Nucleon Electromagnetic Form Factors

- Introduction
- Experimental Status of EMFF
- Analysis and Interpretation
- Outlook
- Summary

Kees de Jager
Exclusive Workshop
Jefferson Lab
May 18 - 21, 2010

Nucleon Electro-Magnetic Form Factors

- Fundamental properties of the nucleon
  - A testing ground for theories constructing nucleons from quarks and gluons
  - Provides insight in spatial distribution of charge and magnetization
    - Wavelength of probe can be tuned by selecting momentum transfer Q:

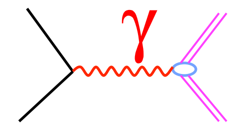
< 0.1 GeV^2	integral quantities (charge radius,…)
0.1-10 GeV^2	internal structure of nucleon
> 20 GeV^2	pQCD scaling

Caveat: If Q is several times the particle that the virtual photon is interacting with (~Compton wavelength), dynamical (relativistic) effects make a physical interpretation more difficult

- Over the last decade there has been a dramatic improvement in precision and Q^2-coverage thanks to the development of polarized beam (> 100 μA, > 85 %), polarized targets and polarimeters with large analyzing powers
- The observation of a linear decrease with Q^2 of G_E^p/G_M^p established the role of quark Orbital Angular Momentum (OAM) in the nucleon, confirmed by nucleon spin structure studies ("spin crisis", ΔG,…)

Formalism

Dirac (non-spin-flip) F_1 and Pauli (spin-flip) F_2 Form Factors



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

with E (E') incoming (outgoing) energy, θ scattering angle, μ anomalous magnetic moment and $\kappa = Q^2/4M^2$

Alternatively, Sachs Form Factors G_E and G_M can be used

$$F_1 = G_E + \tau G_M \qquad F_2 = \frac{G_M - G_E}{\kappa(1+\tau)} \qquad \tau = \frac{Q^2}{4M^2}$$

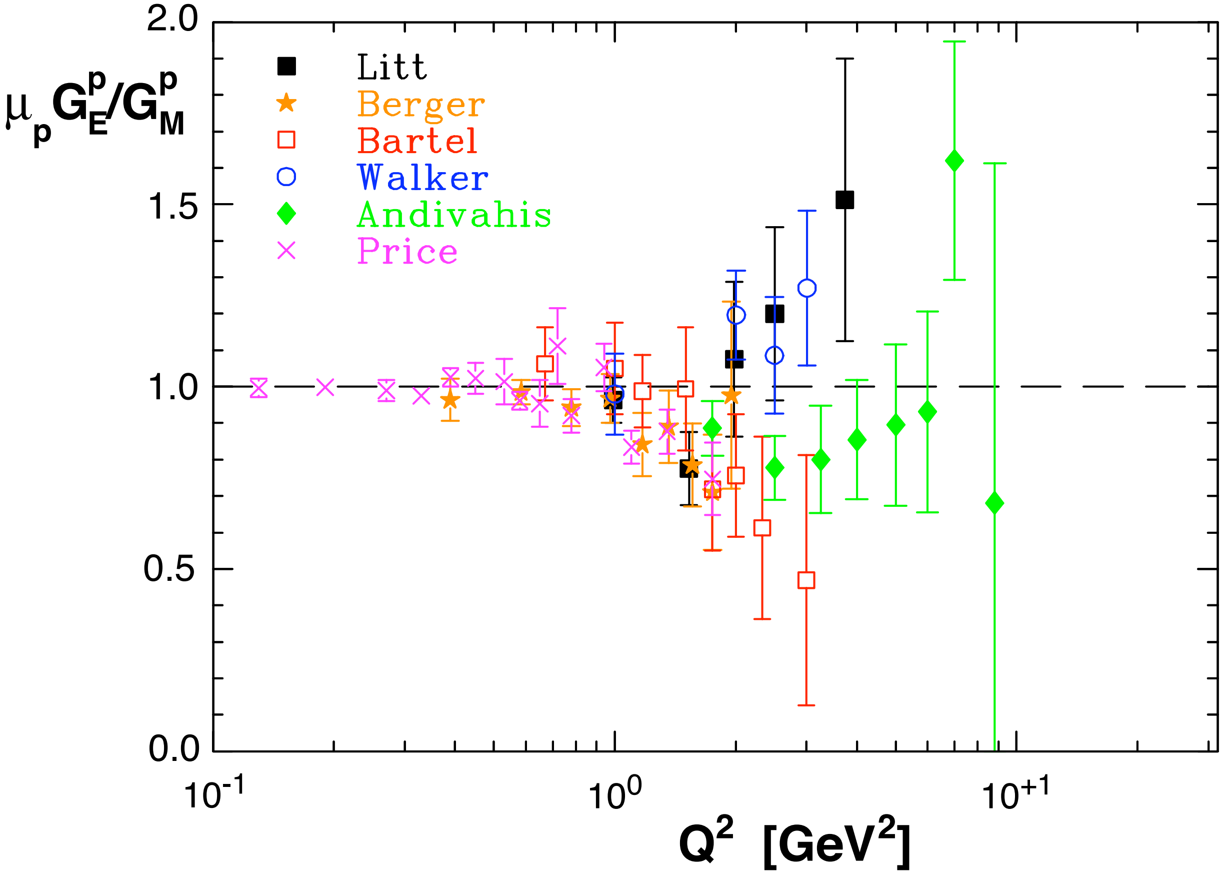
$$\frac{d\sigma}{d\Omega}(E,\theta) = \sigma_M [\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2(\frac{\theta}{2})]$$

