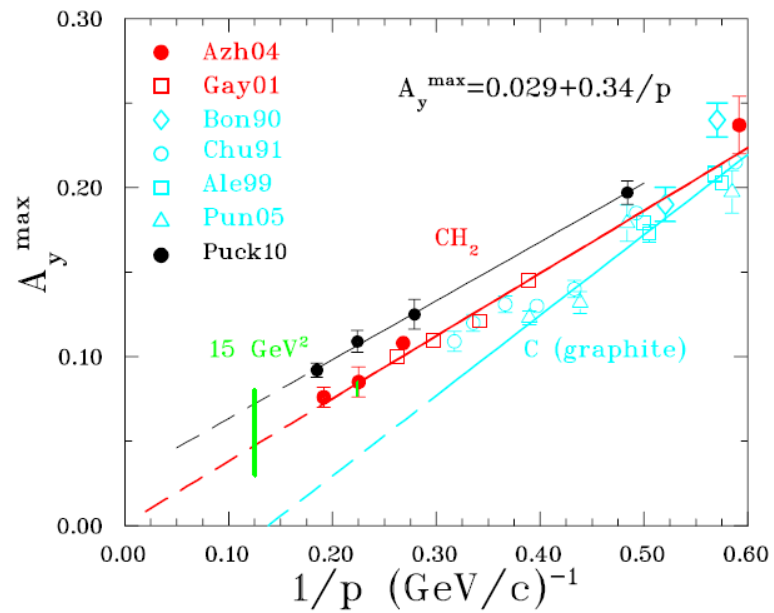
One problem facing higher Q^2 experiments is decreasing cross sections: (valid for G_{Ep}/G_{Mp} and G_{Mn}, not G_{En}):

$$
\begin{aligned}
\text{Form factor} &\propto \frac{1}{Q^4} \\
\text{Cross section} &\propto \frac{E^2}{Q^4} \times \frac{1}{Q^8} \\
\text{Figure}-\text{of}-\text{Merit} &\propto \epsilon A_y^2 \times \sigma \times \Omega \\
&\propto \frac{E^2}{Q^{16}}
\end{aligned}
$$

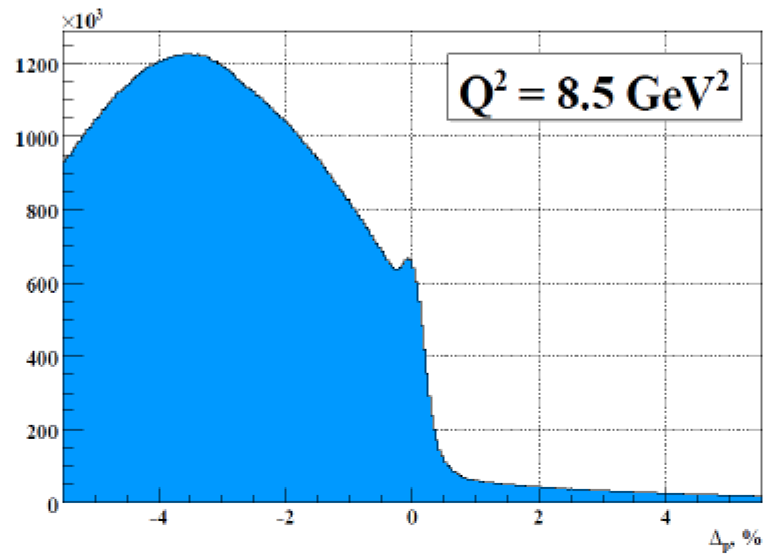
Another Problem with Recoil Polarization: A_y

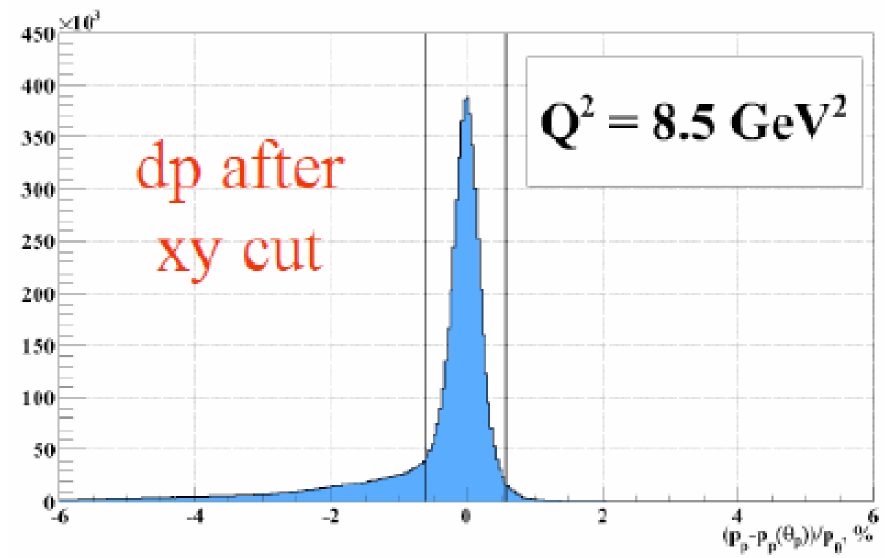
The proton analyzing power decreases with momentum.
Will measure A_y to 7.5 GeV/c in Dubna in next 12 months





Next problem is background from π^0 photoproduction…





a) Mostly π^0 photoproduction from photons radiated in target, near max. energy (i.e. ~ beam energy); decay into two γ's detected in the electromagnetic calorimeter
Kinematics nearly undistinguishable from elastic ep.

b) Compton scattering of radiative photon from target; negligible at these kinematics.

