Nucleon Form Factors

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Jefferson Lab

Proton and Neutron FFs in space-like domain (focus on new development)

EINN-2007

Milos

September 12-15, 2007

Outline

- Introduction - EM FFs,
    - » New parameterizations
- Recent experimental results -
    - » low Q^2
    - » high Q^2
- Theory links observations and ideas -
    - » Charge density
    - » GPDs fit from FFs
- Experimental outlook - GEP-III, …, 12 GeV

- Summary

Reviews and Analysis

Reviews

Ch. Hyde-Wright and C. de Jager, Ann. Rev. Nucl. Part.Sci. 54, 217 (2004)
H. Gao, Int. J. Mod. Phys A20, 1595 (2005)
Ch. Perdrisat, V. Punjabi, and M. Vanderhaeghen, hep-ph/06012014
J. Arrington, C.D. Roberts, and J.M. Zanotti, nucl-th/0611050

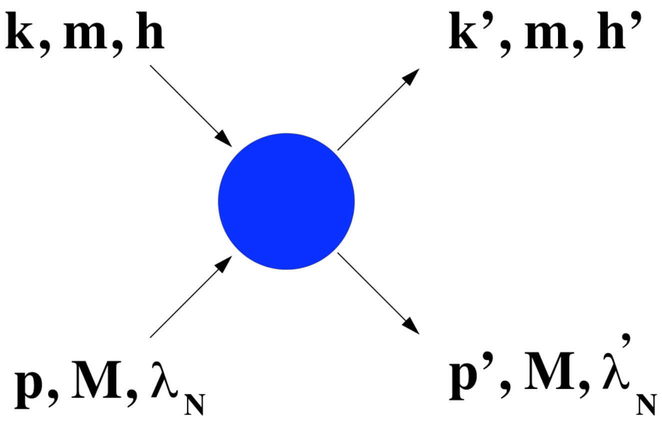
Parameterizations

P. Bosted, PRC 64, 409 (1995) - Fit of pre-JLab data
E. Brash et al. PRC 65, 051001(R) 2002 - Fit with JLab GEP/GMP
J.J. Kelly, PRC 66, 065203 (2002) - Breit frame densities
BABB, arXiv:hep-ex 0708.1946 - Fit with local duality constraints
J. Arrington, W.Melnitchouk, J.A.Tjon, nucl-ex/0707.1861 - 2-gamma

GPD

M.Diehl et al., Eur.Phys.J. C39 (2005) 1-39, GPDs from FFs data
M.Guidal et al., PRD 72, 054013 (2005) , FFs from GPDs

Lepton-Nucleon scattering



$$l(k,h) + N(p,\lambda_N) \rightarrow l(k',h') + N(p'\lambda'_N)$$

h, h', λ_N, and λ'_N are helicities

$$P = \frac{p+p'}{2},\ K = \frac{k+k'}{2},\ q = k - k' = p' - p$$

$$s = (p+k)^2,\ t = q^2 = -Q^2,\ u = (p-k')^2$$

$$T^{h',h}_{\lambda'_N,\lambda_N} \equiv \langle k',h';p',\lambda'_N \big| T \left| k,h;p,\lambda_N \right\rangle$$

Total 16 amplitudes.
Parity invariance ⟶ number of independent helicity amplitudes from 16 to 8.
Time reversal invariance ⟶ to 6.
When neglect the lepton mass ⟶ to 3.

Three complex amplitudes

$$T^{+,+}_{+,+}\ ;\quad T^{+,+}_{-,-}\ ;\quad T^{+,+}_{-,+} = T^{+,+}_{+,-}$$
which are functions of $(s-u)$ and t.

Electro-Magnetic Form Factors

One-photon approximation, $\alpha_{em} = 1/137$, hadron current

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

Rosenbluth (1950)

Full expression for M has three complex functions, F_1, F_2, F_3

Guichon & Vanderhaeghen

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

Afanasev et al.

Blunden et al.

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

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

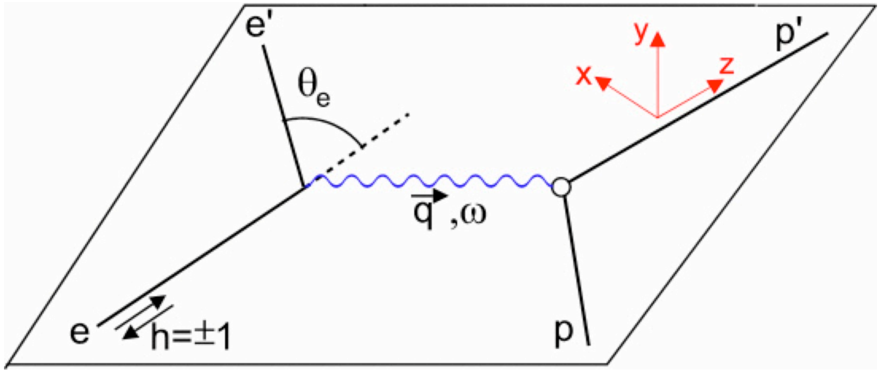
$$d\sigma = d\sigma_{NS}\left\{\varepsilon\left(\tilde{G}_E + \frac{s-u}{4M^2}\tilde{F}_3\right)^2 + \tau\left(\tilde{G}_M + \varepsilon\frac{s-u}{4M^2}\tilde{F}_3\right)^2\right\}$$

old $G_{E,M}$ are real functions of $t=-Q^2$

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

Extra terms contribute less than few % to σ_R

Double Polarized Observables



$$P_x = -2\sqrt{\tau(\tau+1)}\,G^p_E G^p_M \tan\frac{\theta_{e'}}{2}/I_0$$

$$P_z = \frac{E_e+E_{e'}}{M_p}\sqrt{\tau(\tau+1)}\,(G^p_M)^2\tan^2\frac{\theta_{e'}}{2}/I_0$$

$$I_0 \propto \epsilon(G^p_E)^2 + \tau(G^p_M)^2$$

$$\boxed{\frac{G^p_E}{G^p_M}\Big|_{1-\gamma} = -\frac{P_x}{P_z}\frac{E_e+E_{e'}}{2M_p}\tan(\theta_e/2)}$$

$$\mu\frac{G^p_E}{G^p_M}\Big|_{1,2-\gamma} = \mu\frac{G^p_E}{G^p_M}\Big|_{1-\gamma} + \delta$$

Similar result for polarized target case

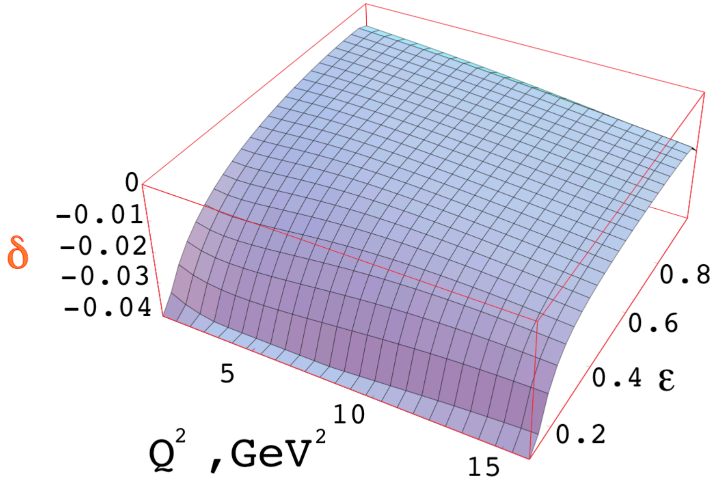
$$N(\vec{e}, e'\vec{N})$$

Akhiezer et al., (1958)

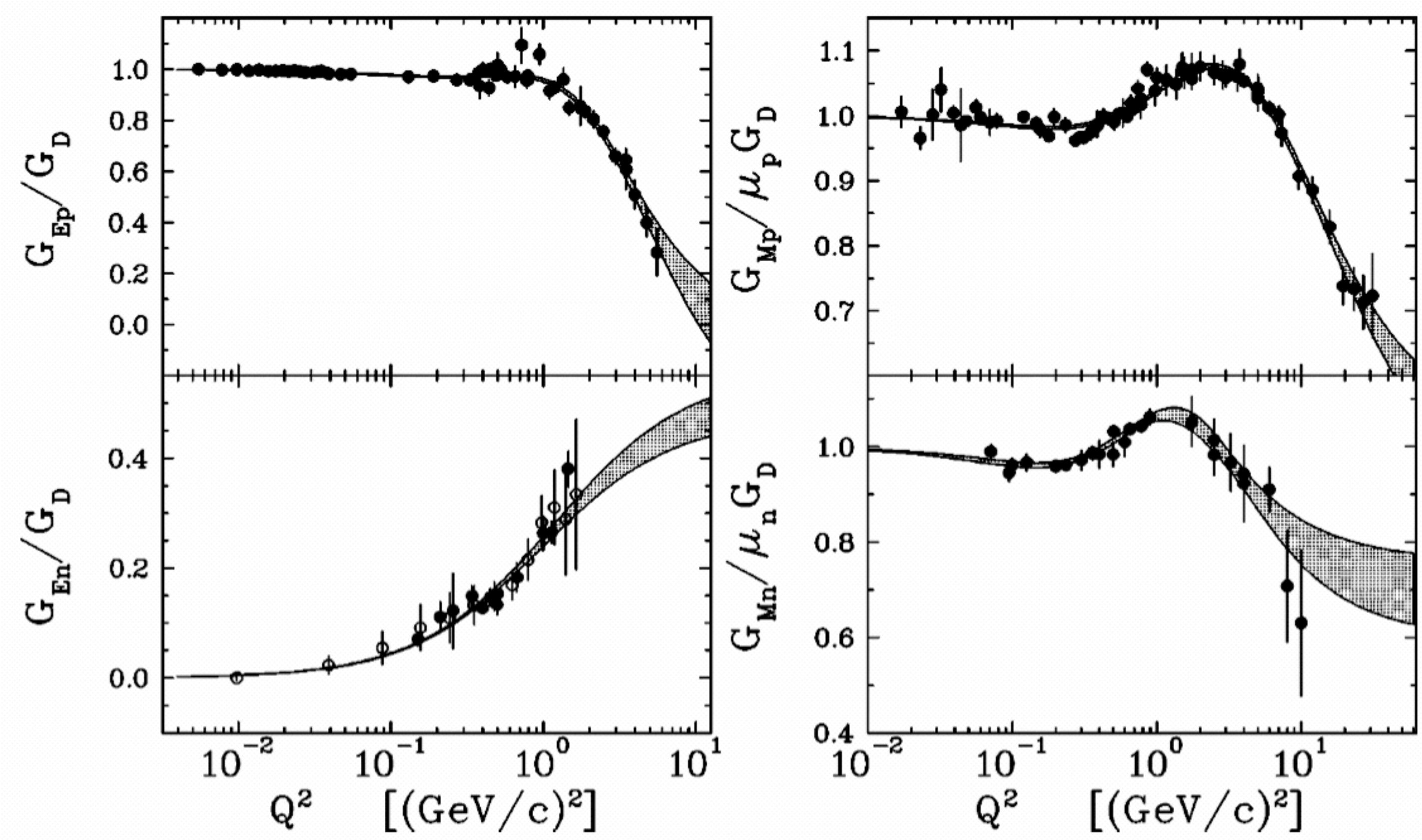
Arnold et al., (1981)

Guichon &
Vanderhaeghen (2003)

Two-photon correction, $\delta \sim 0.02$
at typical values $\varepsilon = 0.3$ –:–0.8



Kelly's Parameterization

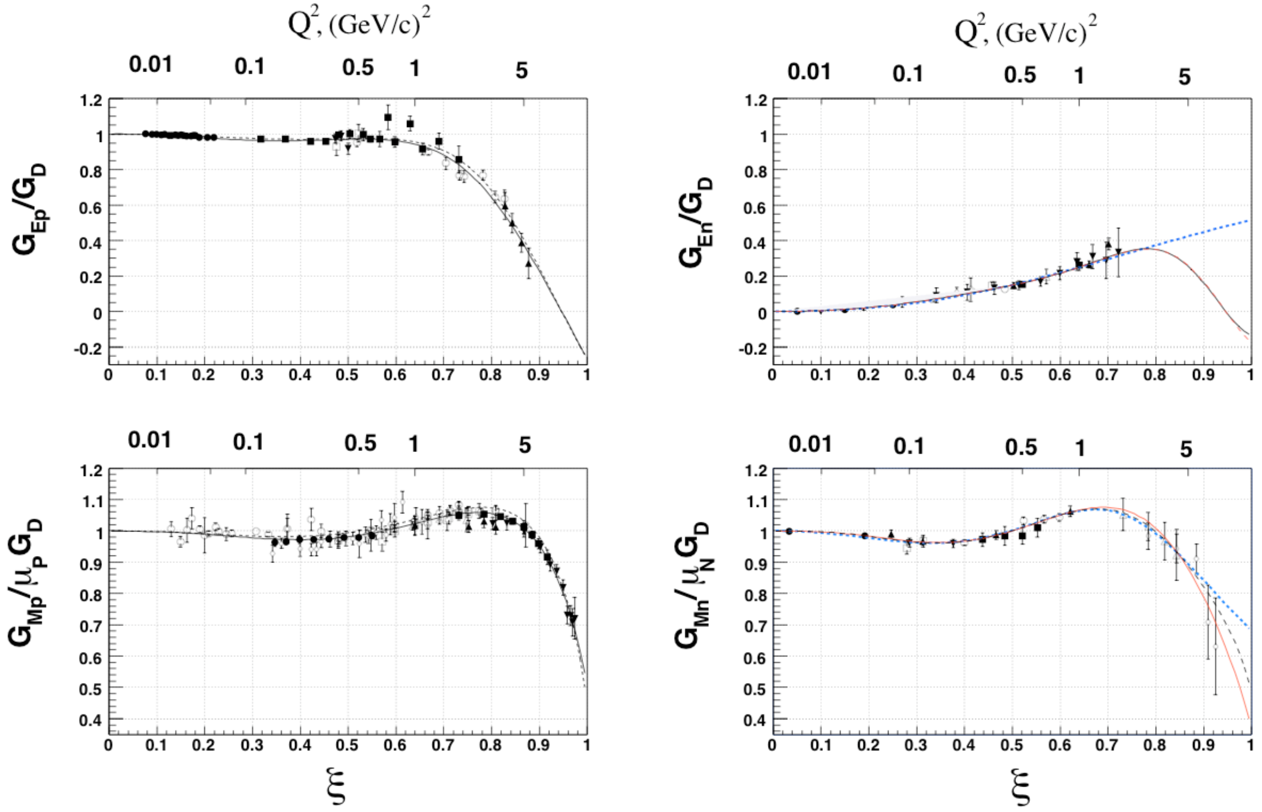


J. Kelly,
PRC 70,
068202
(2004)

$$G\left(Q^2\right) = \sum_{k=0}^{n=1} a_k \tau^k / (1 + \sum_{k=1}^{n+2=3} b_k \tau^k)$$