$$\sigma_M = \frac{\alpha^2 E' \cos^2(\frac{\theta}{2})}{4E^3 \sin^4(\frac{\theta}{2})}$$

Separate the two Sachs FFs by measuring the cross section at one Q^2-value for various Θ-values (Rosenbluth separation).

In the Breit (centre-of-mass) frame the Sachs FF can be written as the Fourier transforms of the charge and magnetization radial density distributions

World Data Set on G_E^p by mid 1990s



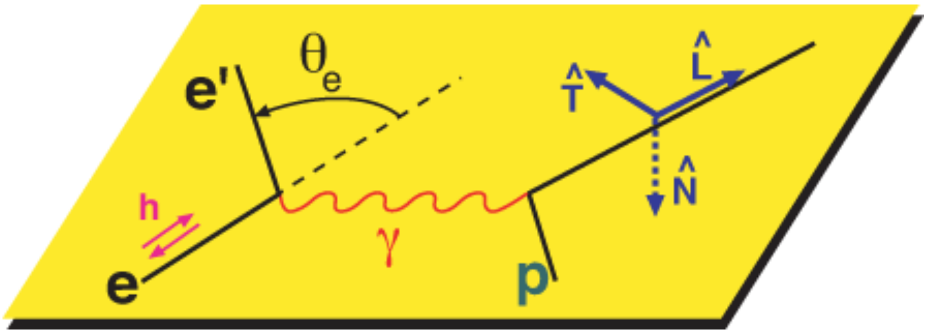
- Relied on Rosenbluth separation
- General assumption that $G_E^p/G_M^p \approx 1$
- Although data showed large scatter

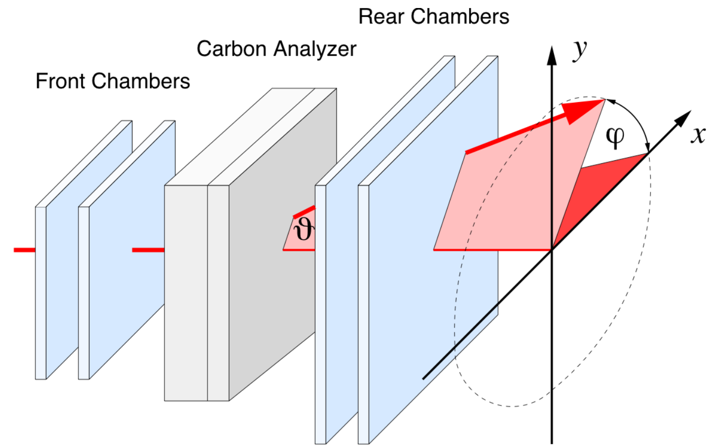
$$Q^2 = 4EE'\sin^2(\frac{\theta}{2})$$

$$\sigma_R\left(Q^2,\varepsilon\right) = \varepsilon\left(1+\frac{1}{\tau}\right)\frac{E}{E'}\frac{\sigma(E,\theta)}{\sigma_{Mott}} = (G_M^p)^2\left(Q^2\right) + \frac{\varepsilon}{\tau}(G_E^p)^2\left(Q^2\right)$$