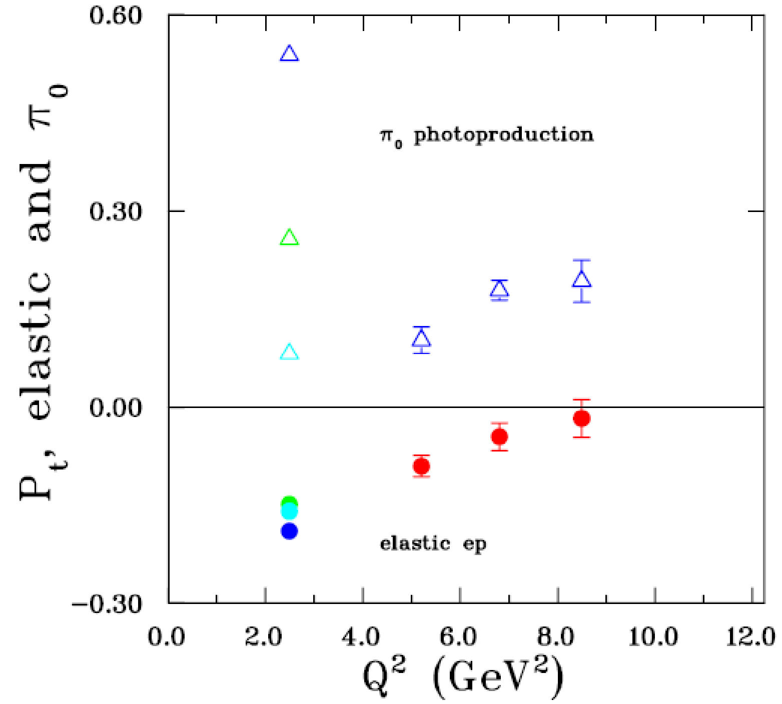
irreducible residual background @ 8.5 GeV^2 in Gep(III): 5.6%

…and the background protons have opposite transverse polarization

$$P_t = -\sqrt{2(1-\varepsilon)/\tau}\,\frac{r}{1+\frac{\varepsilon}{\tau}r^2}$$

$$\varepsilon = 1 + 2(1+\tau)\tan^2\frac{\theta_e}{2} \qquad r = \frac{G_{Ep}}{G_{Mp}}$$

$$\frac{G_{Ep}}{G_{Mp}} = -\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}}\,\frac{P_t}{P_\ell}$$



Pt versus Q^2 for elastic ep and photo-produced π^0

from Wei Luo, Lanzhou U.

New Concept for New Experiments

Classically: permanent magnetic spectrometers at Jlab Hall *A* and *C* have solid angle of 5-7 mr, used to detect recoil proton, equipped with a polarimeter (FPP).
The electron can then be detected in an calorimeter with solid angle defined by the Jacobian of the 2-body *ep* kinematics.
In GEp(III) the solid angle of the calorimeter for 8.5 GeV^2 had to be ~140 mr.

The new way: to go beyond 10 GeV^2 one has to increase the solid angle of the proton detector; spectrometers no longer appropriate. May be at the cost of angular/momentum resolution.
Use of GEM technology to improve angular resolution, compensate for loss of momentum resolution and handle much higher rates

WHY? (and WHAT?)

G_{Ep}/G_{Mp} should be measured to as high a Q^2 as possible.
and so should G_{En} and G_{Mn} (and G_{Mp} should be remeasured)

Why?

Having all 4 form factors characterized to similarily large Q^2 will

a) Constrain GPD's and help build the tomographic mapping of the nucleon.

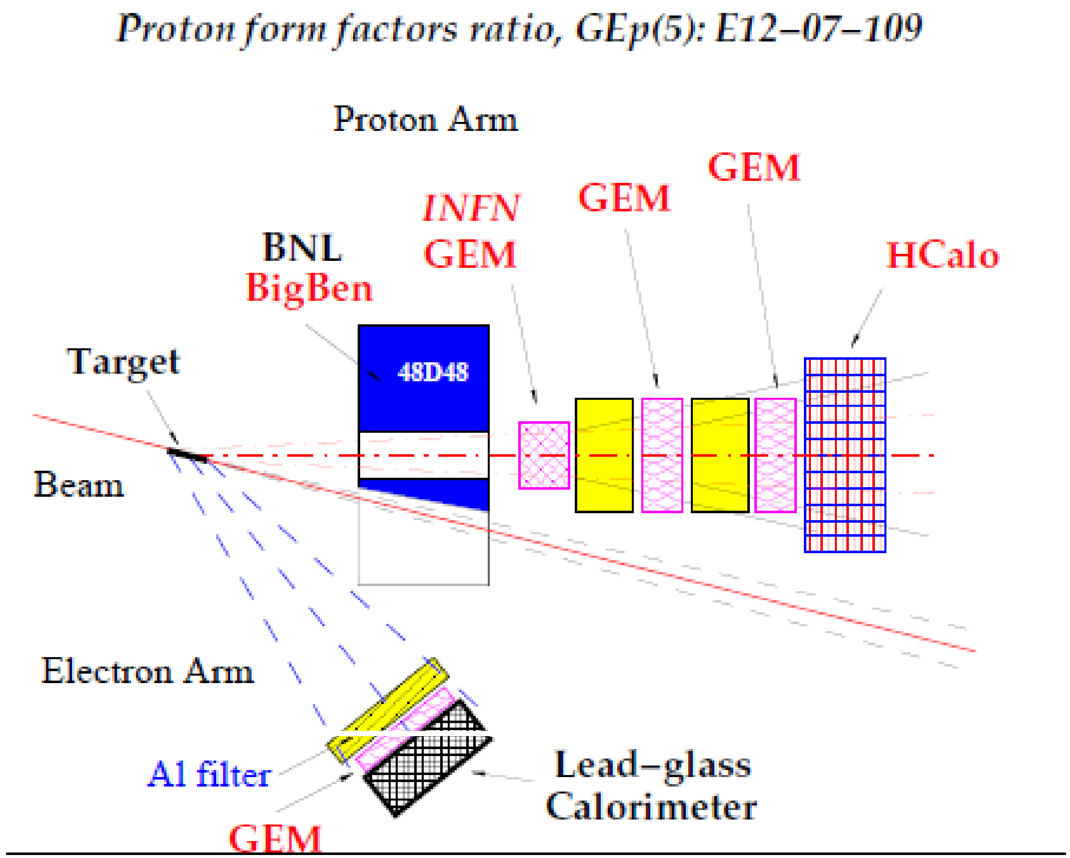
b) Make flavor decomposition of the FF possible as the photon-quark interaction becomes harder and more localized.