$$\text{scaling constraint: } Q \to \infty,\ G \sim Q^{-4}$$

Duality constrained parameterization



Bodek,
Avvakumov,
Bradford, Budd
arXiv:hep-ex
0708.1946

ξ is Nachtman scaling variable

Two constraints
QCD motivated

Kelly's

(d/u) = 0, 0.2

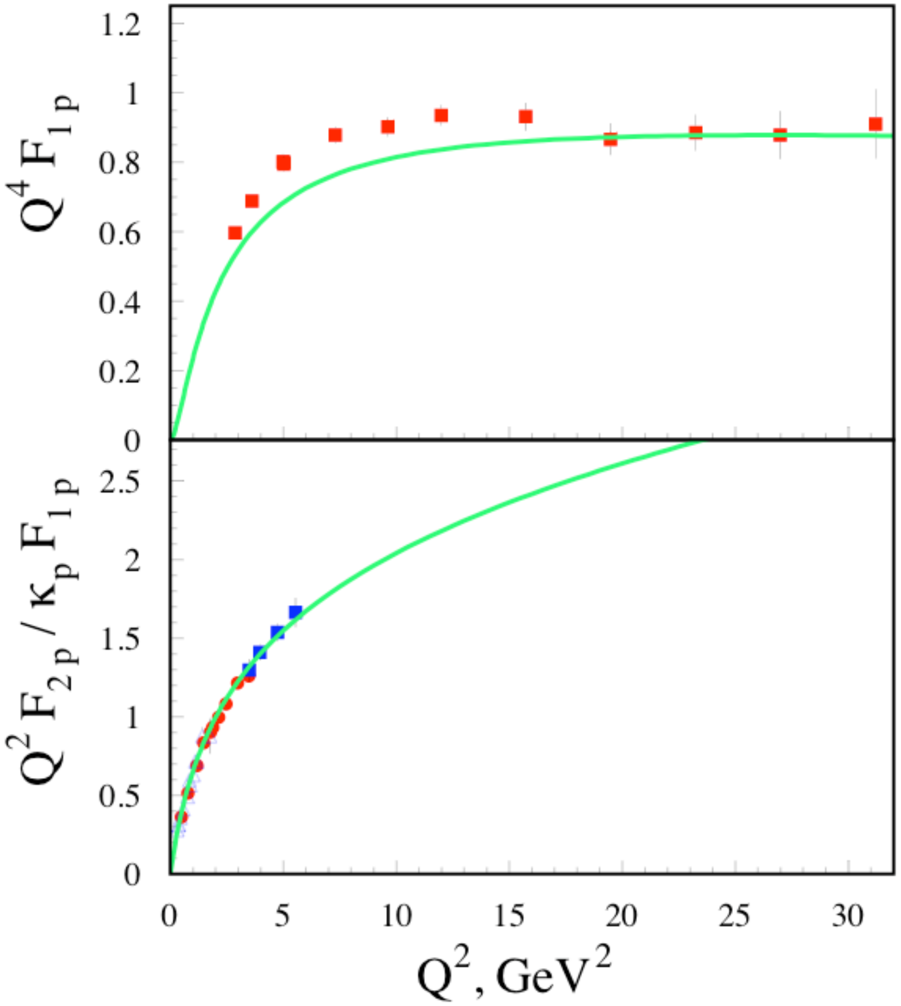
$$\xi^{p,n} = 2/(1+\sqrt{1+\tau_{p,n}^{-1}})$$

constrains: at $\xi \rightarrow 1$

$$G_{BABB} = A(\xi) \times G_{Kelly}(Q^2)$$

1) $\frac{G^2_{Mn}}{G^2_{Mp}} = \frac{1+4(d/u)}{4+(d/u)}$ 2) $\frac{G^2_{En}}{G^2_{Mn}} = \frac{G^2_{Ep}}{G^2_{Mp}}$

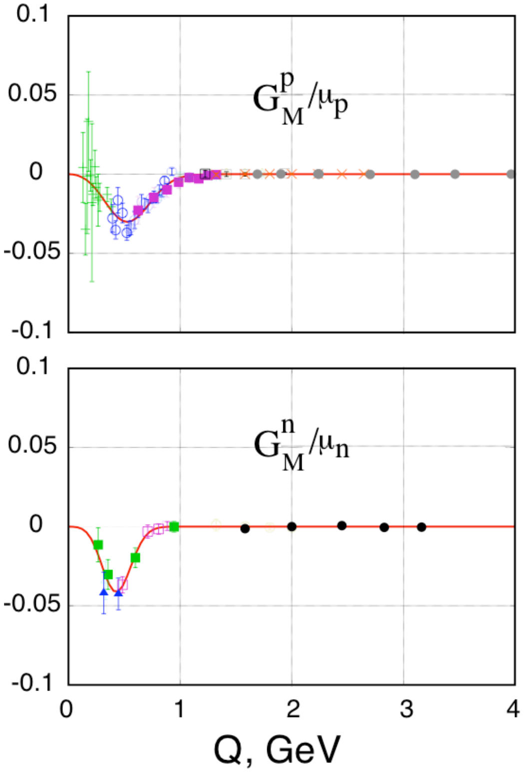
FFs from GPDs

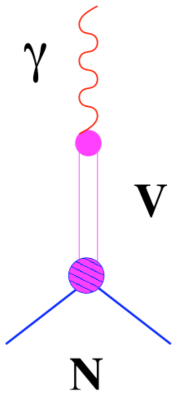


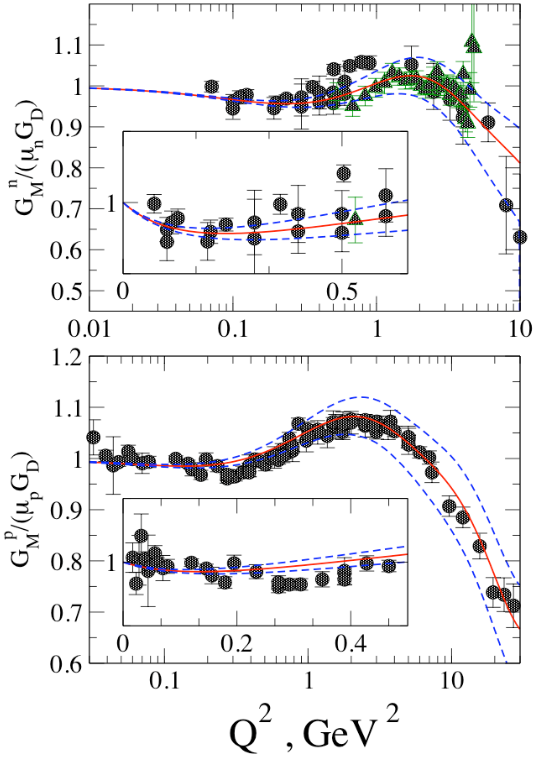
Guidal et al.,
PRD 72, 054013,
(2005)

FFs from GPDs and test of the scaling behavior of the proton FFs

Form Factors at low Q^2







Friedrich&Walcher, EPJ (2003) have found a bump in all four FFs relatively to a two-dipoles fit

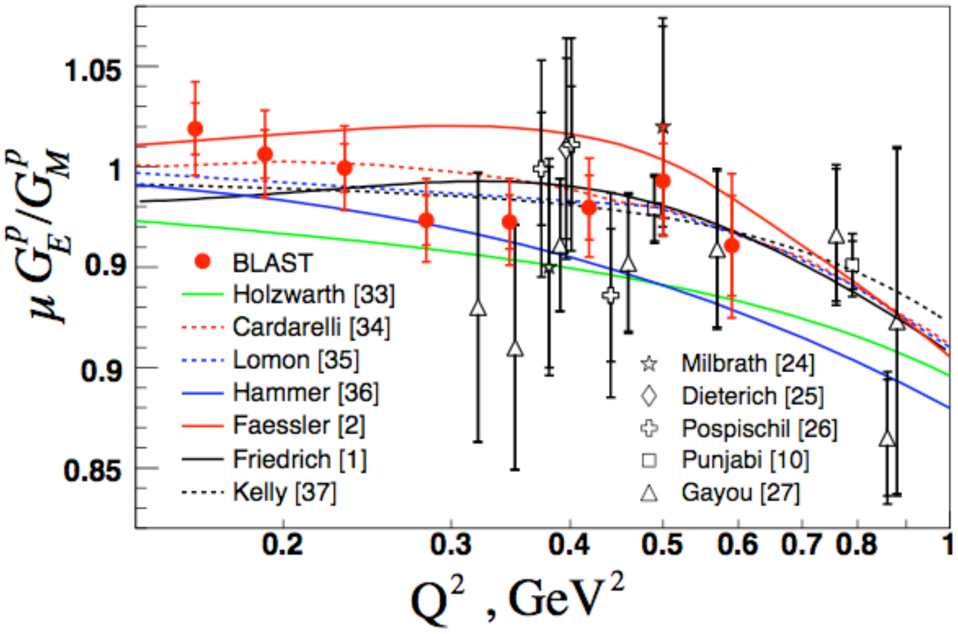
Belushkin et al, PRC (2007) get a good description of most data with dispersion analysis including meson continua

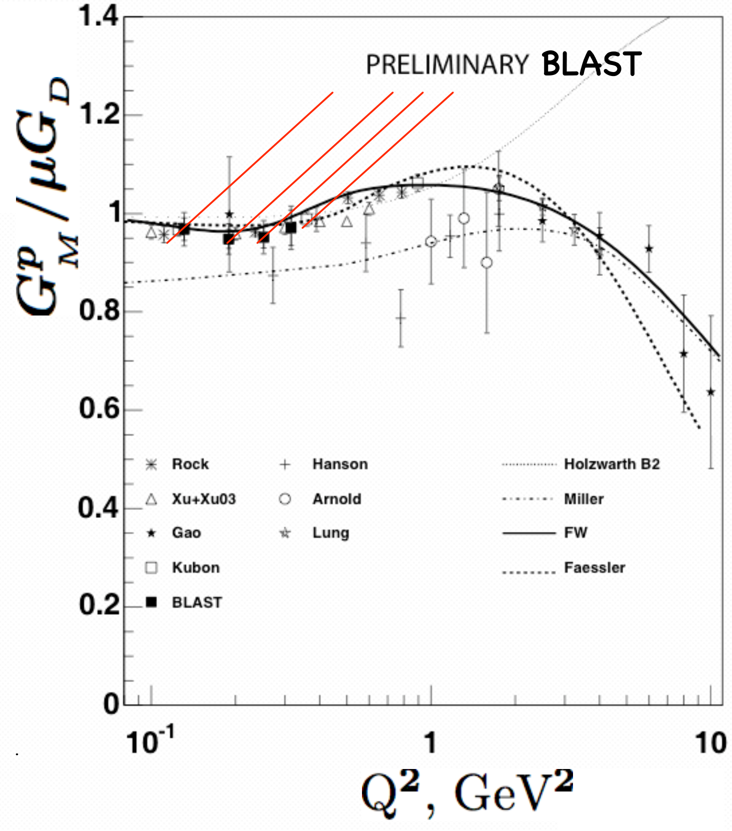
It will be very exciting to find deviation from DA fit => revived interest in precision experiments at Q^2 range below 1 GeV^2

Low Q^2 FFs from BLAST

Crawford et al., PRL 98, 052301 (2007)

Alarcon, Eur.Phys.J. A32,477 (2007)