$$\varepsilon = \frac{1}{1+2(1+\tau)\tan^2(\theta/2)}$$

Alternative: Spin Transfer Reaction $^1H(\vec{e},e'\vec{p})$



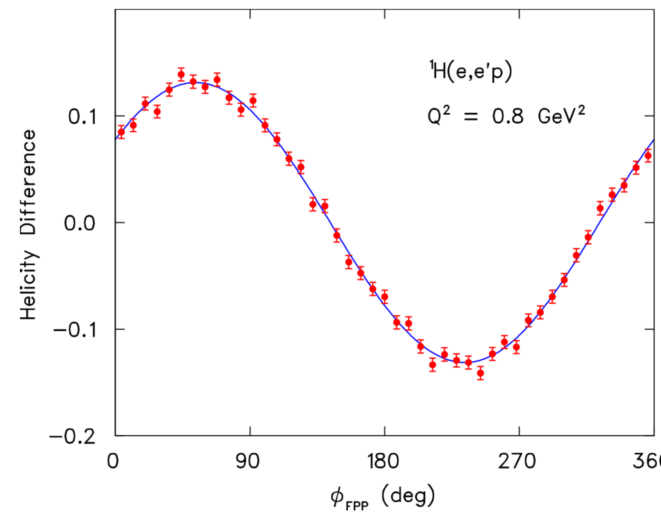


$$P_n = 0$$

$$\pm hP_t = \mp h 2\sqrt{\tau(1+\tau)} G_E^p G_M^p \tan\left(\frac{\theta_e}{2}\right) / I_0$$

$$\pm hP_l = \pm h(E_e + E_{e'})\left(G_M^p\right)^2 \sqrt{\tau(1+\tau)} \tan^2\left(\frac{\theta_e}{2}\right) / M / I_0$$

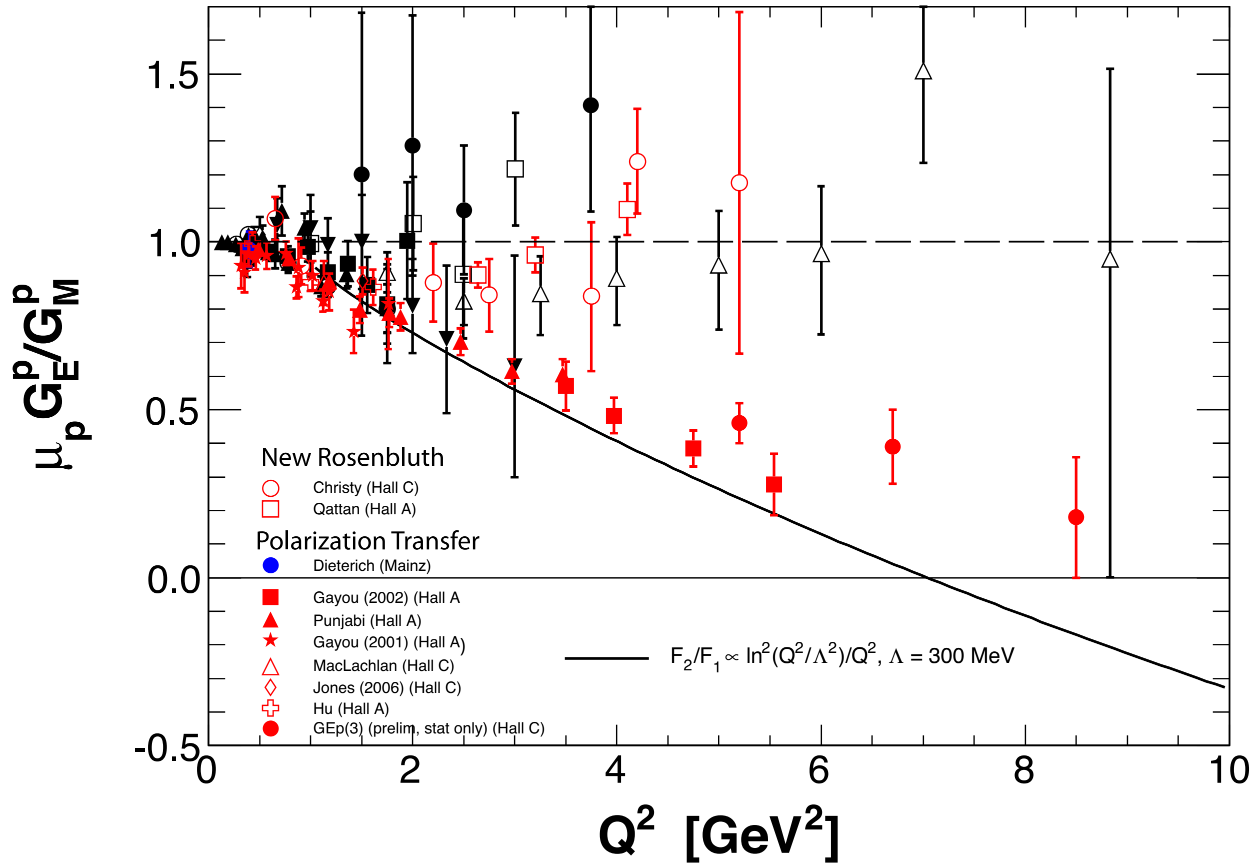
$$I_0 = \left\{G_E^p(Q^2)\right\}^2 + \tau\left\{G_M^p(Q^2)\right\}^2\left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]$$