c) Reduce the present number of models of the nucleon to a few, and get us closer to a QCD based understanding of the nucleon structure

d) Be a response to the NSAC/DOE goals set to justify the upgrade of JLab to 12 GeV

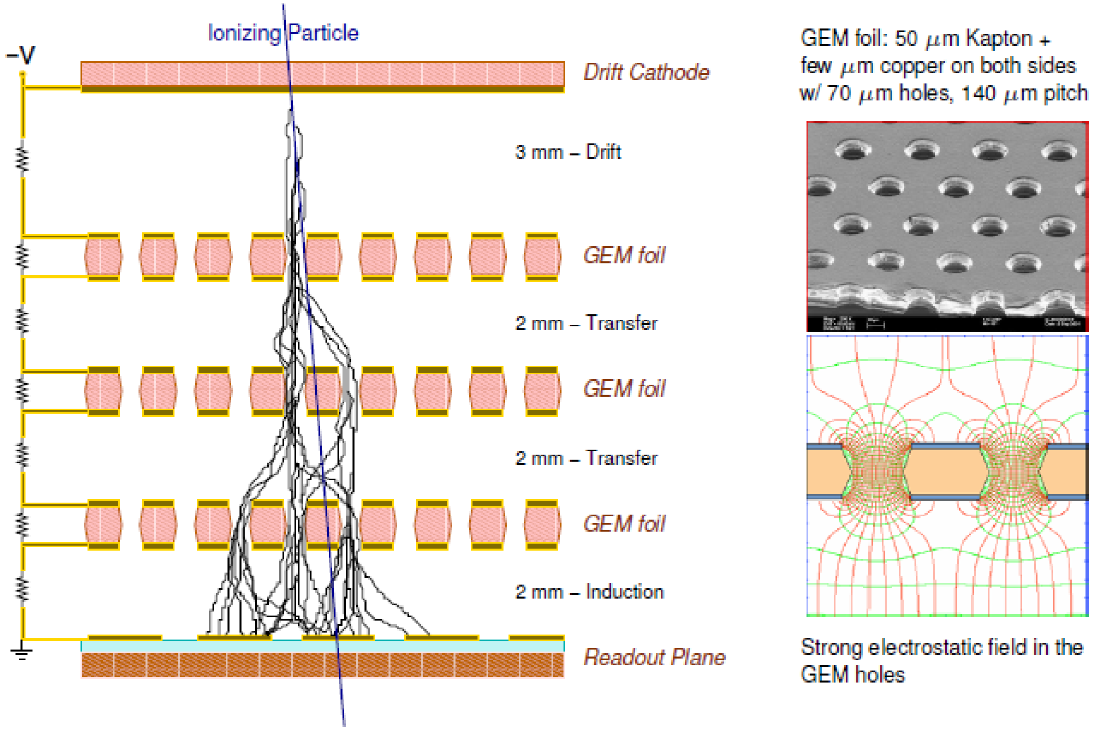
e) JLab 12 GeV will be (for the forseeable future) the only laboratory where space-like form factors can be measured to Q^2 equal or larger than 10 GeV^2.

The solution: the SBS in Hall A, Gep(V)



Gas Electron Multipliers

Increasing solid angle means using a single dipole, no quadrupole, and detectors in full view of the target.
Cannot be done with drift chambers, use GEMs (Gas Electron Multiplier), invented by F. Sauli at CERN 15 years ago.



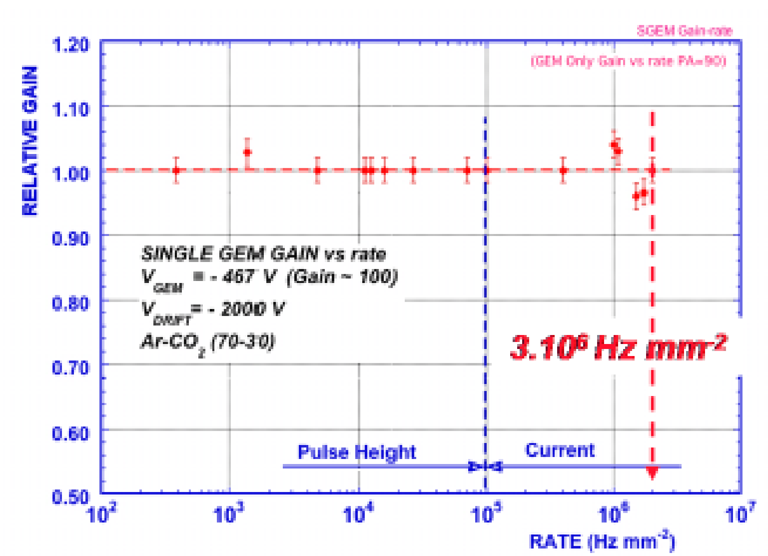
Recent technology: F. Sauli, Nucl. Instrum. Methods A386 (1997) 531.

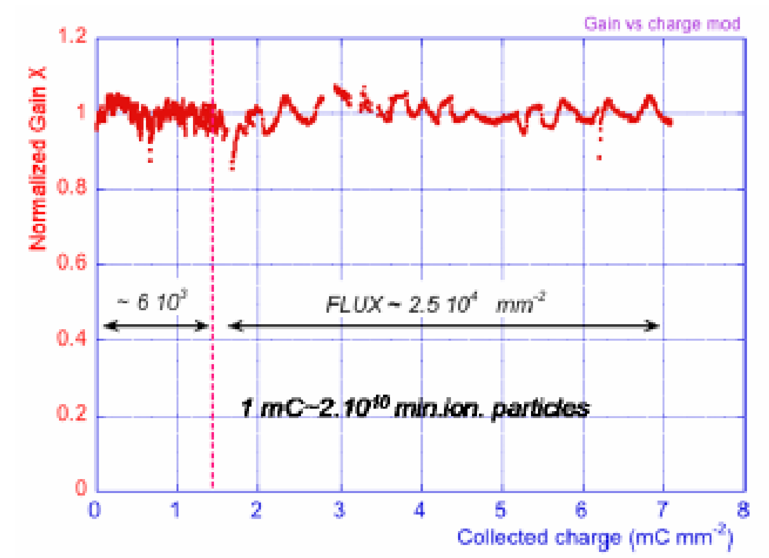
Readout independent from ionization and multiplication stages.