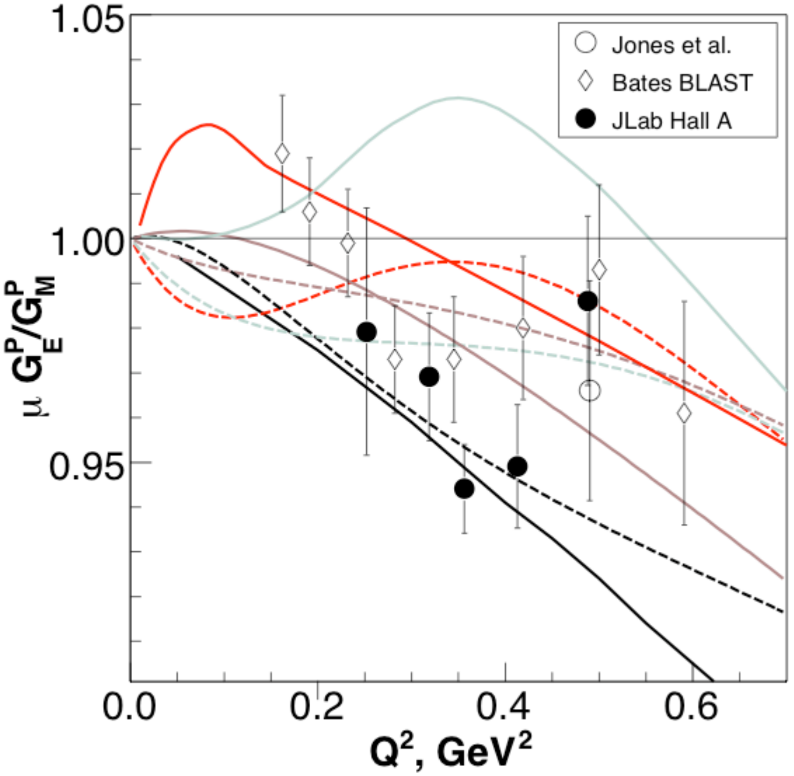


Consistent with unity in 0.2-:-0.6 GeV^2

Show a dip at 0.2 GeV^2

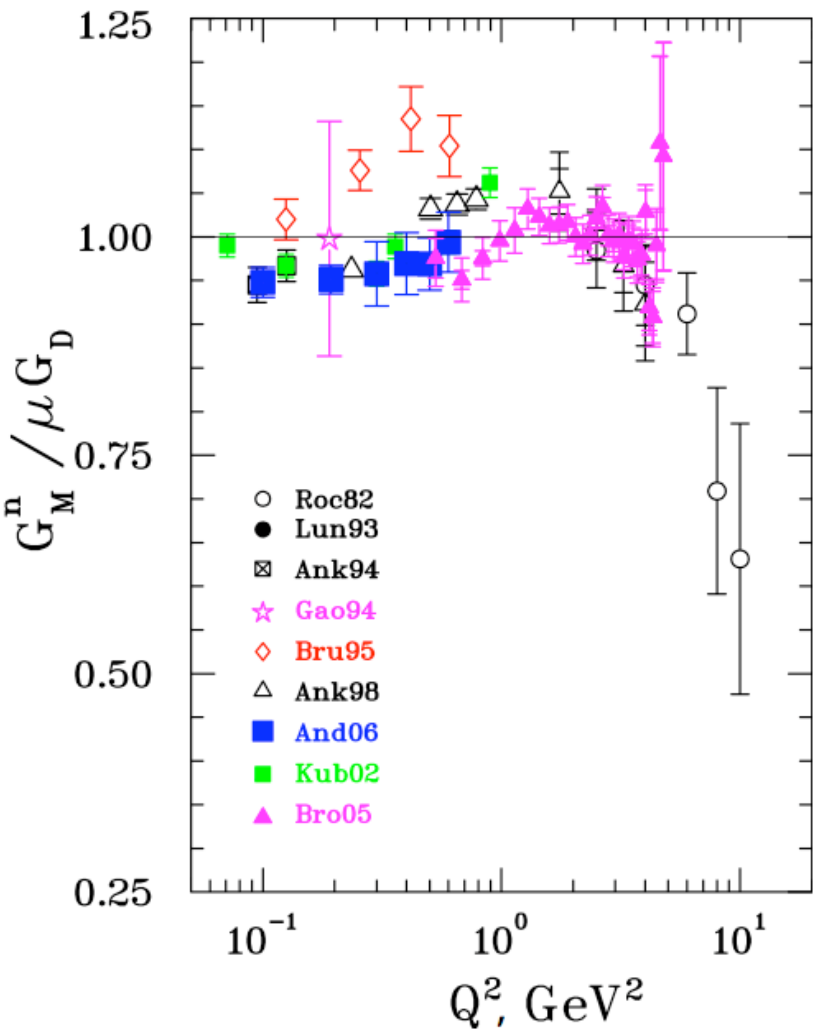
Low Q^2 GEP/GMP

New polarization transfer data
from JLab Hall A:
G.Ron at al., arXiv:0706.0128



A ratio less than **unity** in range from 0.2 to 0.5 GeV^2

Low Q^2 GMN inconsistency



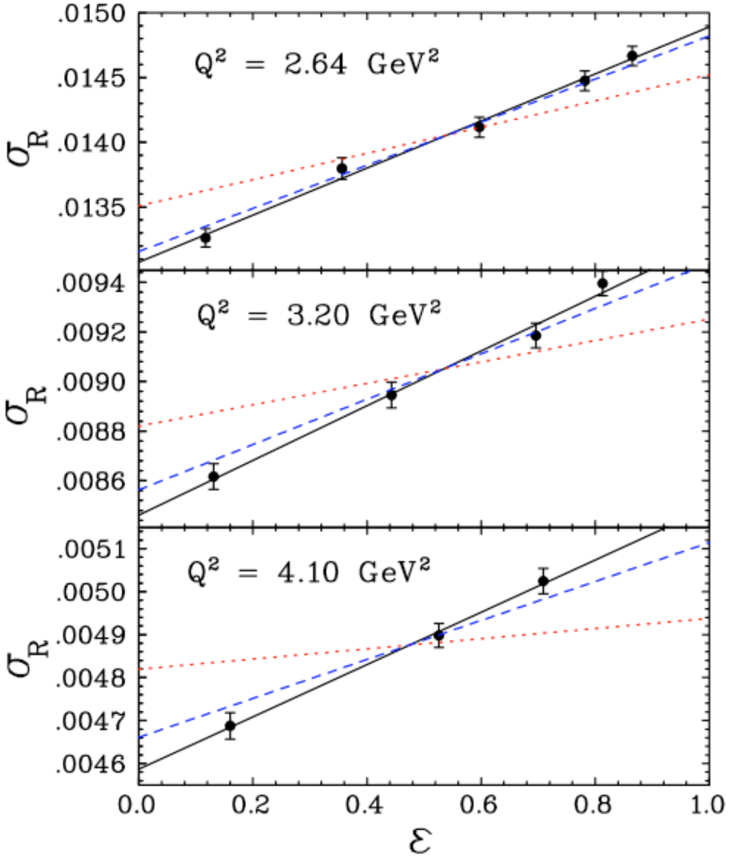
A systematic difference of several % between results (■ ■ ▲) in Q^2 range 0.4 -:- 0.8 GeV^2. A final analysis and paper from CLAS is coming soon.

Reminder that at least two independent experiments are always needed.

Super ratio Rosenbluth

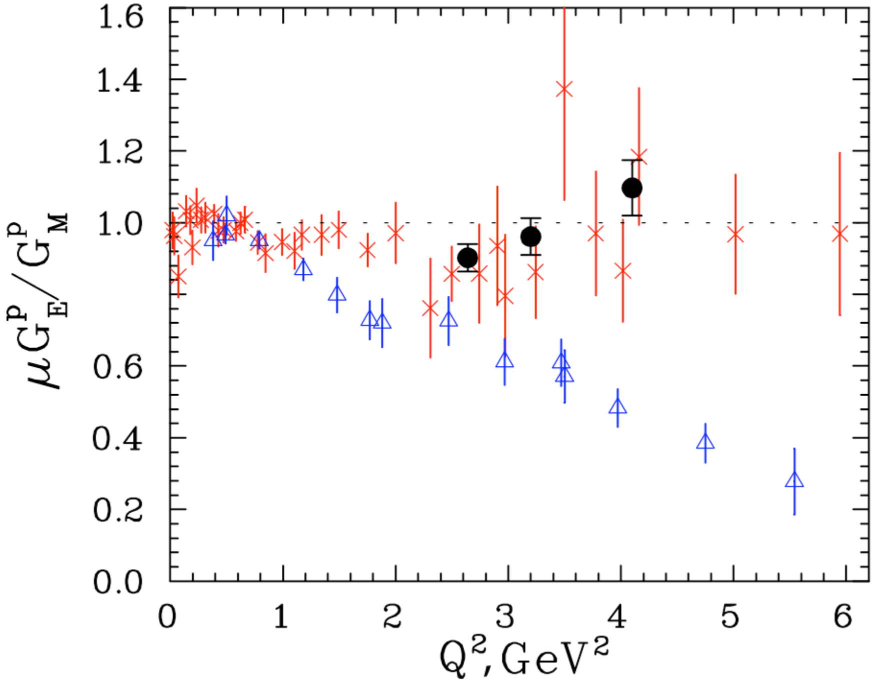
Arrington & Segel

$\sigma_{\varepsilon 1}/\sigma_{\varepsilon 2}/\sigma_{\varepsilon 3}$ ...



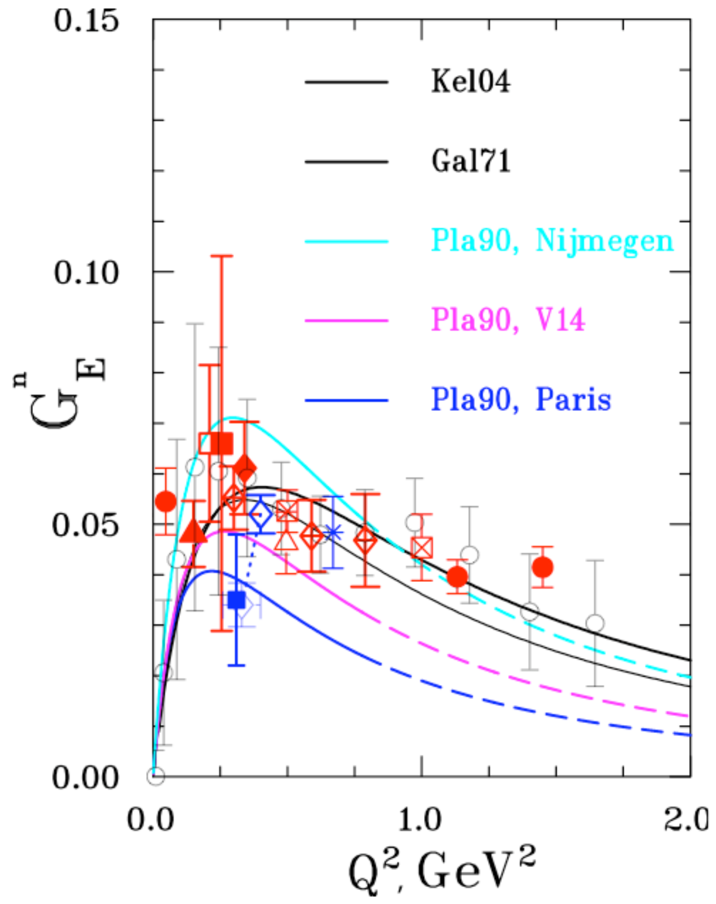
$H(e,p)e'$

Qattan et al., PRL 94, 142301 (2005)

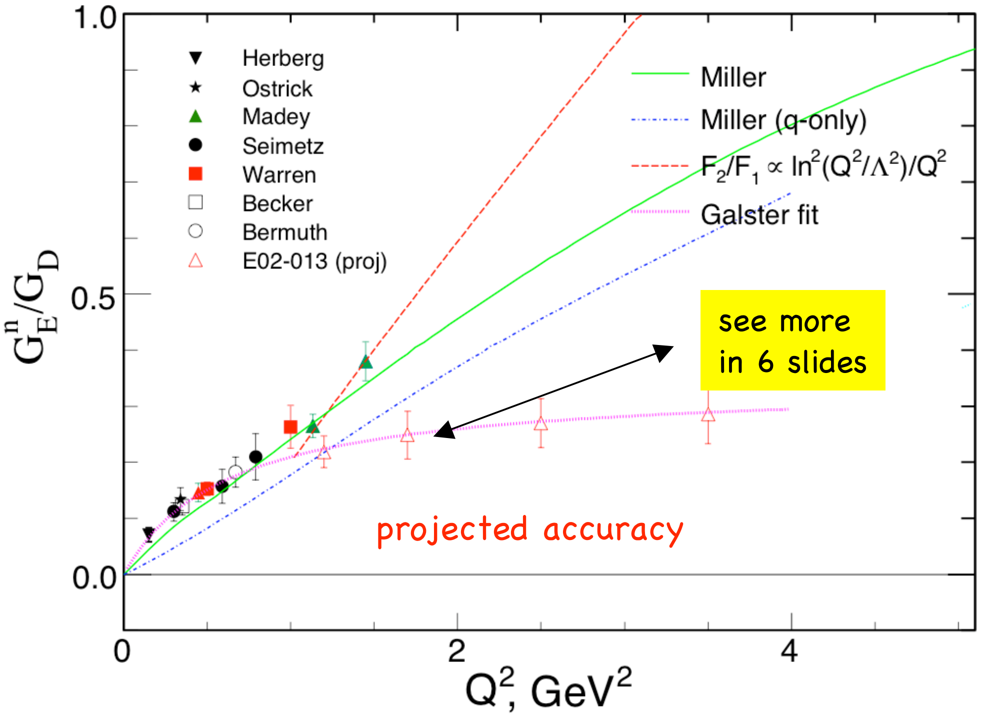


New L/T experimental results consistent with old set

Hall A GEN (E02-013)



G.Cates, N.Liyanage, and BW



see more in 6 slides

projected accuracy

Factor 2 increase of Q^2 require x30 larger Figure-of-Merit

High Q^2 GEN

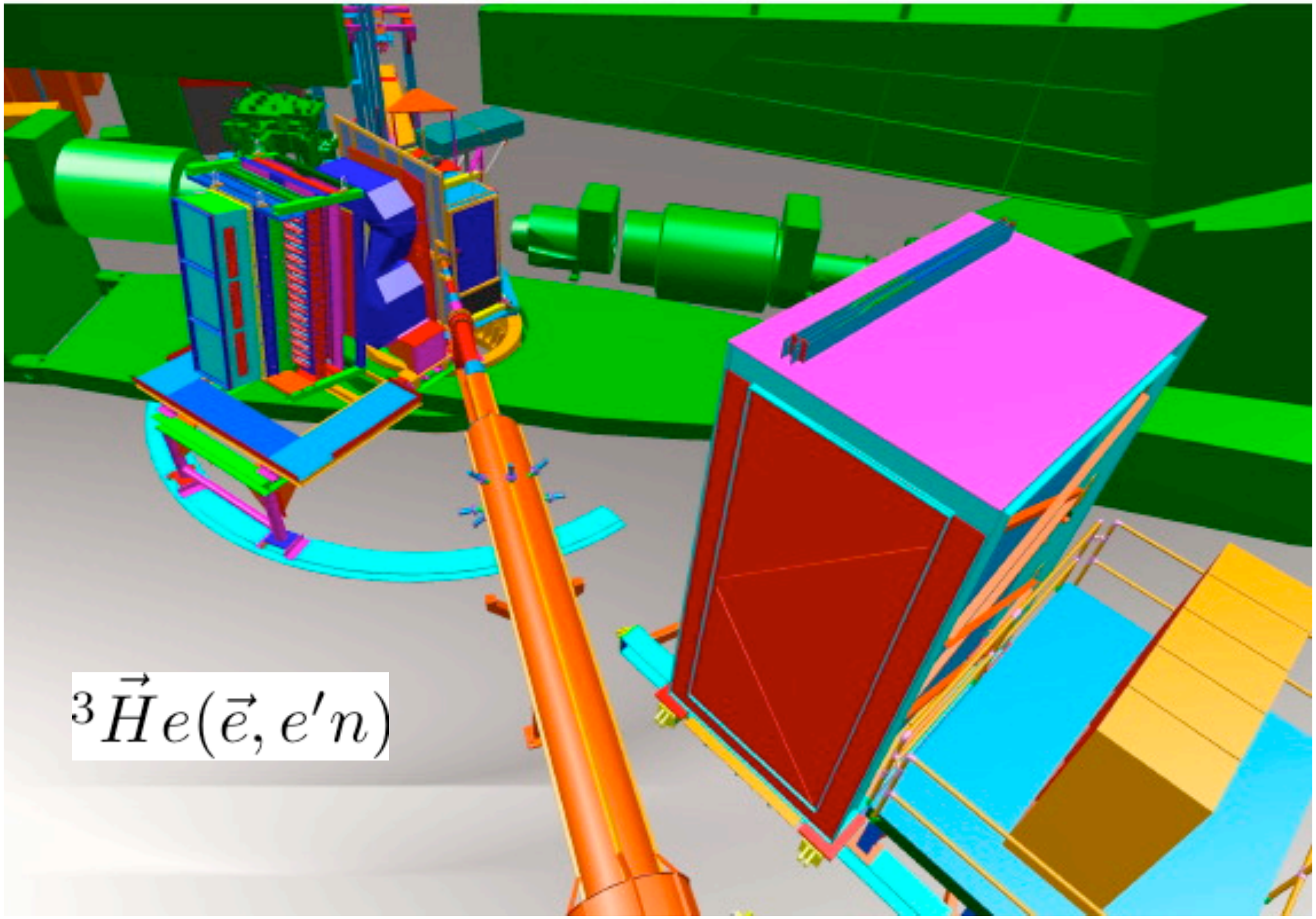
✓ Since 1984, when Blankleider&Woloshin suggested $^3\vec{H}e(\vec{e},e'n)$, several experiments of this type have been performed at NIKHEF-K and Mainz (A1, A3) for Q^2 up to 0.7 GeV^2 , a big success in part due to a new accurate 3-body calculation possible at low Q^2 (Glockle et al.)