$$\frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l}\frac{E_e + E_{e'}}{2M}\tan\left(\frac{\theta_e}{2}\right)$$

No error contributions from
- analyzing power
- beam polarimetry

World Data Set on G_E^p ten years later



→ Large new data set based on polarization transfer showed linear decrease of G_E^p/G_M^p with Q^2

→ In contrast with Rosenbluth data

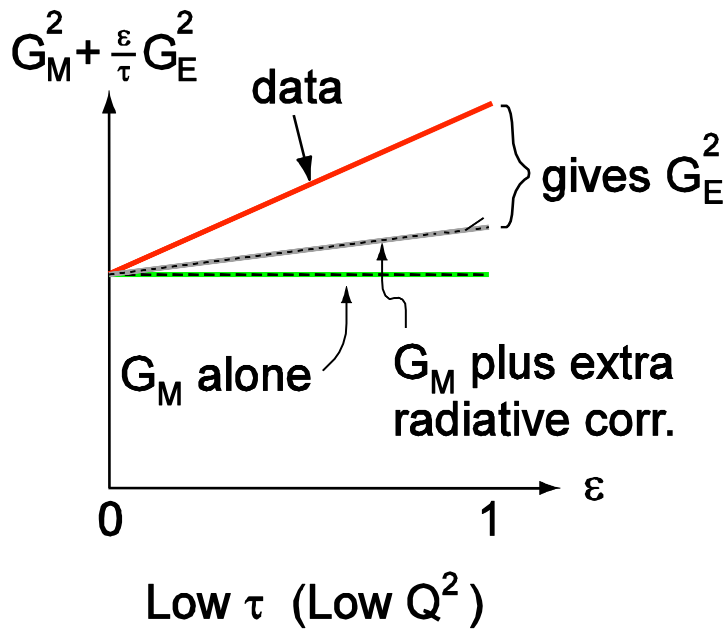
Andrew Puckett

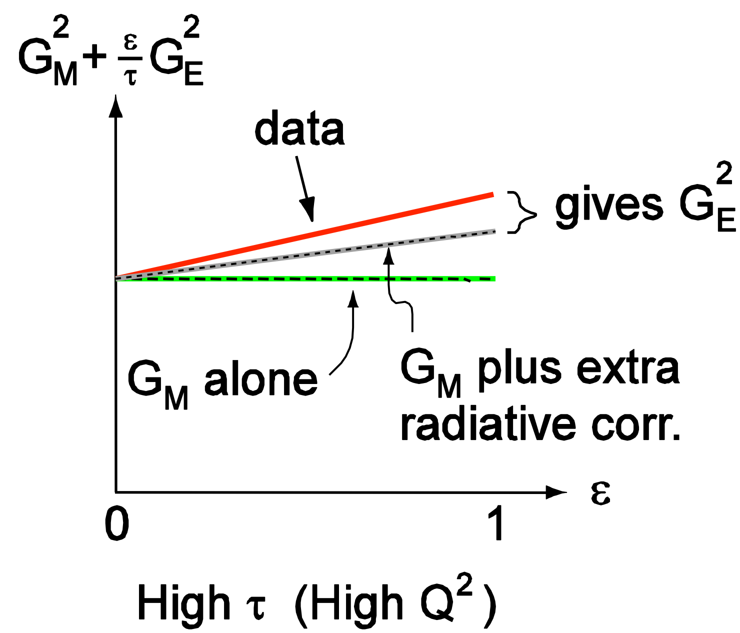
- Detailed reanalysis of SLAC data resulted in acceptable scatter of data
- JLab Rosenbluth data in agreement with SLAC data
- No reason to doubt quality of either Rosenbluth or polarization transfer data
- Investigate possible theoretical sources for discrepancy