GEM performances

About 12 GEM detectors have been in use at CERN in the COMPASS experiment since 2001.

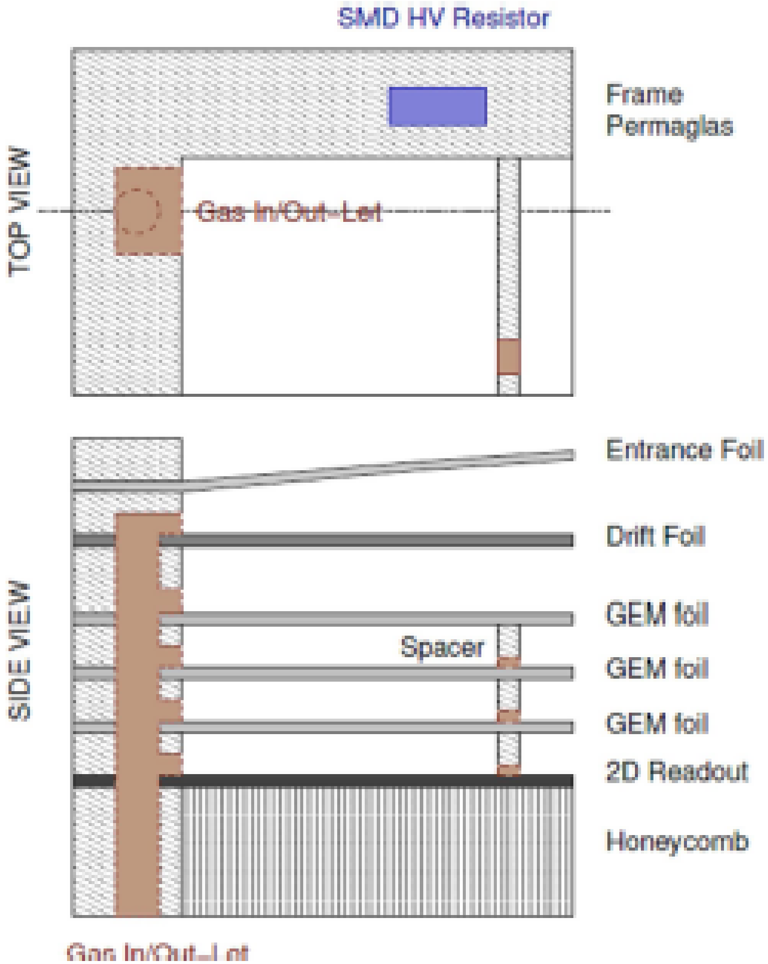
The rate capability and long term stability are excellent.
Size required for Gep(V): 40 cm by 50 cm; technology available.





- No gain loss up to ~ 300 MHz/cm^2.
- No visible aging detected as a function of integrated charge. 2000 C on 40x40 cm2

Material Budget



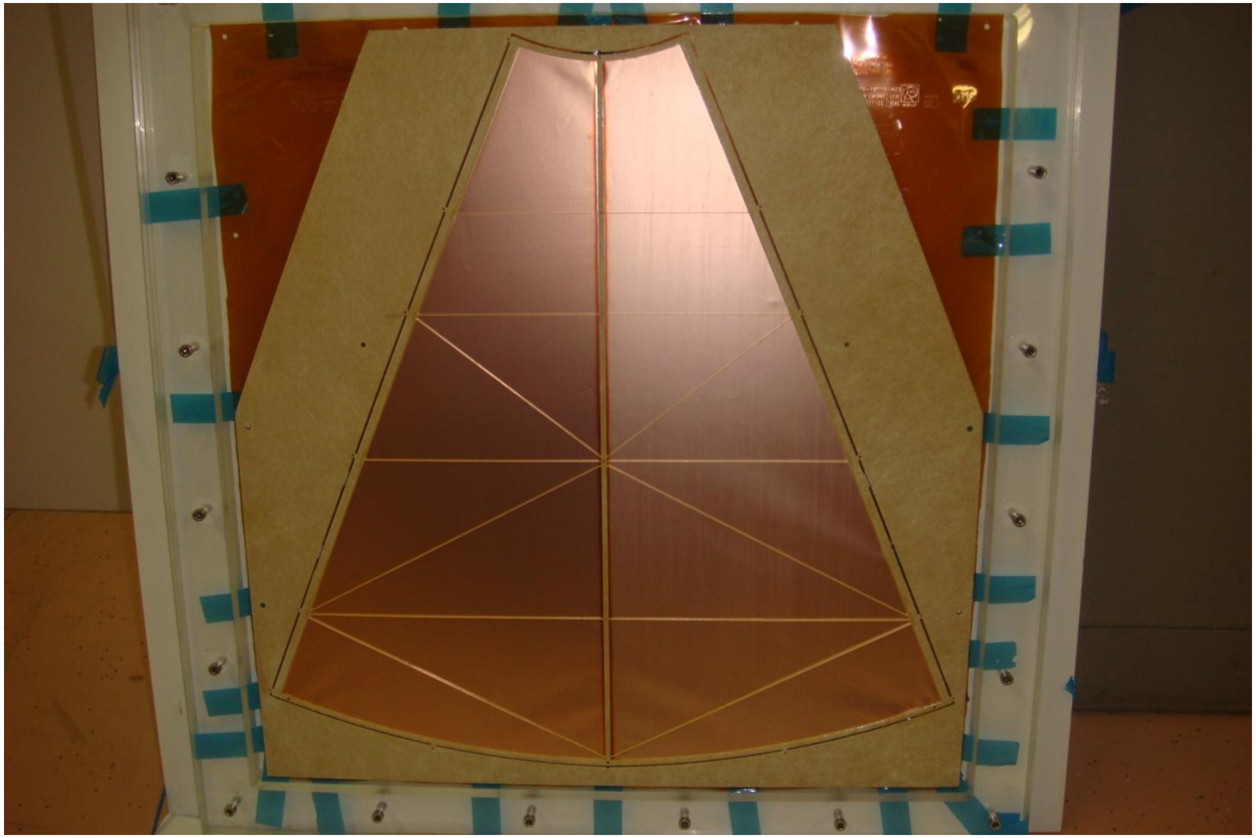
Based on the COMPASS GEM
- single honeycomb
- smaller copper thickness