✓ At Q^2 above 1-2 GeV^2 Glauber method becomes sufficiently accurate (Sarksian)

✓ Electron-polarized neutron luminosity and high polarization of ^{3}He target made measurement about 10 times more effective than with ND_3. In combination with a large acceptance electron spectrometer the total enhancement is more than 100, which allows to reach 3.5 GeV^2

Require super
- Polarized target
- Electron spectrometer
- Neutron detector

Hall A GEN (E02-013)



E02-013 scheme

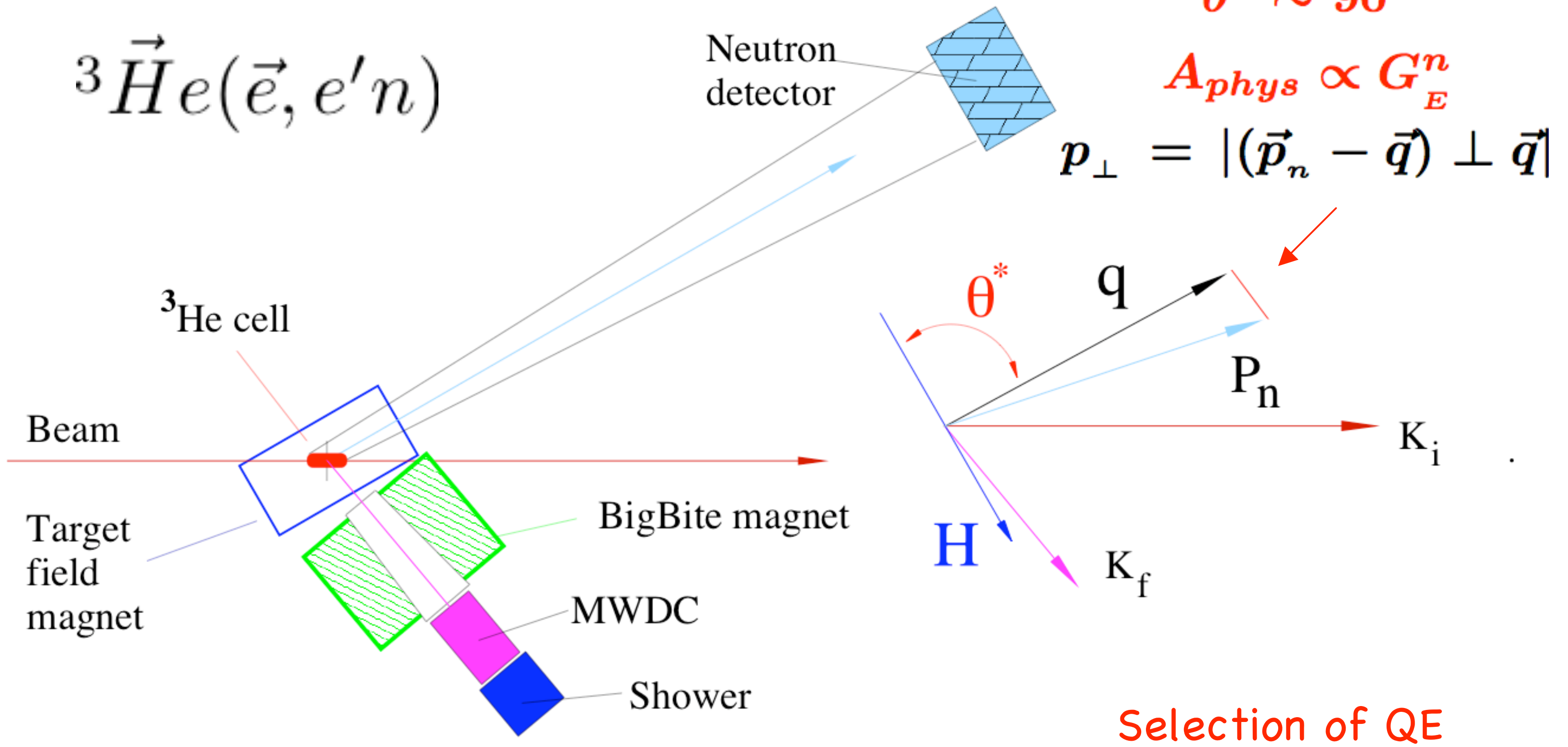
$$A_{phys} = -C1_{kin} \cdot G_E^n G_M^n \sin\theta^\star \cos\phi^\star - C2_{kin} \cdot (G_M^n)^2 \cos\theta^\star$$

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

$\theta^* \sim 90°$

$A_{phys} \propto G_E^n$

$$p_\perp = |(\vec{p}_n - \vec{q}) \perp \vec{q}|$$



Selection of QE

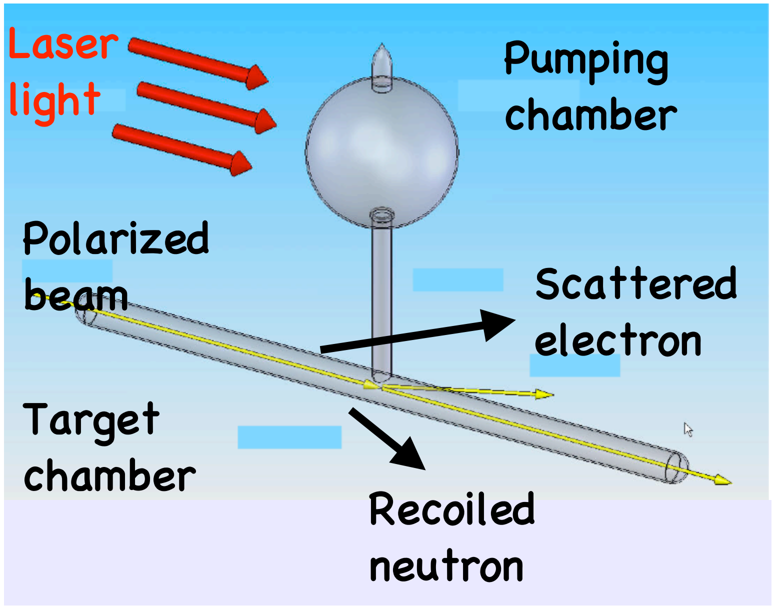
by cut $P_\perp$< 150 MeV

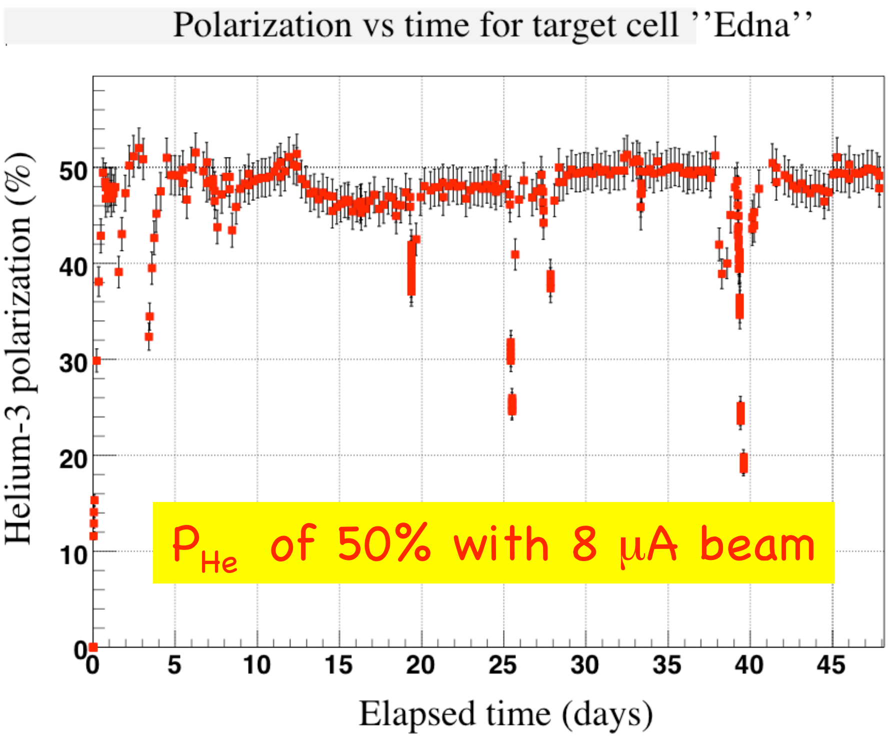
Polarized target

$^3He = p + p + n$

S + S′ + P waves

$P_n = 0.86\ P_{He}$



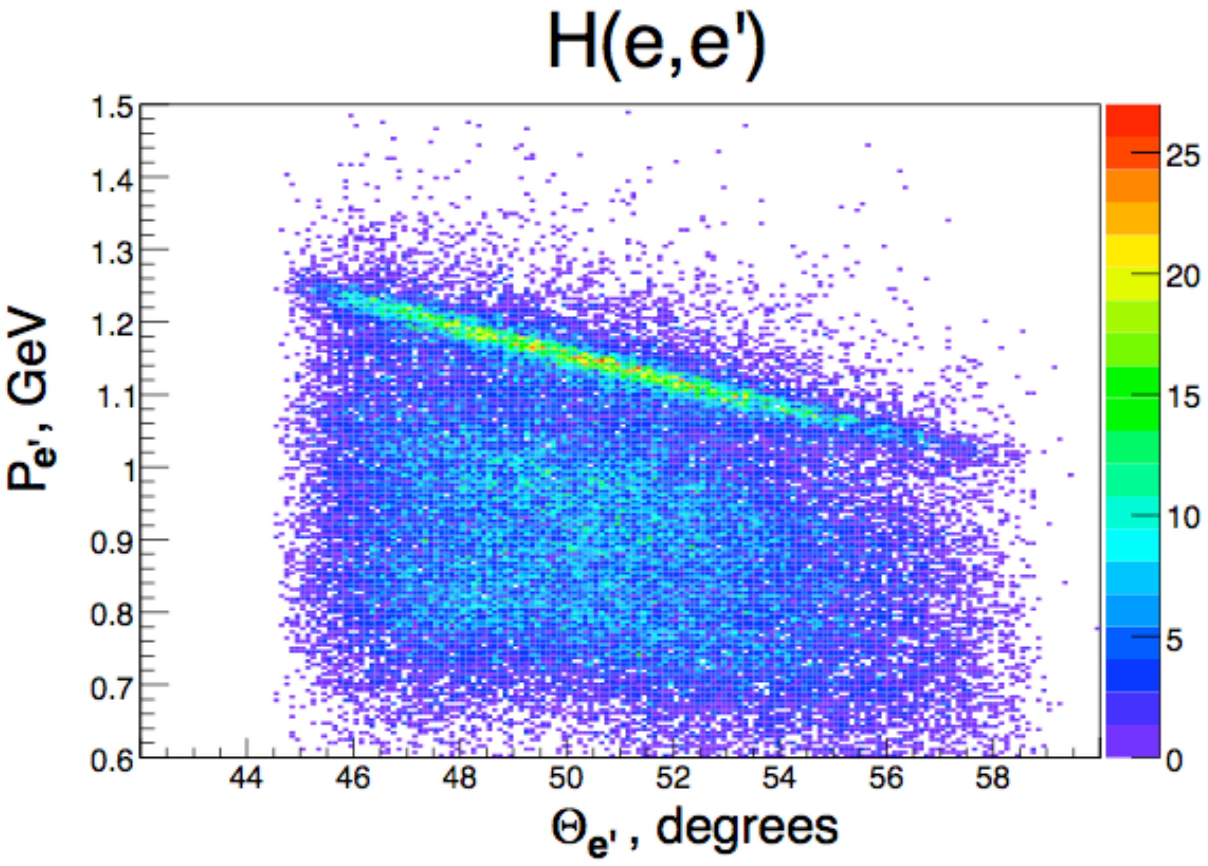


P_{He} of 50% with 8 μA beam

Rb + K mixture has shortened spin-up time to 5-8 hours. The hybrid method of optical pumping was used here for the first time in the nuclear target.

Electron Spectrometer

Useful $\Delta Q^2/Q^2 \sim 0.1$ with max Ω leads to a large aspect ratio, limited just of 30° for the polar. target. BigBite was designed at NIKHEF for aspect ratio $\Delta\theta/\Delta\phi$ = 1/5. Spectrometer has solid angle up to 95 msr.

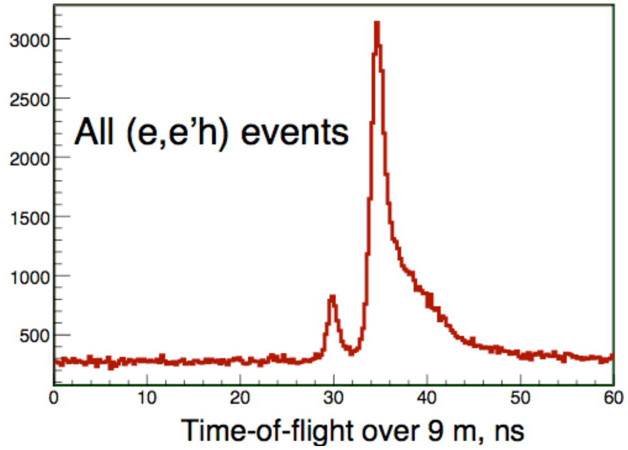


With luminosity of JLab polarized target, 10^{37} cm^{-2}/s, the open geometry – a dipole spectrometer – works well when all MWDCs located behind the magnet.