Speculation : missing radiative corrections

Speculation : there are radiative corrections to Rosenbluth experiments that are important and are not included in the analysis

missing correction : linear in ε, but with no strong Q^2-dependence





G_E term is proportionally smaller at large Q^2

effect more visible at large Q^2

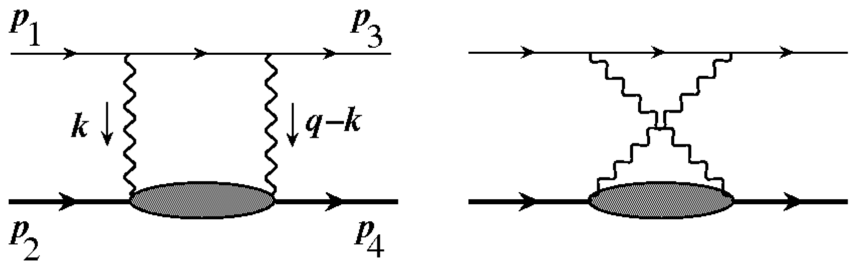
$Q^2 = 6\ GeV^2$

$$\frac{G_E^2}{\tau\, G_M^2} = \frac{4\, M^2}{Q^2\, \mu_p^2} = 7.5\%$$

if both FF scale in same way

John Arrington

Calculations of TPE effects



$d\sigma = d\sigma_0 (1 + \delta)$

$$\delta = 2f(Q^2,\varepsilon) + \frac{2\Re\left\{\mathfrak{M}_0^\dagger \overline{\mathfrak{M}_1}\right\}}{\left|\mathfrak{M}_0\right|^2} \longrightarrow \delta_{2\gamma} = \frac{2\Re\left\{M_\gamma^\dagger M_{2\gamma}\right\}}{|M_\gamma|^2}$$

$f(Q^2, \varepsilon)$ is the standard Mo & Tsai correction (soft photon exchange), which has some ε-dependence and is IR divergent

IR divergent terms are canceled by soft-photon emission terms

Two methods of calculating $\delta_{2\gamma}$:

Hadronic
Use nucleon-pole diagrams with on-shell form factors in photon-nucleon vertices
Blunden, Melnitchouk,Tjon (BMT), PRC 72, 034612 (2005)

Partonic
Factorize TPE amplitude into hard process of e-q scattering and a soft process described by GPDs

Effect on L-T Extractions

Arrington, Melnitchouk, Tjon
PRC 76, 035205 (2007)

full reanalysis of data, incorporating BMT calculations, but adding extra (small) phenomenological correction above $Q^2 = 1\ GeV^2$

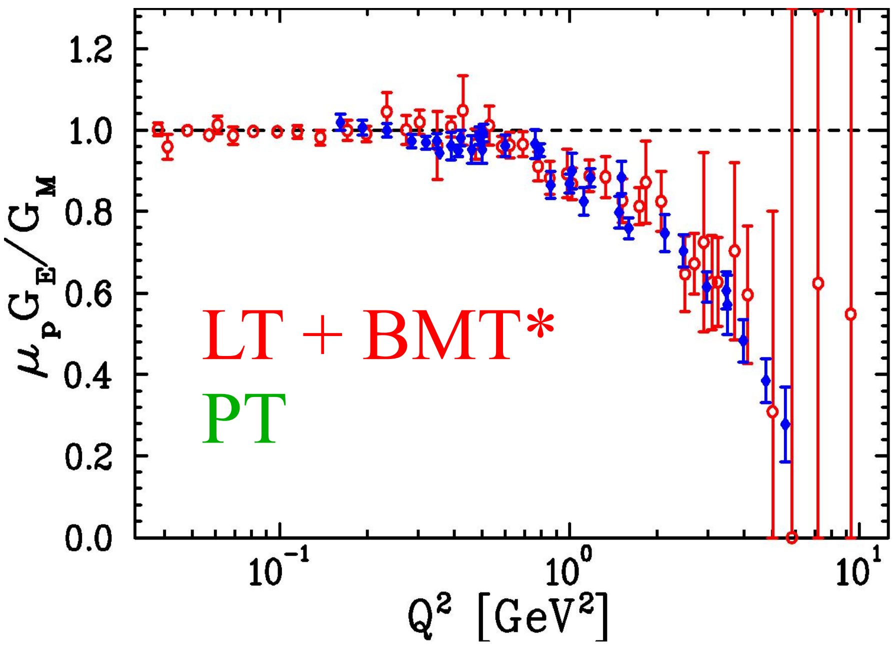
$$\delta^*_{2\gamma} = 0.01[\varepsilon - 1]\frac{\ln Q^2}{\ln 2.2}$$