	Quantity	Thickness µm	Density g/cm3	X0 mm	Area Fraction	X0 %	S-Density g/cm2
Window							
Mylar	1	10	1.39	287	1	0.0035	0.0014
Drift							
Copper	1	3	8.96	14.3	1	0.0210	0.0027
Kapton	1	50	1.42	286	1	0.0175	0.0071
GEM Foil							
Copper	6	3	8.96	14.3	0.8	0.1007	0.0129
Kapton	3	50	1.42	286	0.8	0.0420	0.0170
Grid Spacer							
G10	3	2000	1.7	194	0.008	0.0247	0.0082
Readout							
Copper-80	1	3	8.96	14.3	0.2	0.0042	0.0005
Copper-350	1	3	8.96	14.3	0.75	0.0157	0.0020
Kapton	1	30	1.42	286	0.2	0.0021	0.0009
G10	1	120	1.7	194	1	0.0619	0.0204
NoFlu glue	1	60	1.5	200	1	0.0300	0.0090
Honeycomb							
Nomex	1	6000	1	13125	1	0.0457	0.6000
G10	2	120	1.7	194	1	0.1237	0.0408
Gas							
(CO2)	1	9000	1.84E-03	18310	1	0.0492	0.0017
					Total	**0.542**	**0.725**

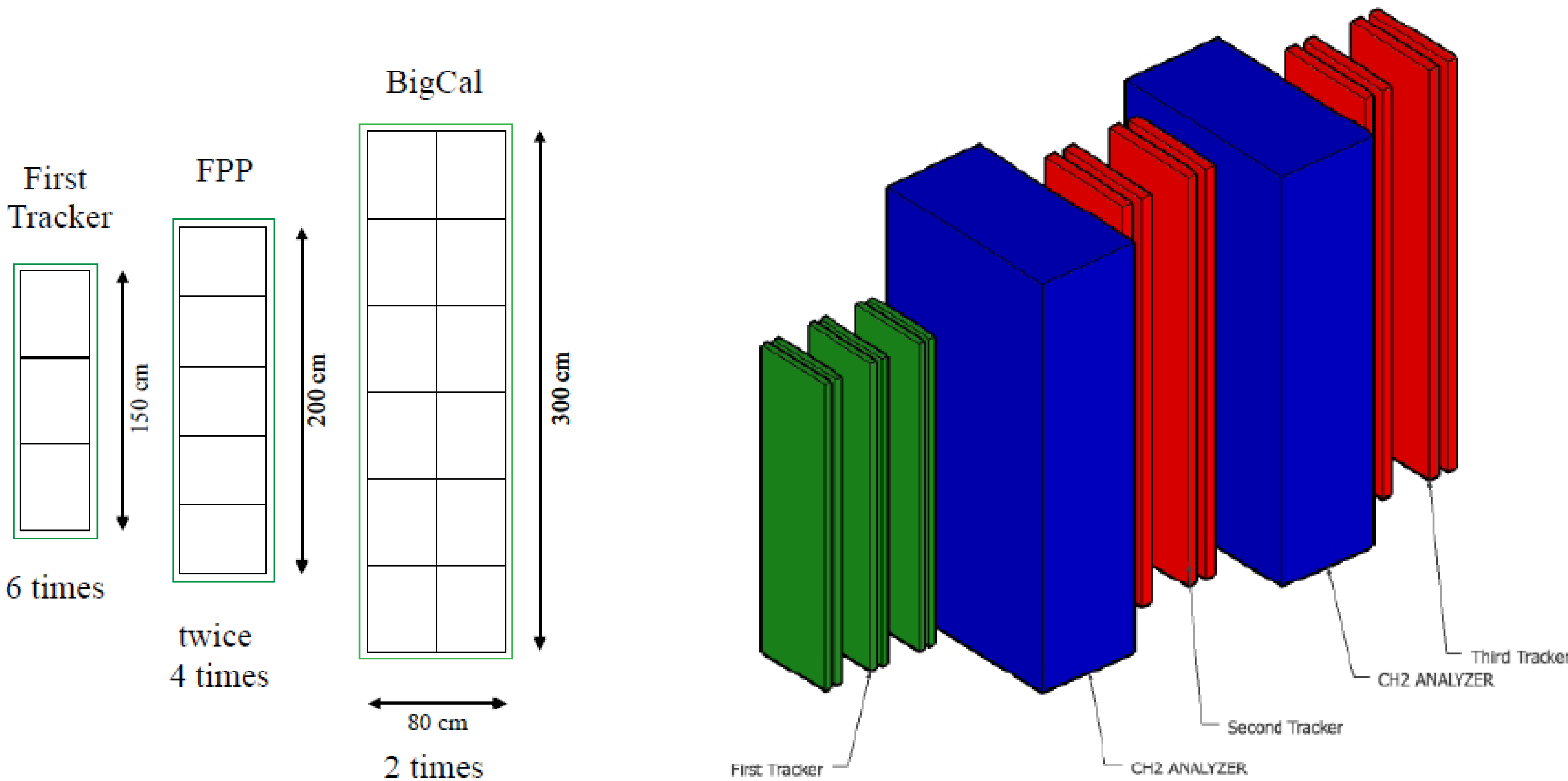
Minimise material to reduce background and multiple scattering

Manufacture of GEMs at CERN

Frames made of polyglass, allowing 10 μm machining accuracy.
Note sectoring to keep capacity of sectors small, and reduce discharge energy.
Note thinness of frame with cross section 8 mm x 2 mm thick.