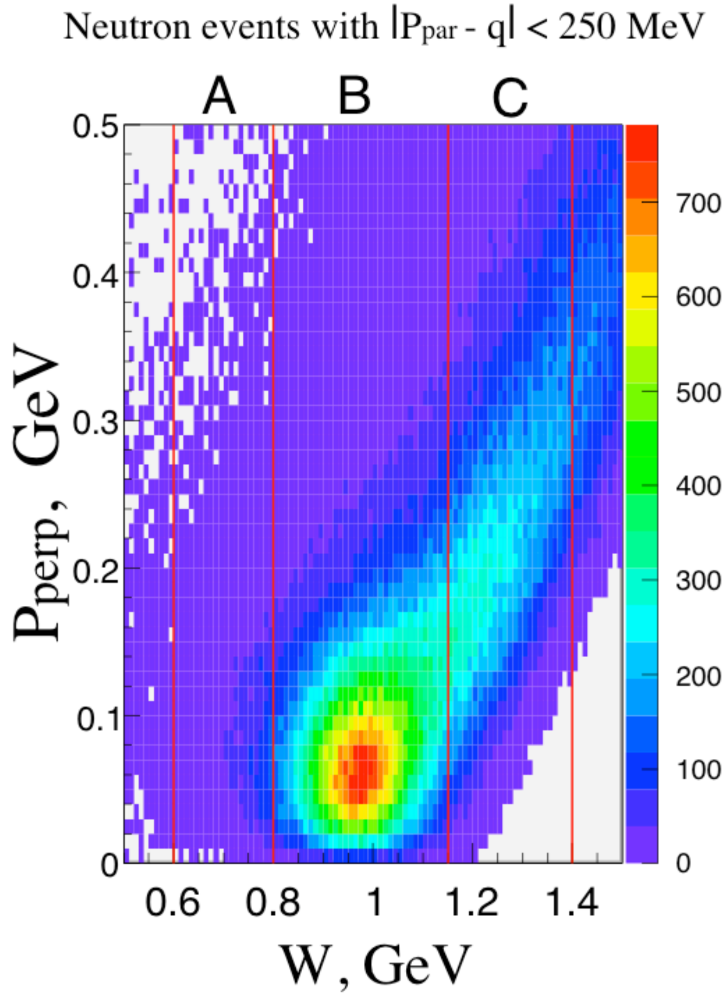
Neutron Detector

- Match BigBite solid angle for QE kinematics
- Flight distance ~ 10 m
- Operation at $3{\cdot}10^{37}$ cm^2/s

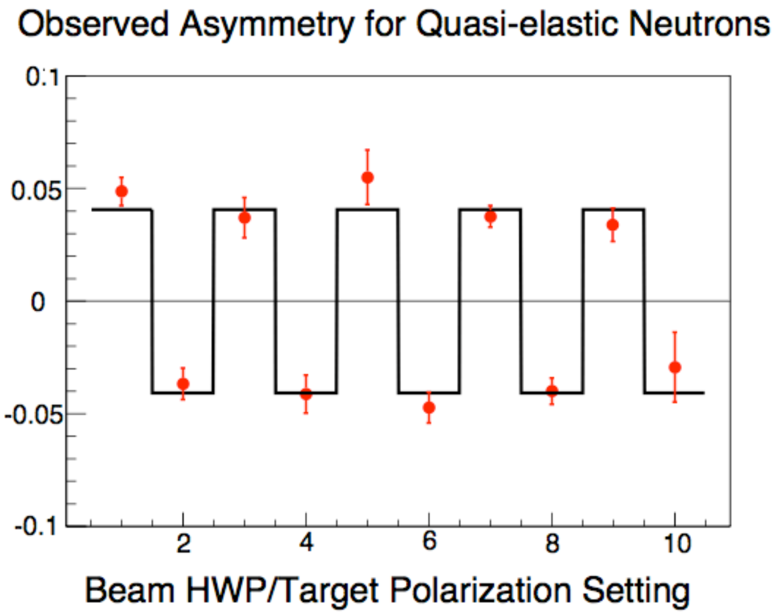
- 1.6 x 5 m^2 active area
- 6-7 layers (~ 250 bars)
- 2 veto layers (~ 200)
- 0.38 ns time resolution



Data analysis



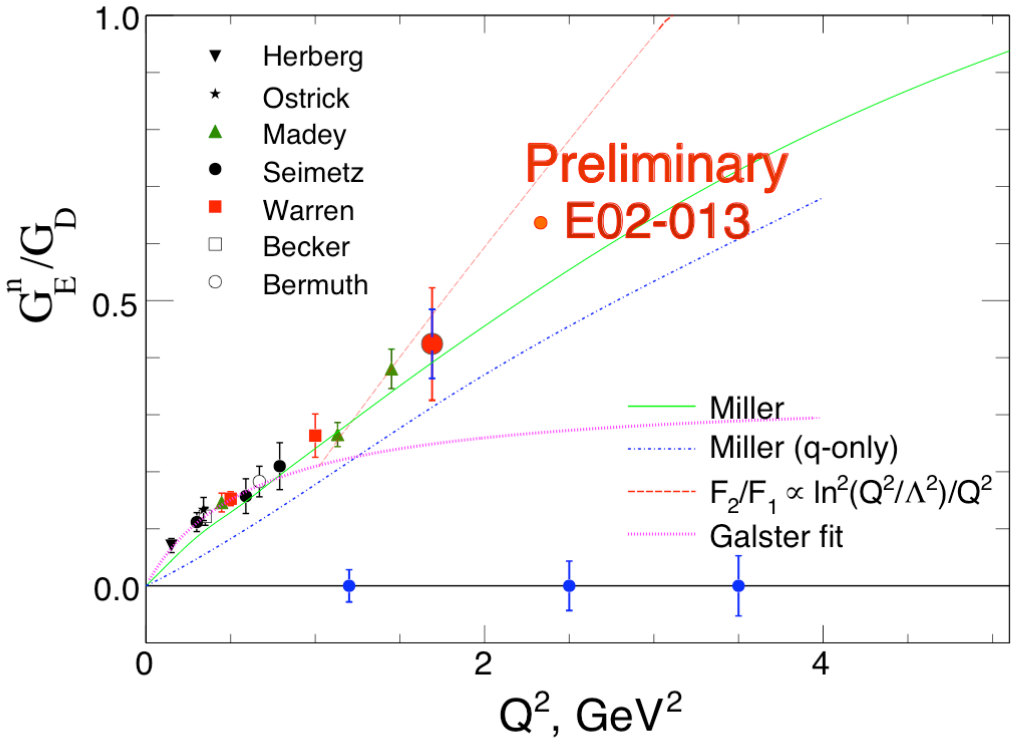
Selection of QE (e,e′n) events



Asymmetry than corrected for

1. p-n misidentification
2. accidental events
3. $A_{||}$ contribution
4. FSI for e,e′n process
5. Target, beam polarizations

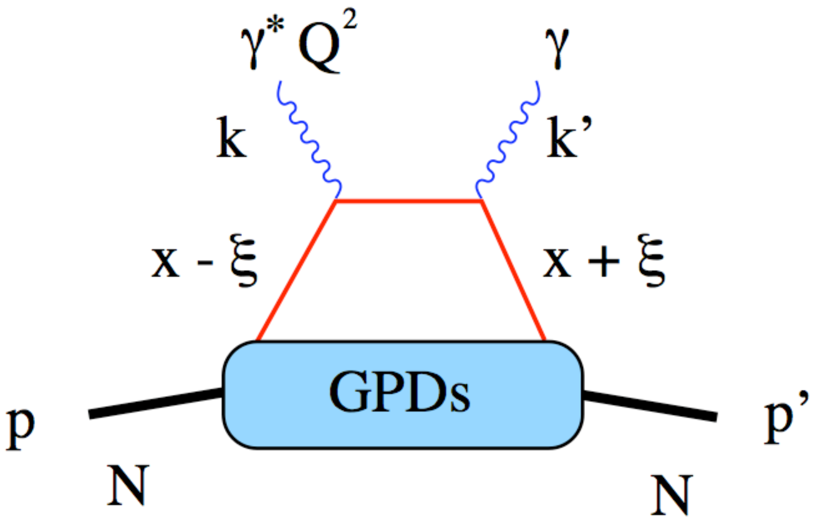
First physics result from Hall A GEN



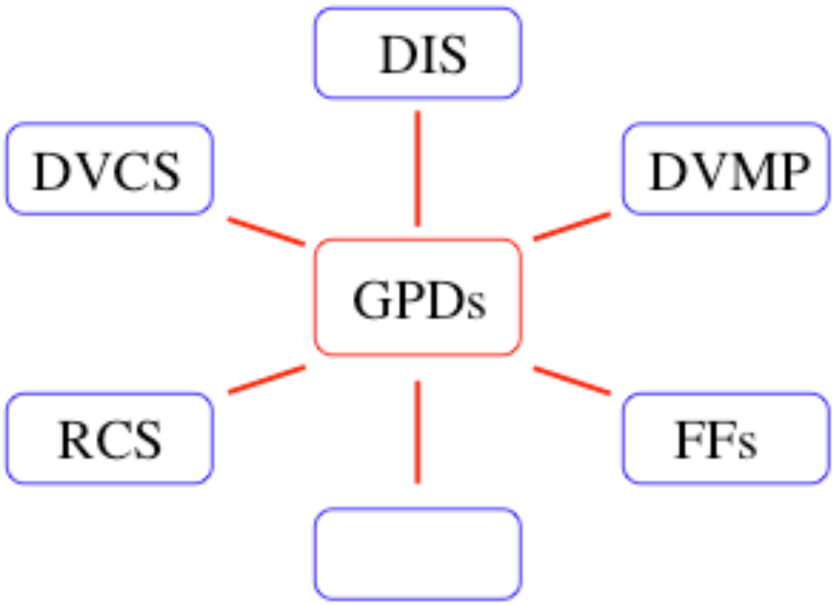
- Result is well above Galster.
- Nuclear corrections include neutron polarization and estimate of Glauber (~5%).
- Present error (~20%) dominated by preliminary "neutron dilution factor", and is expected to be ~7% stat. and 8% syst. with further analysis.
- 3.4 GeV^2 result to be released in October DNP meeting at Newport News.

GPDs of nucleon

Müller (94), Ji (97), Radyushkin (97)



where $\xi = (p_q^+ - p_q'^+)/(p_q^+ + p_q'^+)$



Quark dynamics of nucleon encoded in GPD functions

$H(x,\xi,t)$, $\tilde{H}(x,\xi,t)$ hadron helicity-conserving; vector and axial-vector

$E(x,\xi,t)$, and $\tilde{E}(x,\xi,t)$ helicity-flipping; tensor and pseudo-scalar

GPDs information

P.Kroll, Excl.-07

a lot to
measure

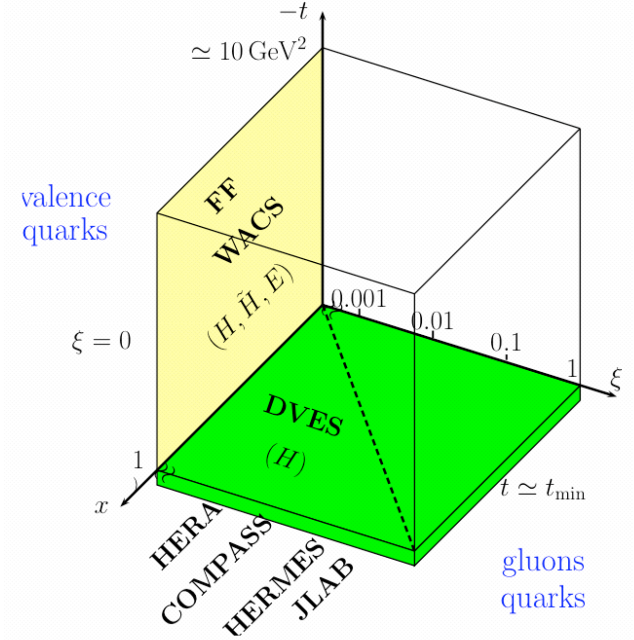
Reduction formulas at $\xi = t = 0$
for DIS and $\xi = 0$ for FFs

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

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

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

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



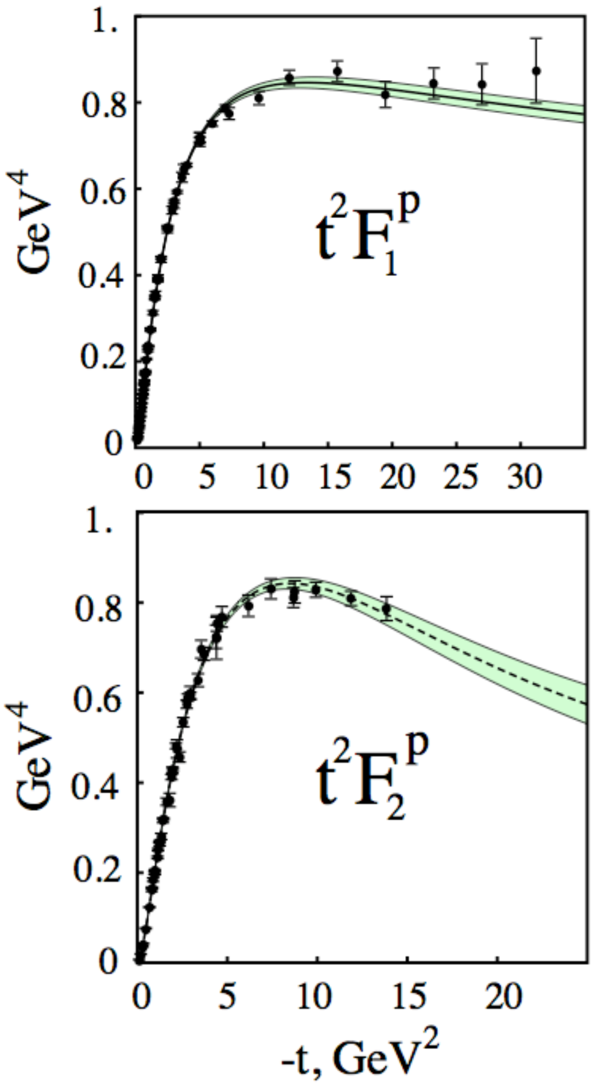
Ji's sum rule for quark orbital momentum

$$\langle L_v^q \rangle = \frac{1}{2} \int_0^1 dx \left[x E_v^q(x, \xi = 0, t = 0) + x q_v(x) - \Delta q_v(x) \right]$$

DVCS will access low t, large Q^2 kinematics

FFs presently are the main source for E_v^q

Model of GPD and Form Factors



Diehl et al (2005),
Guidal et al (2005)

use all available data on $G^p_M, G^n_M, G^p_E, G^n_E, F_A$

and CTEQ6 parametrization of $q(x), \Delta q(x)$

in order to determine $H^{u,d}_v,\ \tilde{H}^{u,d}_v,\ E^{u,d}_v$

ANSATZ: $H^q_v(x,t) = q_v(x) \exp\left[f_q(x)t\right]$

$$f_q = \left[\alpha' \log(1/x) + B_q\right](1-x)^{n+1}$$
$$+A_q x(1-x)^n$$

fixed $\alpha' = 0.9\ GeV^{-2}, n = 1, 2$;