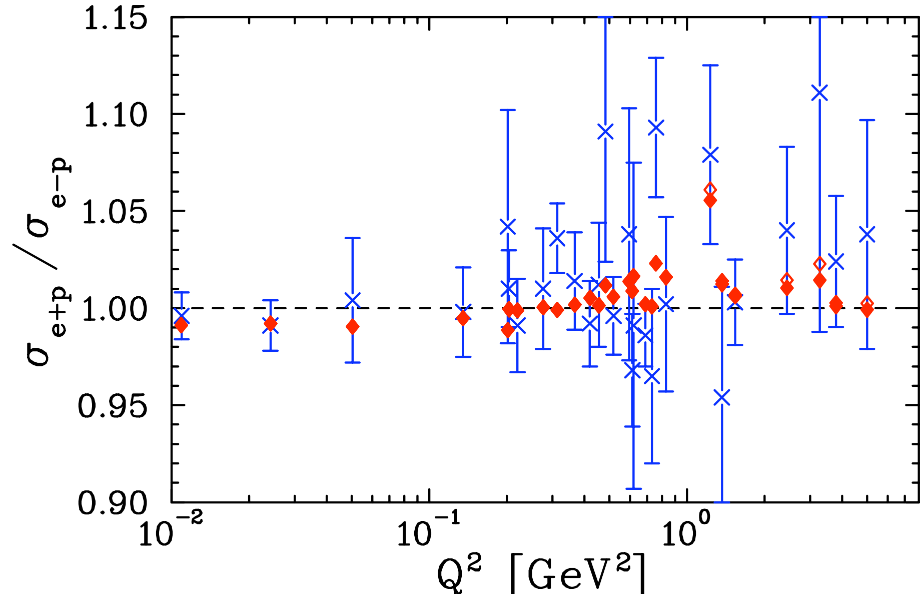
~1% at 2 GeV^2, 2% at 5 GeV^2

- Apply 100% of the extra correction as an uncertainty (affects G_M^p uncertainty)

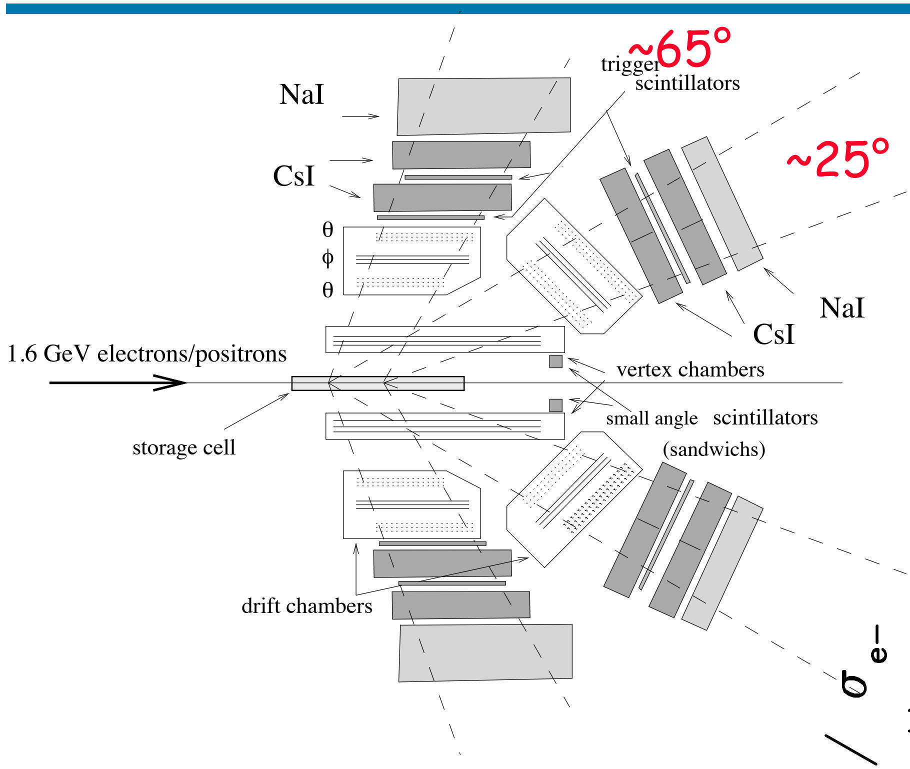
- Corrections hardly visible in e^+/e^- ratio