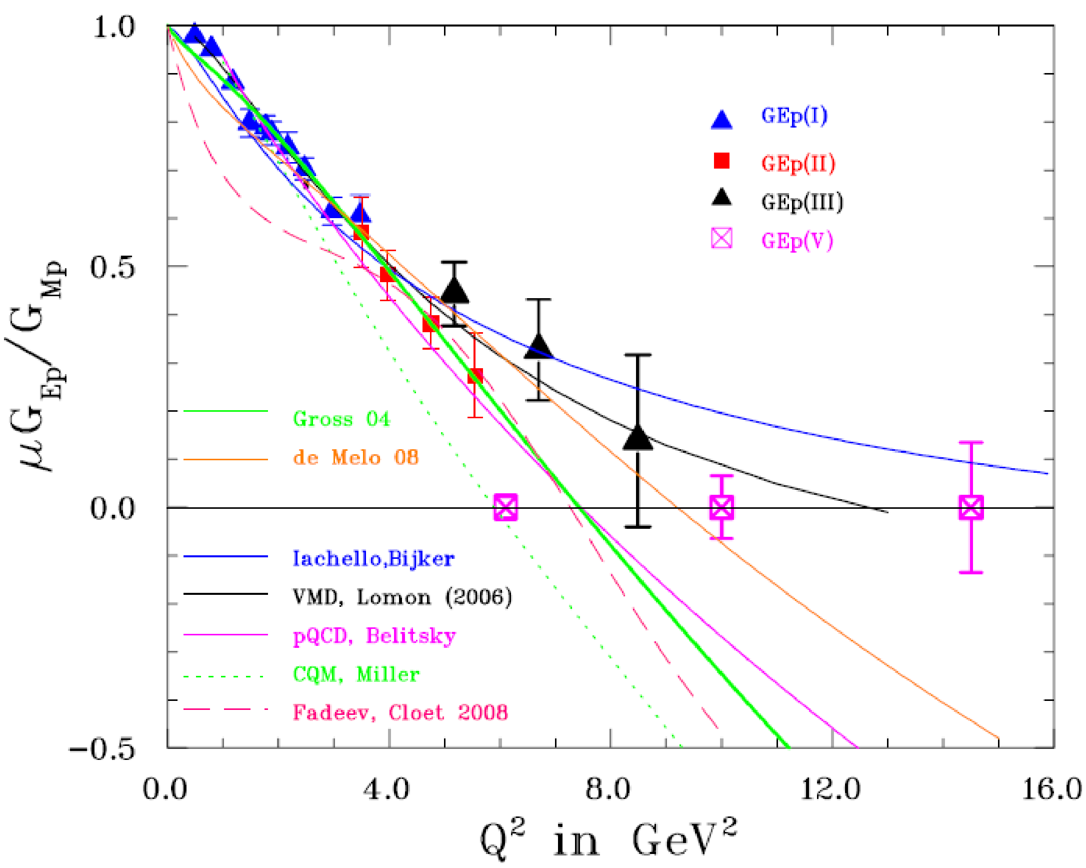


TOTEM 1 Upgrade prototype

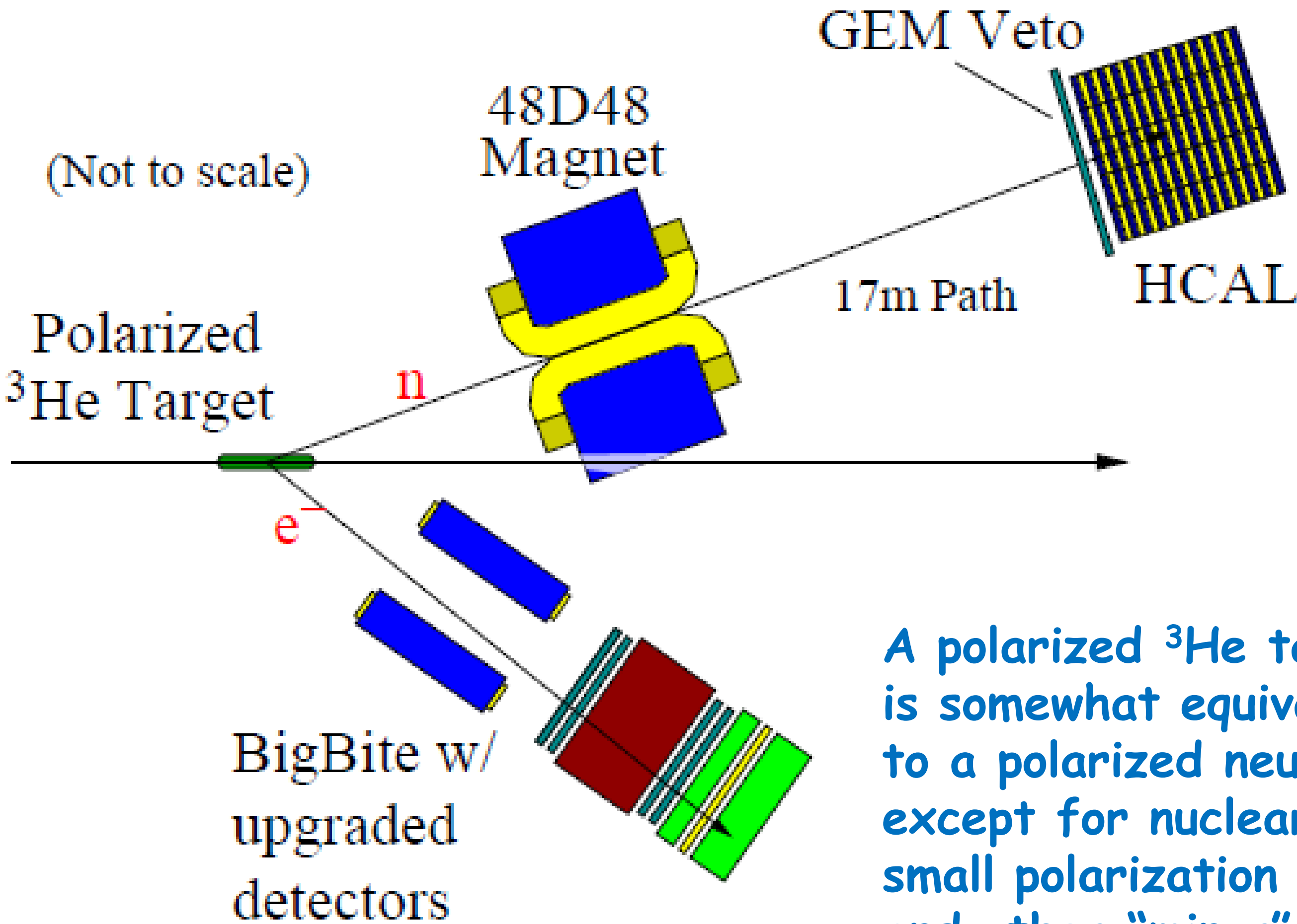


First Tracker
FPP
BigCal
150 cm
200 cm
300 cm
80 cm
6 times
twice
4 times
2 times
First Tracker
CH2 ANALYZER
Second Tracker
CH2 ANALYZER
Third Tracker

Anticipated statistical uncertainties from original GEp(5) proposal with 60 days of beam. Actual time may be shorter, currently not defined; statistical uncert. larger!