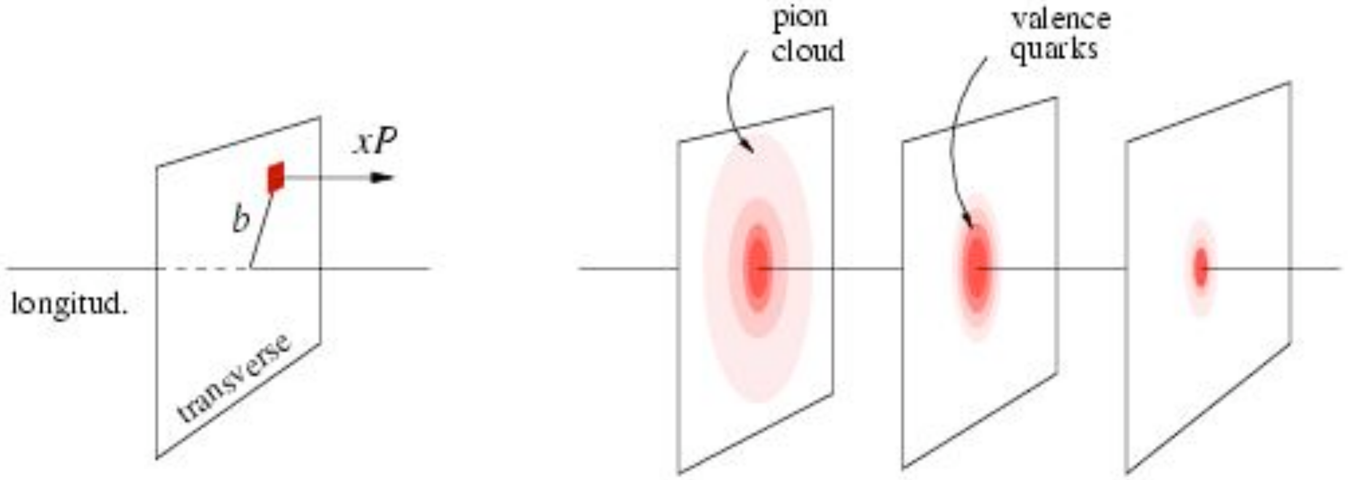
only A_q, and B_q parameters are fitted

GPDs and impact parameter

Transverse momentum invariance allows frame independent Fourier transform from $H(x,\xi,t)$ to $q(x,\xi,\mathbf{b})$ with impact parameter **b** defined relative to center of momentum

Burkardt, Int. J. Mod. Phys. A 18, 173 (2003)

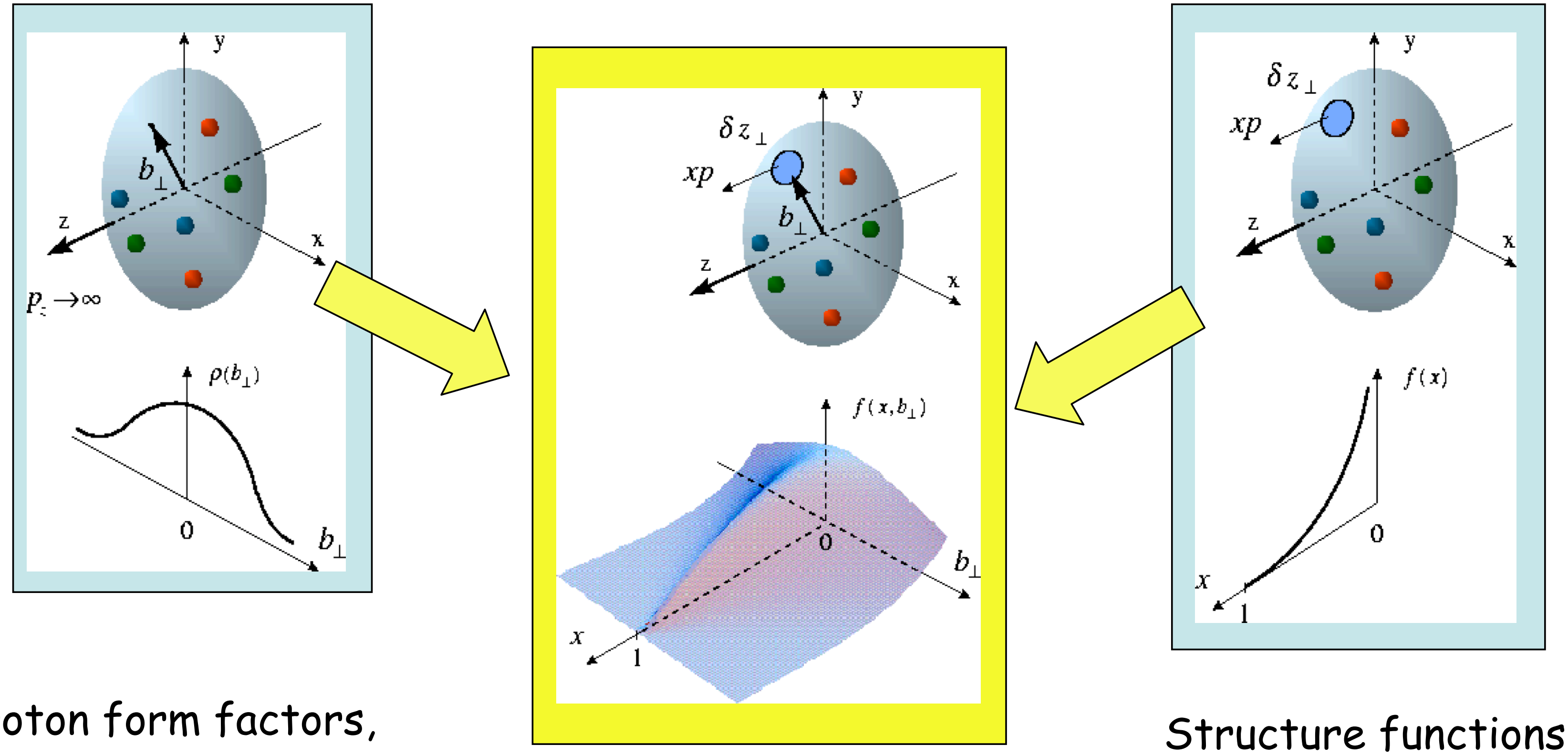
Fourier transform in momentum transfer



$x < 0.1$ $x \sim 0.3$ $x \sim 0.8$

gives transverse size of quark (parton) with longitud. momentum fraction x

3-d picture of the nucleon



Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

Nucleon Density from GPD

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

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

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

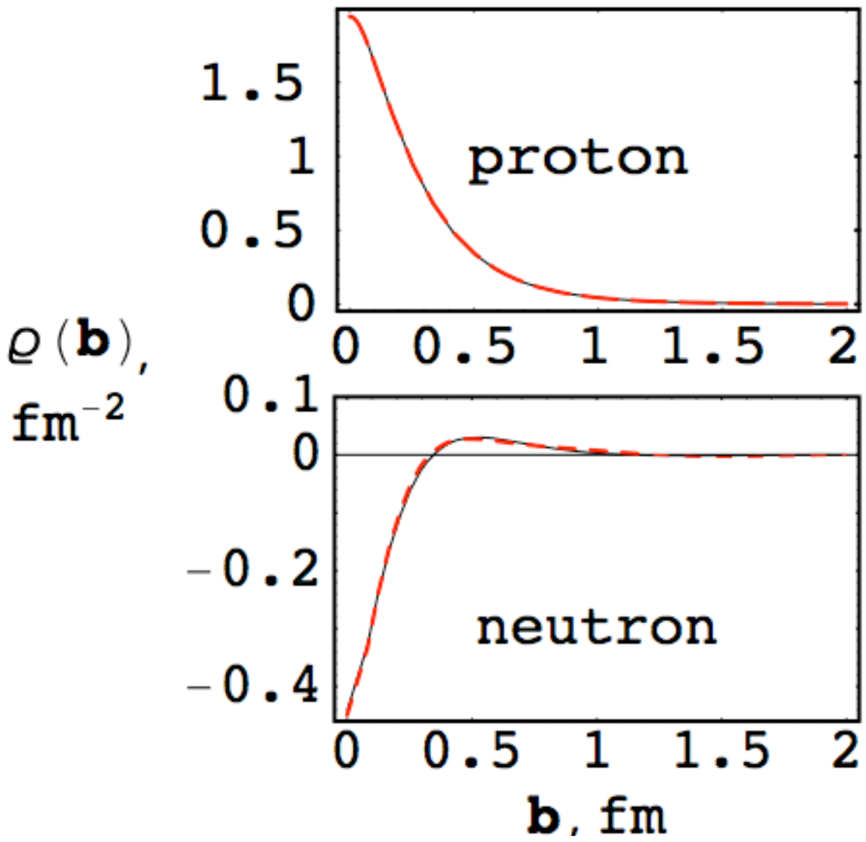
$$\rho(b) = \int_0^\infty \frac{Q\cdot dQ}{2\pi} J_0(Qb) \frac{G_E(Q^2)+\tau G_M(Q^2)}{1+\tau}$$

G.Miller,
arXiv:0705.2409

center of momentum $R_\perp = \sum_i x_i \cdot r_{\perp,i}$

b is defined relative to $R_\perp$

Neutron is negative inside



G.Miller, arXiv:0705.2409
using FFs from
Kelly's fit
BBBA's fit

Does it contradict intuition ?
Static picture: a neutron is
a proton in the center plus π^-

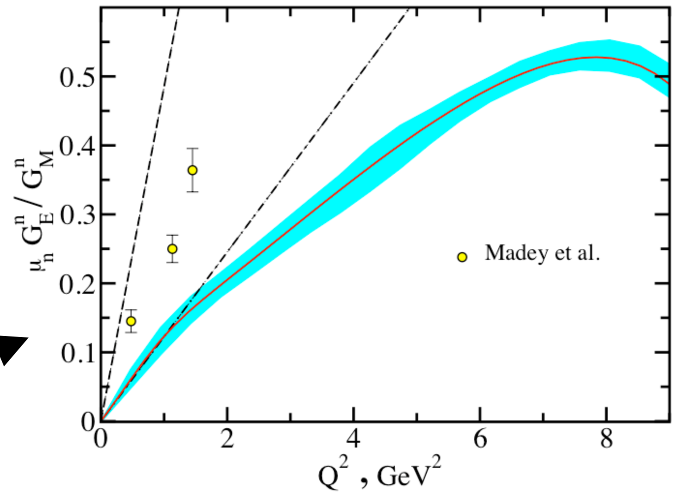
Intuitive picture of static constituent quarks is not applicable for large Q^2 where quark DFs play role

- Negative density at low **b** in a neutron => d quarks dominate
- High Q^2 elastic process in Feynman mechanism requires a large x quark, so d quarks dominate at large x, in agreement with DIS

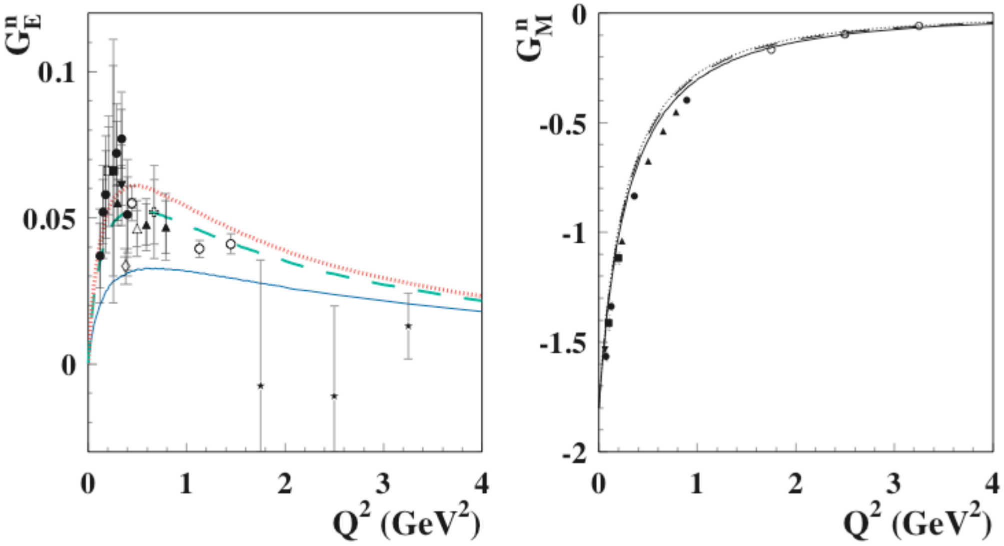
Nucleon models

See recent review Arrington, Roberts, Zanotti: nucl-th/0611050

- Miller, since 2002, Spin densities in LF-Cloudy-Bag-Model lead to non-spherical shape of the proton.
- Bhagwat et al., arXiv:nucl-th/0610080, the Dyson-Schwinger equations used to calculate FFs



- Pasquini&Boffi, arXiv:0707.2897 developed nucleon-meson LFQCM and calculated many features of electroweak structure of the nucleon. GEN is sensitive to the % of S′ component, find negative charge in the neutron at small impact parameter b