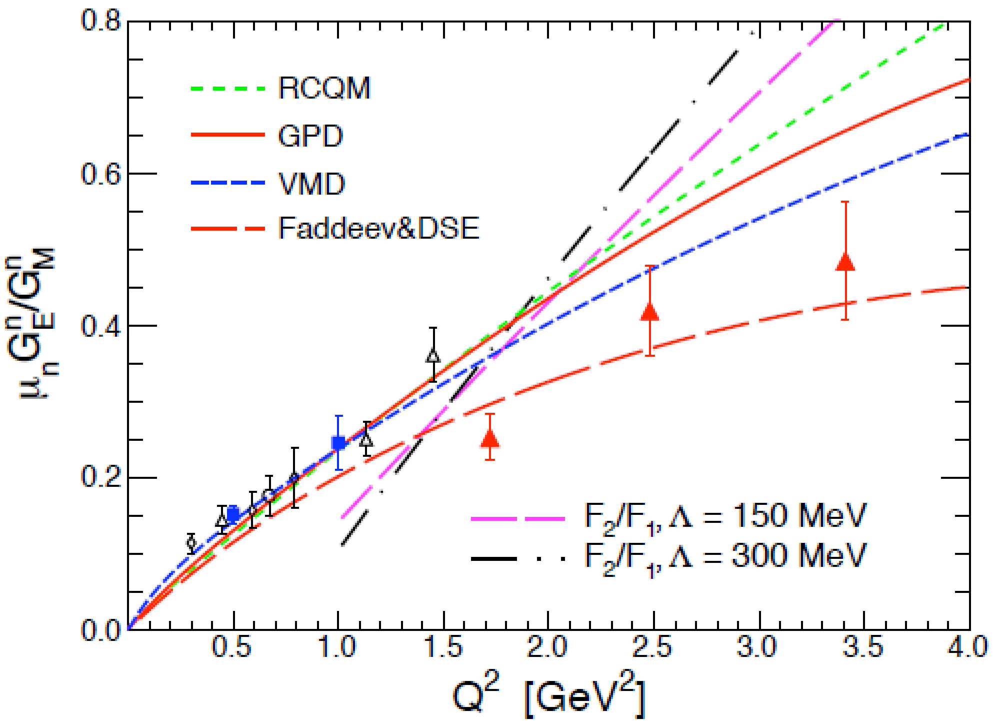


Setup for G_{En}/G_{Mn}, approved for Q^2=5, 6.8 and 10.2 GeV^2

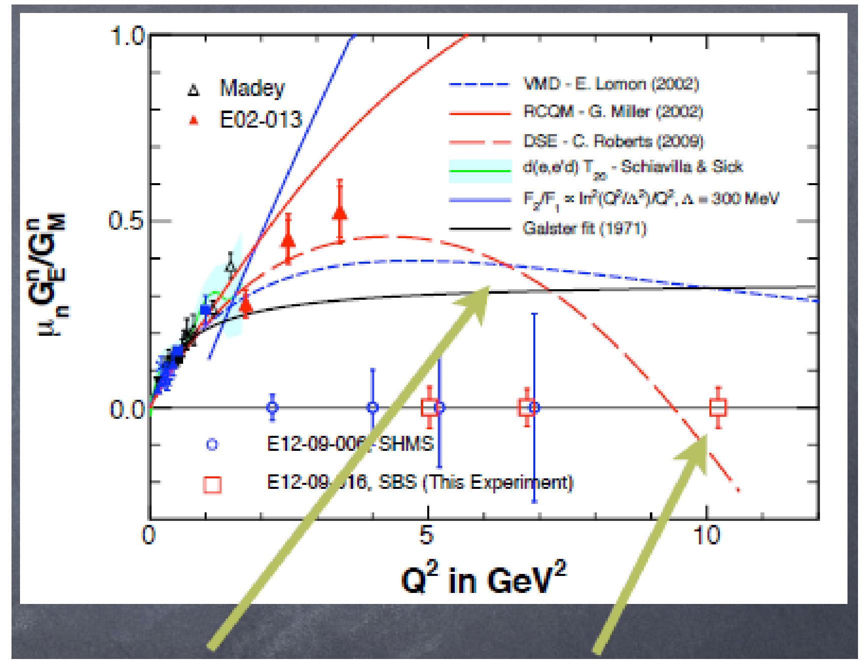


A polarized ^{3}He target is somewhat equivalent to a polarized neutron target, except for nuclear corrections, small polarization of protons and other "minor" problems.

Current and projected situation for the neutron electric form factor



Red filled triangles: GEn(I) data to be published.

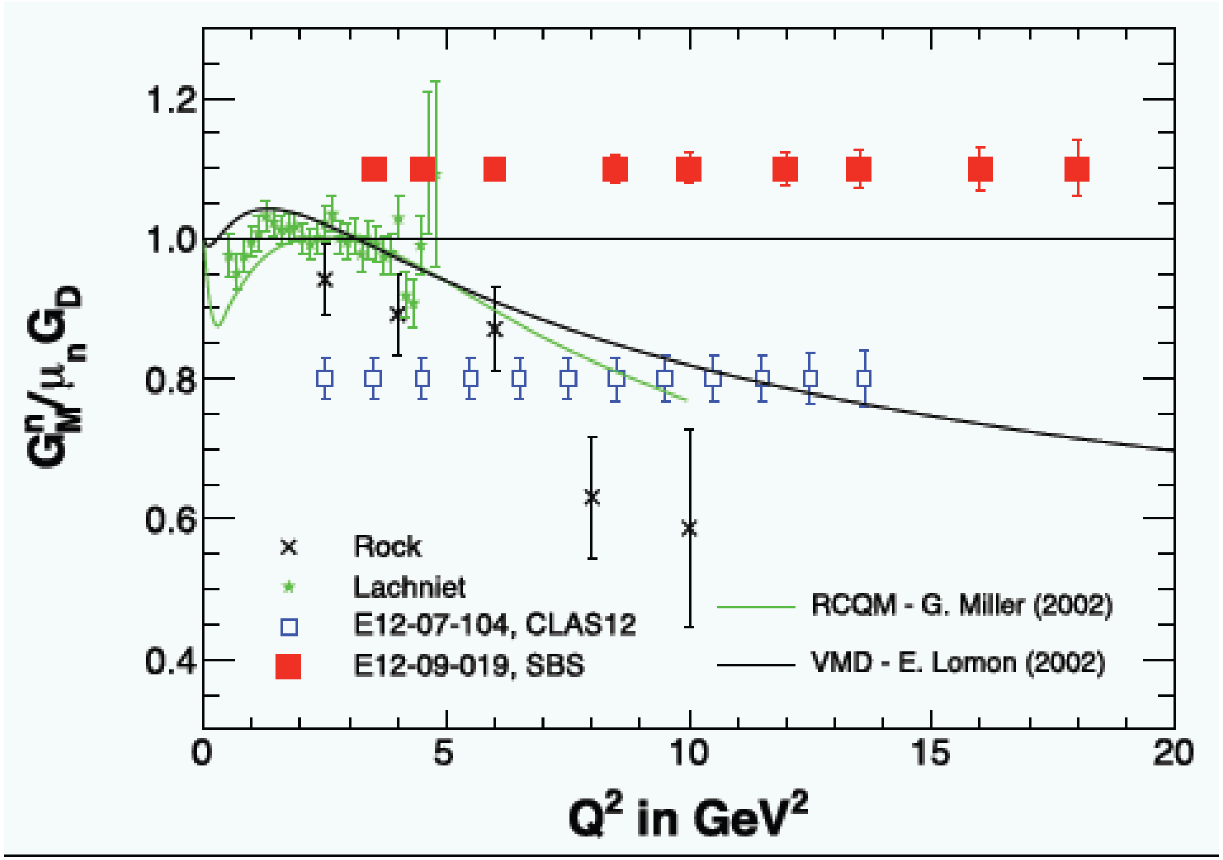


Arrows illustrating the point that one needs to go to 10 GeV² to distinguish between various models. Fadeev, Dyson-Schwinger, Cloet et al

The two approved GMn experiments

In Hall A with the SBS, in Hall C with CLAS12

G_{Mn} by the ratio of the quasi elastic d(e,e'n) to d(e,e'p)the cross sections method, and to Q^2 values of 18 GeV^2.



Other experiments of interest

Re-measure G_{Mp} with high precision cross section, to update old SLAC (Andivahis) data, to 18 GeV^2 in Hall A (Gilad).

Measure G_{En} by recoil polarization (as Madey did up to 1.5 GeV^2 in 2001) in Hall C to 7 GeV^2 (Semenov).

Measure G_{Ep}/G_{Mp} in Hall C (GEp(IV)) with a magnetic spectrometer and an electromagnetic calorimeter, to check the systematical uncertainties of the SBS experiment, to 11-12 GeV^2, Brash et al.

A_{1n} with SBS approved at PAC 34 (Aug. 2010)

Possible use of pol. NH_3 target for GEp/GMp (under discussion).

GEp(V) and SBS collaboration

Core group: INFN(Italy), Jlab, UVa, WM and NSU

Other participants: CMU, JINR(Dubna),Protvino, Rutgers, Glasgow(UK), UNH, U. St. Mary (Canada), MIT

The front set of 6 chambers is being built at INFN.
The GEM detectors for polarimeters 1 and 2 and for the EM calorimeter will be built at U. of Virginia
The electronics will be assembled and tested at Norfolk State U.
The GEMs for the EM calorimeter assembled at William and Mary
The hadron calorimeter at Dubna and CMU
The trigger electronics at Rutgers and New Hampshire (UNH)
The 120 cm x 120 cm dipole and 40 cm LH2 target at Jlab, coil modification, vacuum vessel, cut in dipole iron for beam, support.

Conclusions

I hope to have convinced you that there is a definite and ambitious program to continue form factor measurements to the highest possible Q^2 at Jlab after the 12 GeV upgrade. And strong physics motivation to do so.

The Form Factor program at Jlab involves many Universities.
It includes two Russian Laboratories:
JINR for a new hadron calorimeter (Igor Savin)
and Protvino for the electromagnetic calorimeter (A. Vasiliev).
LHP Dubna is committed to analyzing power calibration
with the Nuclotron (N. Piskunov).

Thanks you for you attention and patience.