GEP-III: G_E^p/G_M^p for 8.6 GeV^2

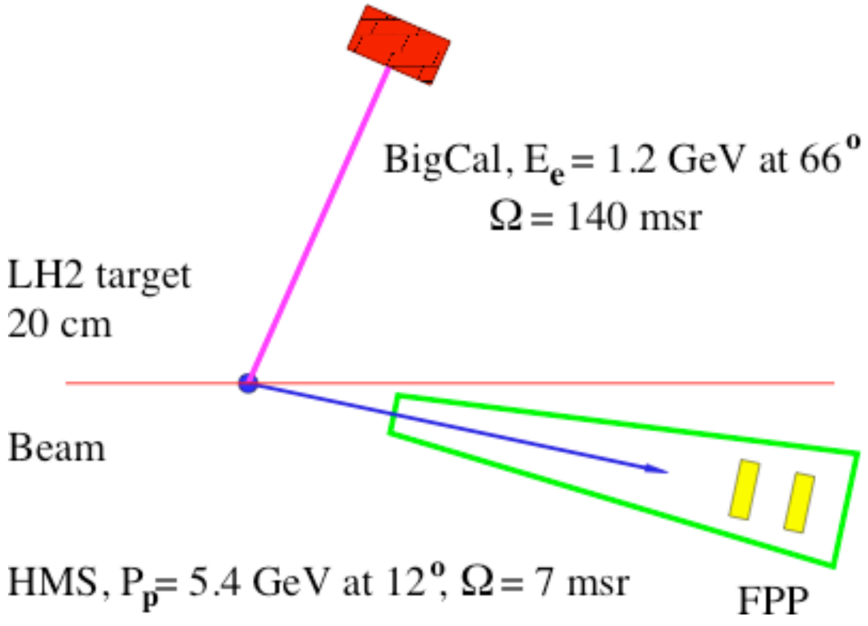
Brash, Jones, Perdrisat, Punjabi

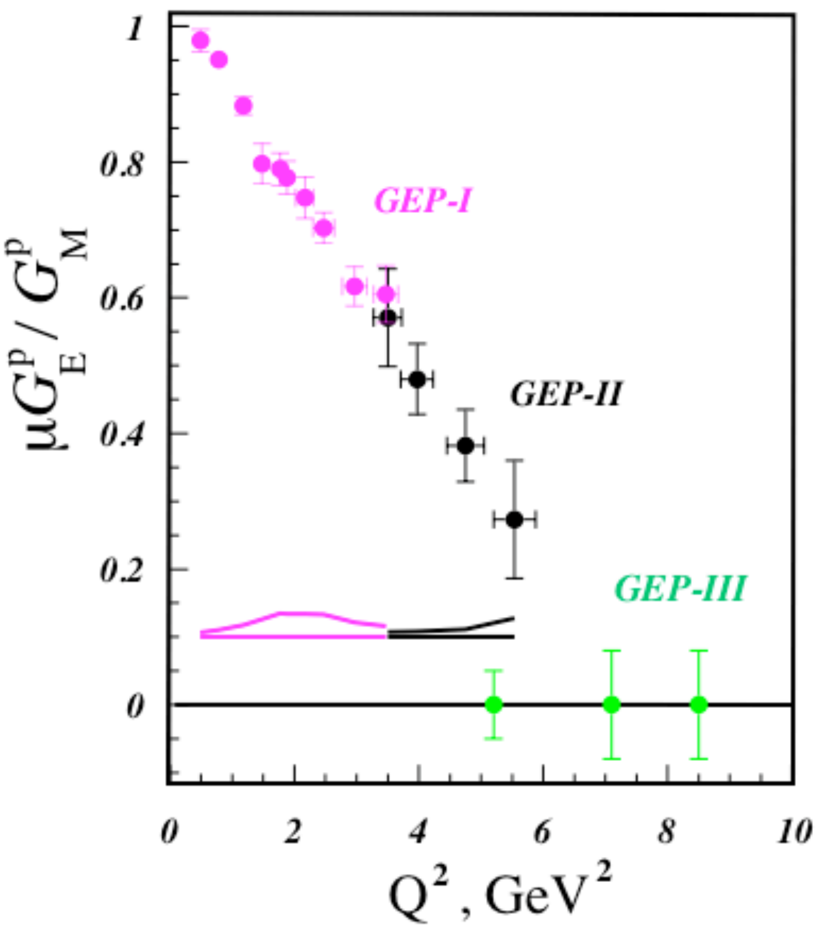
Polarization transfer in $H(\vec{e}, e'\vec{p})$

- New detector for scattered electron
- New polarimeter for recoiled proton

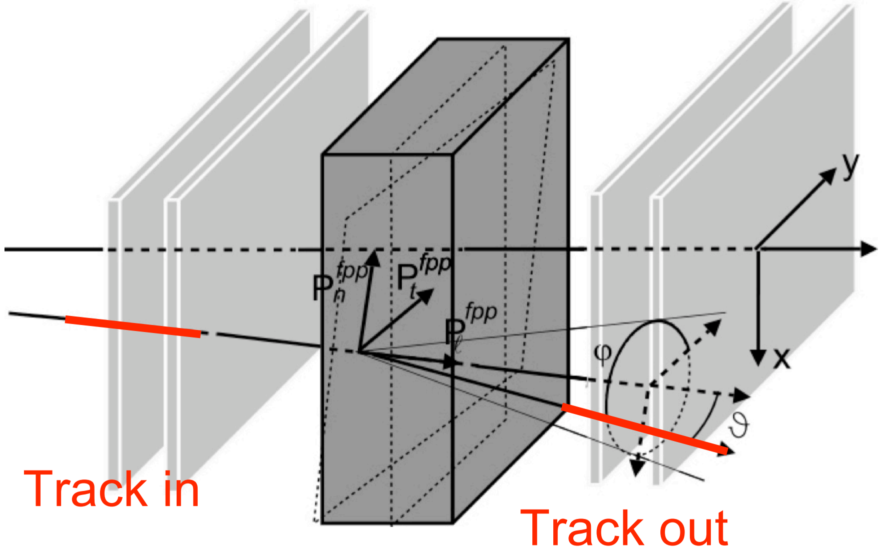
Commissioning will start next month

High Q^2 data will be taken by 5/08





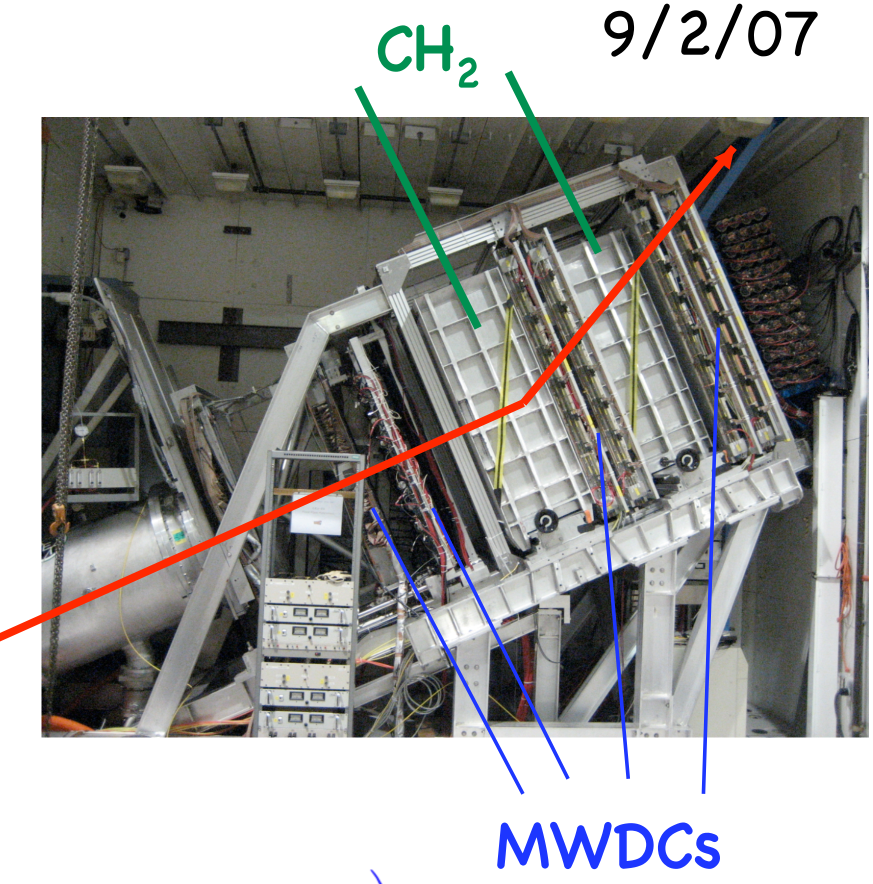
Focal Plane Polarimeter



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

where ± refers to electron beam helicity

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



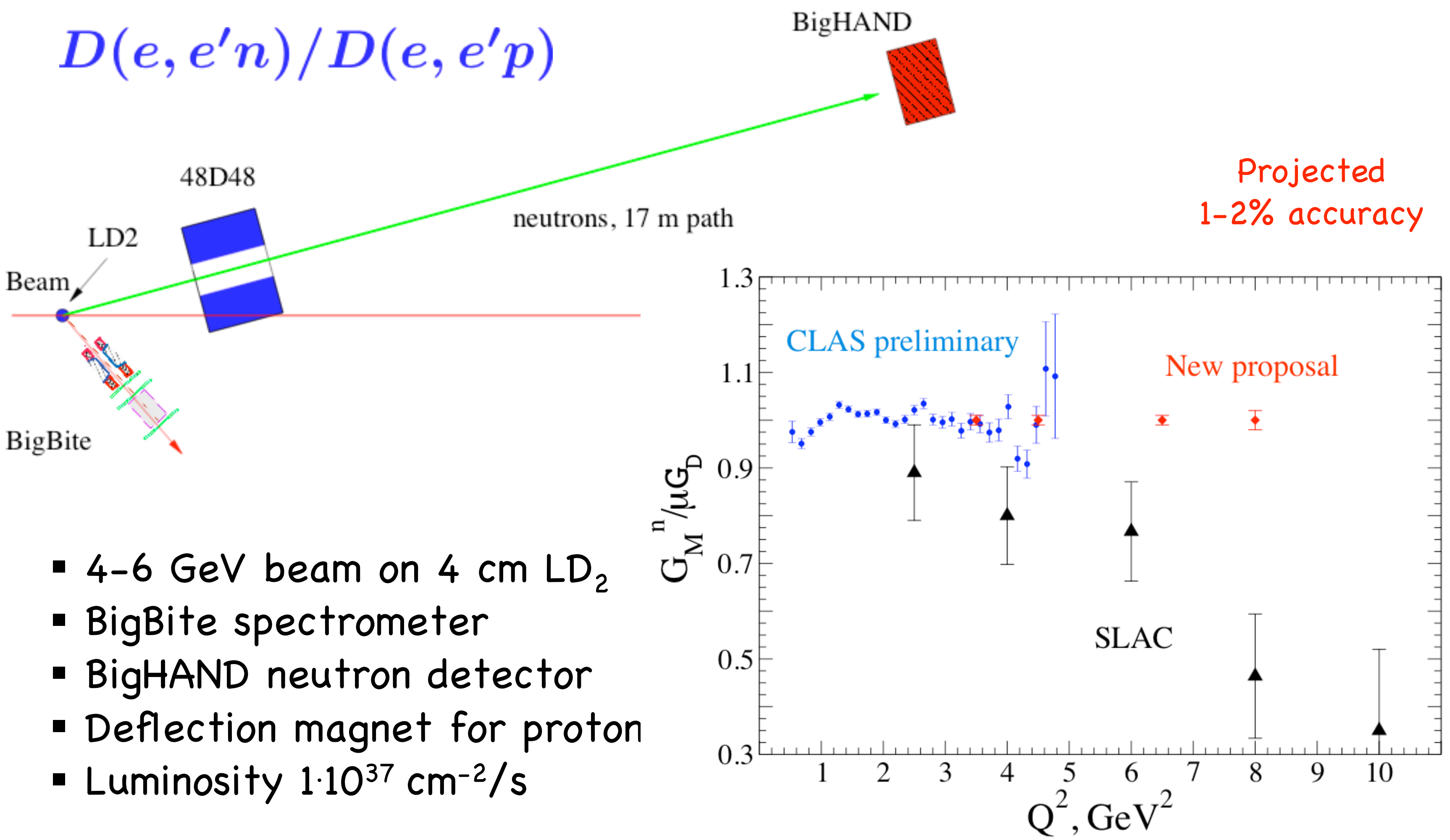
9/2/07

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

Near future: GMN-8 (for PAC33)

B.Quinn and BW

$D(e,e'n)/D(e,e'p)$

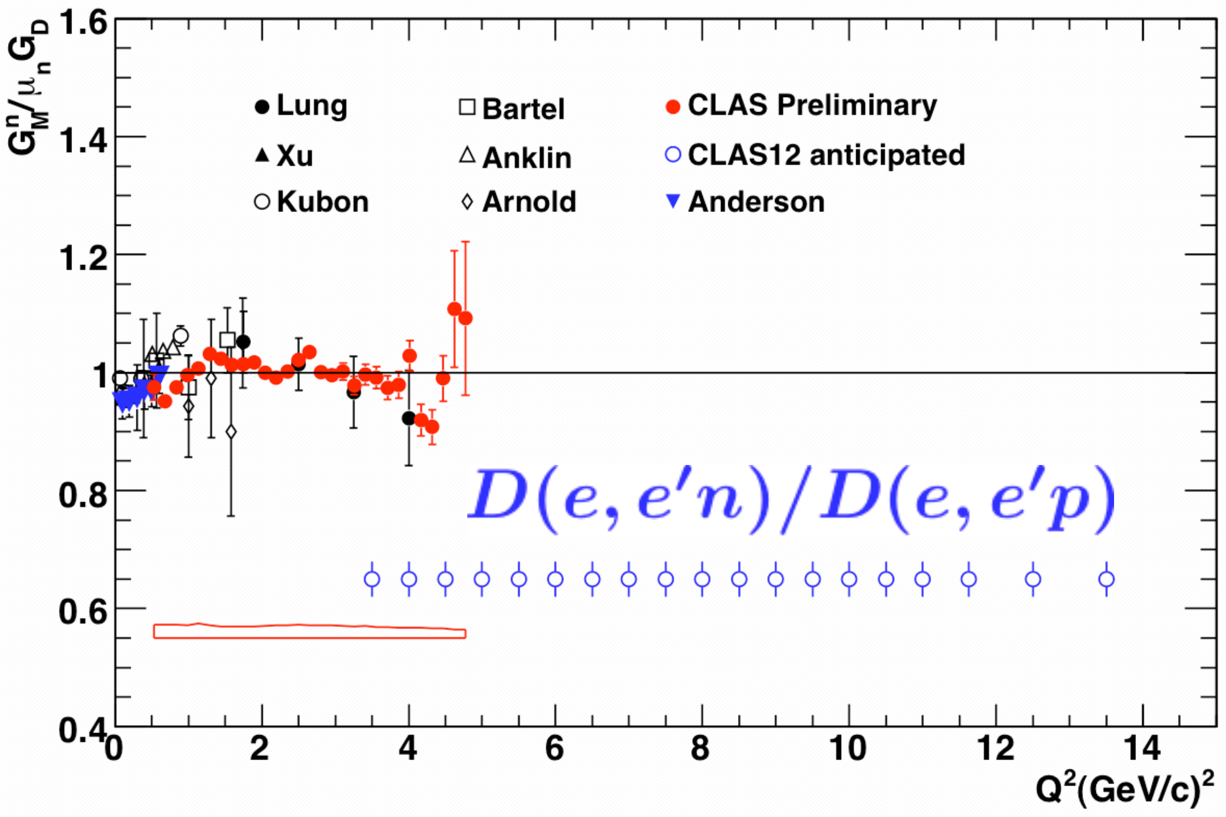


Projected
1-2% accuracy

- 4-6 GeV beam on 4 cm LD_2
- BigBite spectrometer
- BigHAND neutron detector
- Deflection magnet for proton
- Luminosity $1\cdot10^{37}$ cm^{-2}/s

GMN-14 with CLAS++

Gilfoyle, Brooks, Vineyard, Hafidi, Lachniet

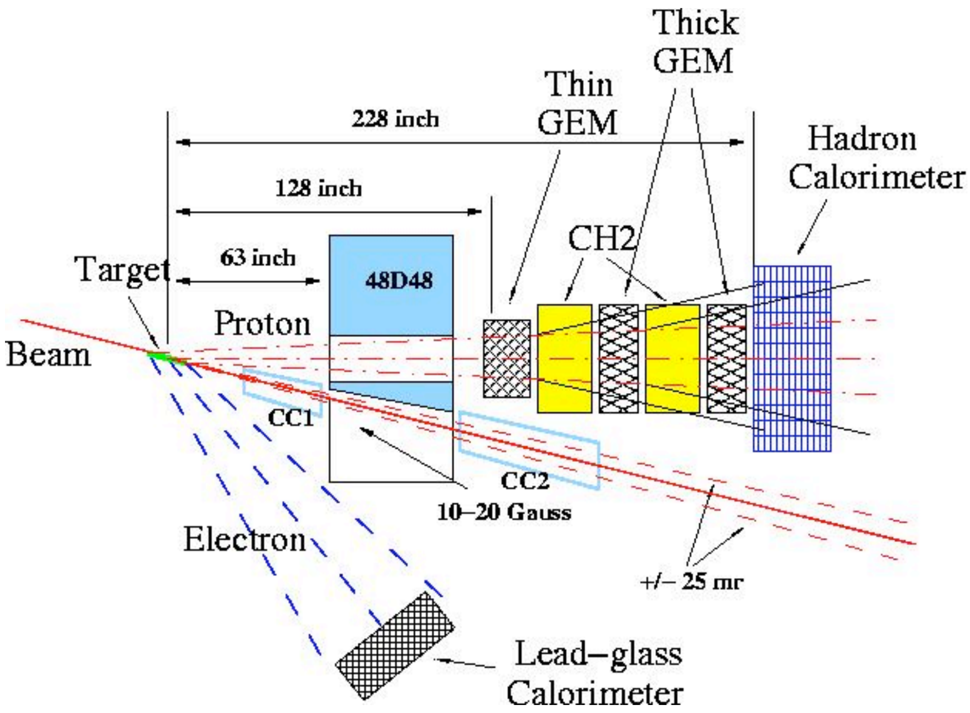


approved by PAC32
for 12 GeV program

GEP-15: G_E^p/G_M^p up to 15 GeV^2

Perdrisat, Pentchev, Cisbani, Punjabi, BW

$$H(\vec{e},e'\vec{p})$$



Beam: 75 μA, 85% polarization

Target is 40 cm liquid H_2

Electron arm at 37°, covers

Q^2 = 12.5 to 16 GeV^2

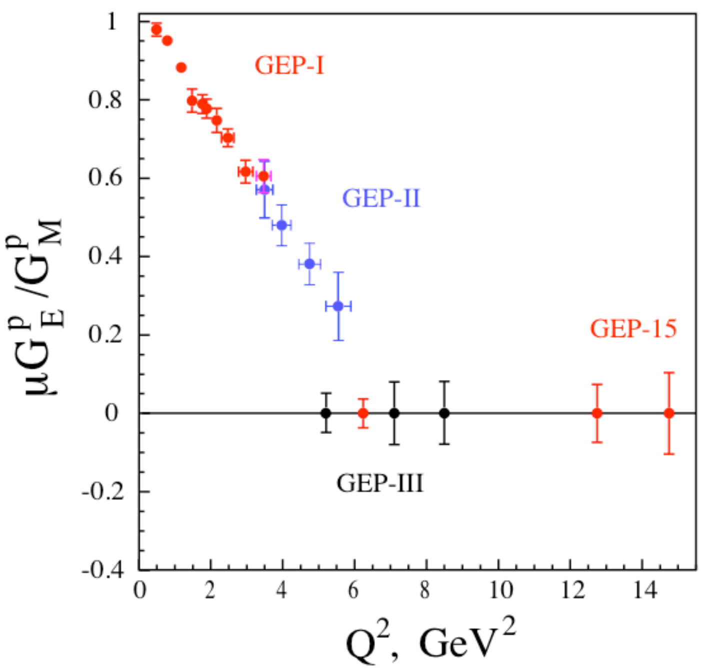
Proton arm at 14°, Ω ~ 35 msr

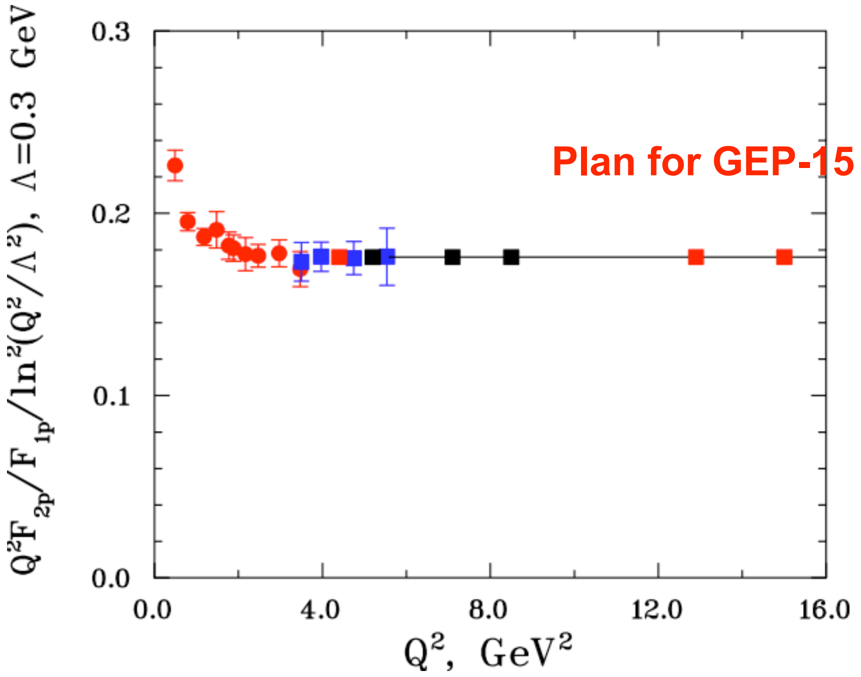
58 days of production time resulting accuracy:

$$\Delta(\mu G_E^p/G_M^p) \;=\; \pm 0.10$$

approved by PAC32
for 12 GeV program

GEP-15: Projected accuracy





$$\Delta(\mu G_E^p/G_M^p) = \pm 0.10$$

$\boldsymbol{\Delta(F_2/F_1)/(F_2/F_1)}$ accuracy will be $\mathbf{3\%}$

compare to $\frac{\boldsymbol{ln^2(Q^2=10/\Lambda^2)}}{\boldsymbol{ln^2(Q^2=15/\Lambda^2)}} = \mathbf{0.85}$

GMP-18: New measurement of G_M^p

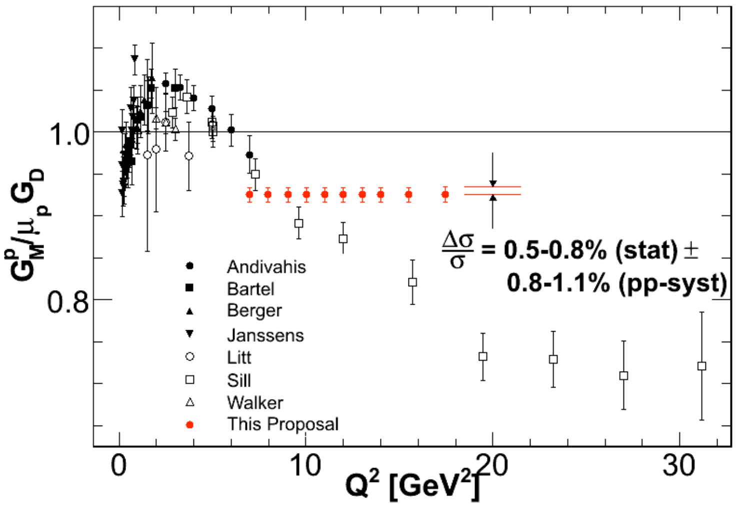
Moffit, Gilad, Arrington, BW

The cross section of H(e,e′)p.

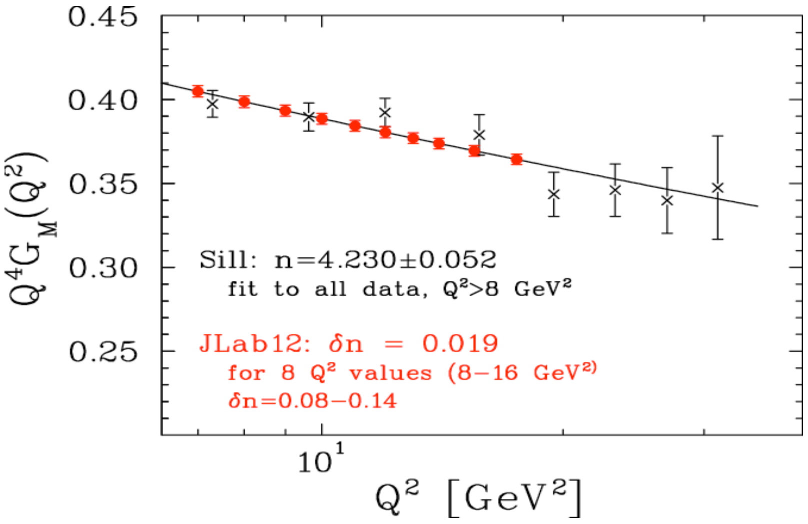
By using two existing Hall A High Resolution Spectrometers with several new ideas for improved control of systematic.

With 11 GeV beam in 31-day run.

approved by PAC32
for 12 GeV program



$\frac{\Delta\sigma}{\sigma}$ = 0.5-0.8% (stat) ±
0.8-1.1% (pp-syst)



Sill: n=4.230±0.052
fit to all data, Q^2>8 GeV^2

JLab12: δn = 0.019
for 8 Q^2 values (8−16 GeV^2)
δn=0.08−0.14

Summary

- ☐ Experiment and theory have created an improved basis for the understanding of the nucleon
- ☐ Future experiments will provide precision FFs data for Q^2 up to 7/14/15/18 GeV^2
- ☐ The GPD approach, as expected, sheds light on the nucleon structure
- ☐ Lattice QCD results for FFs are simmering

It is an exciting time for nucleon FF physics, when we know a lot about FFs and are searching for QCD-based interpretation

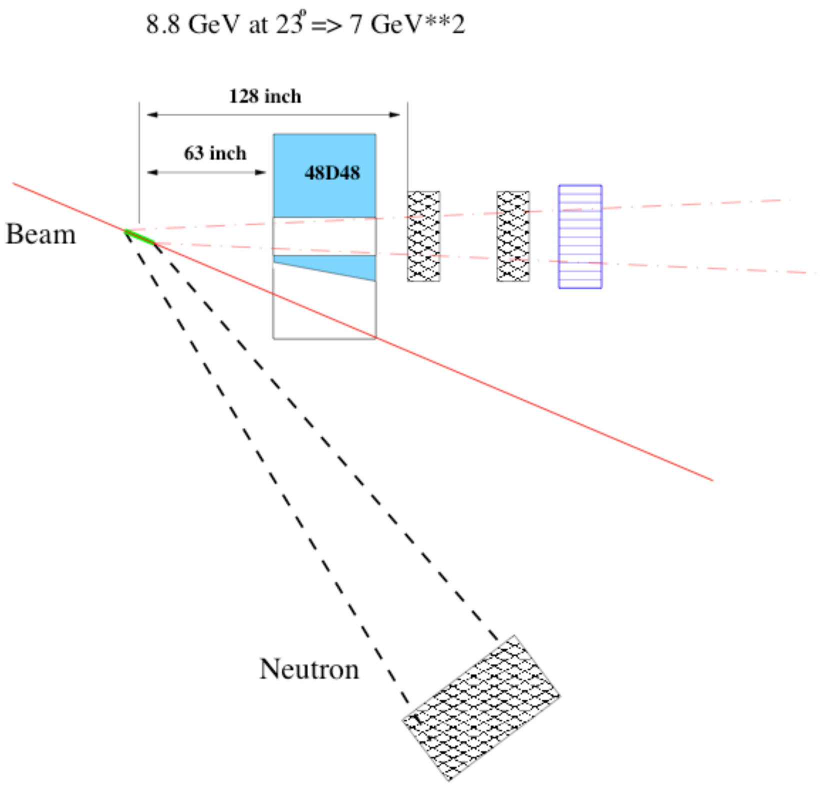
backup
slides
after this

Perspective: G_E^n up to 7 GeV^2

A new plan for GEN-7 includes:

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

- 8.8 GeV 85% polarized beam => triple FOM
- Resolution σ_p/p for electron - BNL magnet, GEM tracker => 3 times higher resolution
- He-3 cell in vacuum => lower background rate in neutron arm by a factor of 3
- Hybrid He-3 cell with narrow pumping laser line => 70% polarization

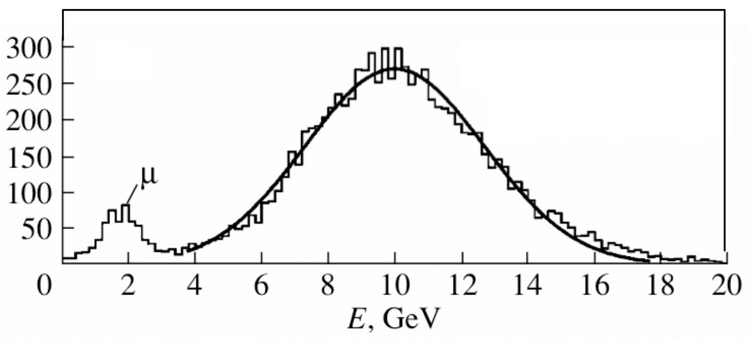


G_E^n at 7 GeV^2 with uncertainty 15% of Miller's value in 30-days run

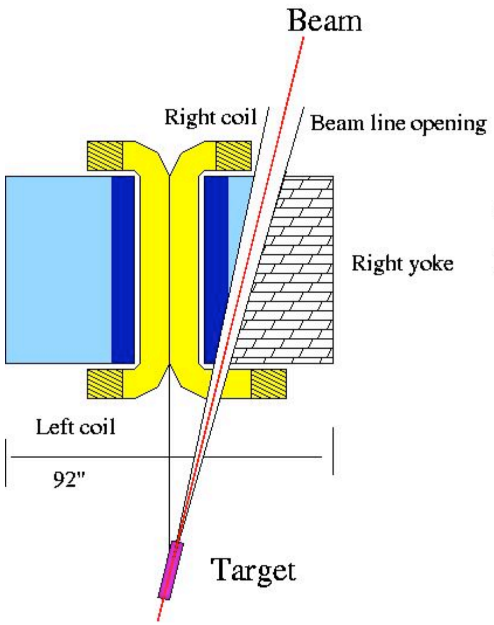
GEP-15: Proton Arm

- Magnet: 48D48 - 46 cm gap, 3 Tm field integral, 100 ton
- solid angle is 35 msr for GEP, could be ~70 msr at larger angle

  GEM chambers for tracking with 70 μm resolution
- momentum resolution is 0.5% for 8.5 GeV/c proton
- angular resolution is 0.3 mrad
- trigger threshold is 4 GeV from hadron calorimeter



Calorimeter response for 10 GeV protons from test for Compass experiment



Top view A-A