New e^+/e^- data expected soon: BINP (data), DESY (2012), CLAS (2012)

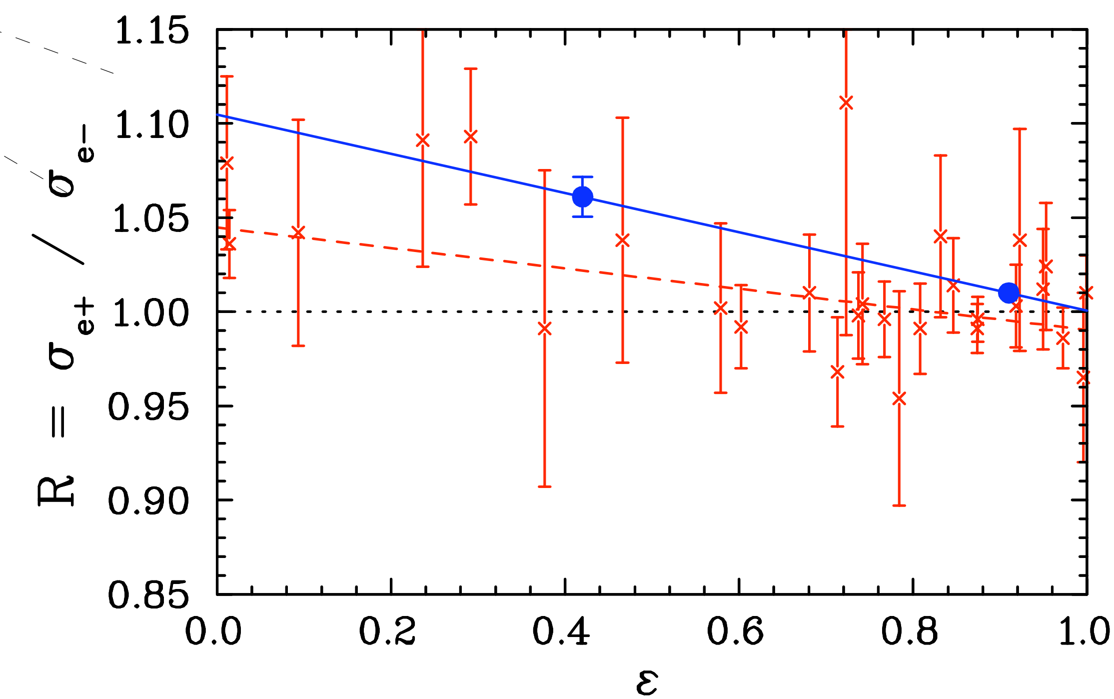




VEPP-3 positron-electron comparison

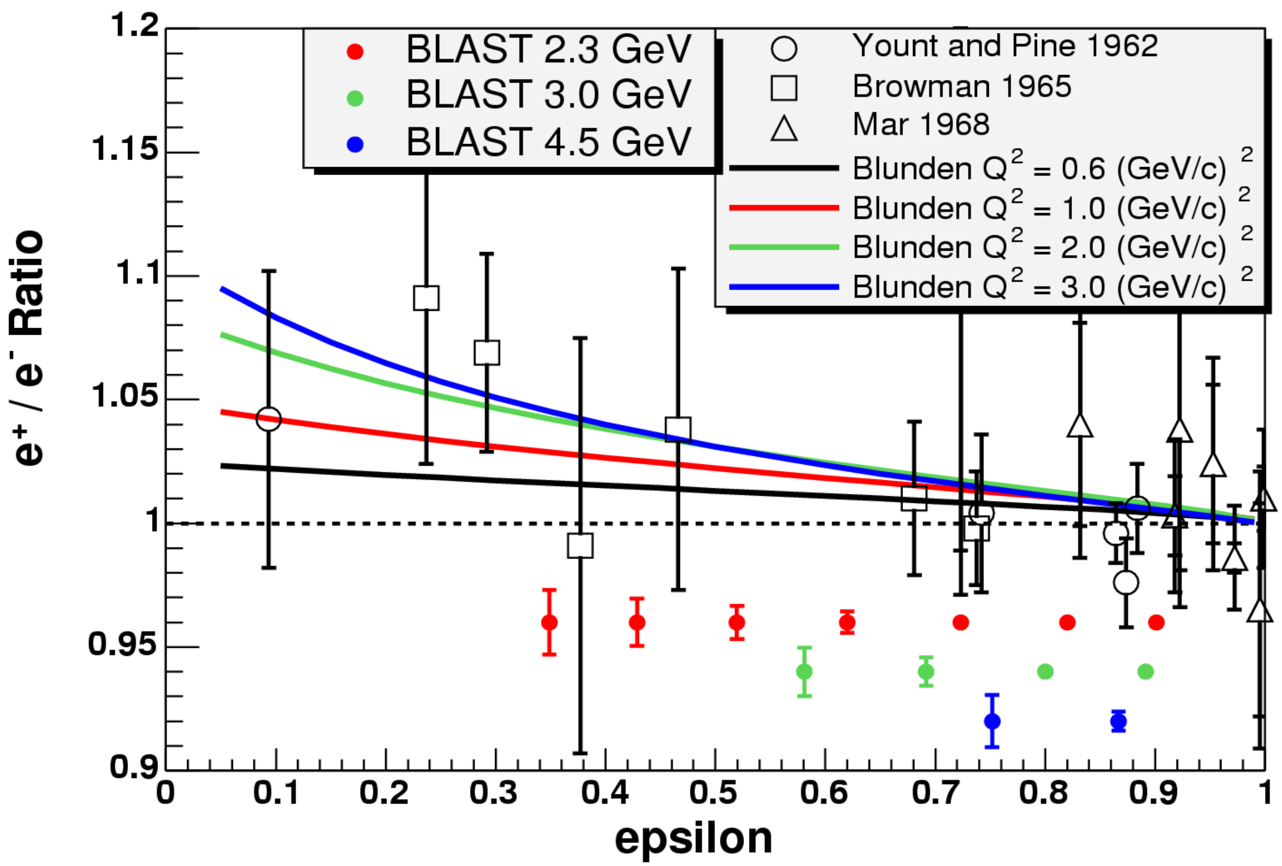


- Use VEPP-3 ring (50 mA)
- e^+/e^- energy 1.6 GeV
- $\theta \approx 25°$ and 65°
- $Q^2 \approx 0.3$ and 1.5 GeV^2
- Internal gas target
- Luminosity $\approx 5 \cdot 10^{31}$ (cm^{2}s)$^{-1}$



J. Arrington, D. Nikolenko, spokespersons, nucl-ex/04-08020

Projected results for OLYMPUS@DESY

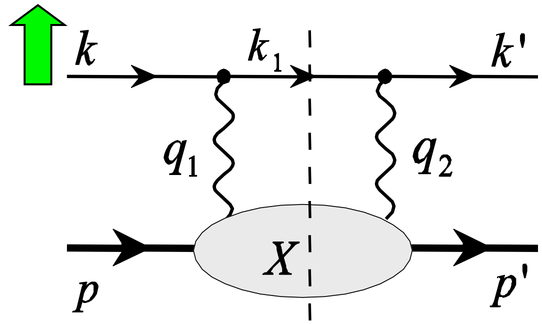


1000 hours each for e^+ and e^-
Lumi = 6×10^{32} cm^{-2} s^{-1}

2008 – Full proposal submtted and approved
2009/10 – Transfer of BLAST
2012 – OLYMPUS Running

SSA in elastic eN scattering

spin of beam OR target OR
recoil proton NORMAL
to scattering plane



$$s = (k+p)^2$$

on-shell intermediate state (M_X = W)

→ involves the imaginary part of two-photon exchange amplitudes

Target: general formula of order e^2

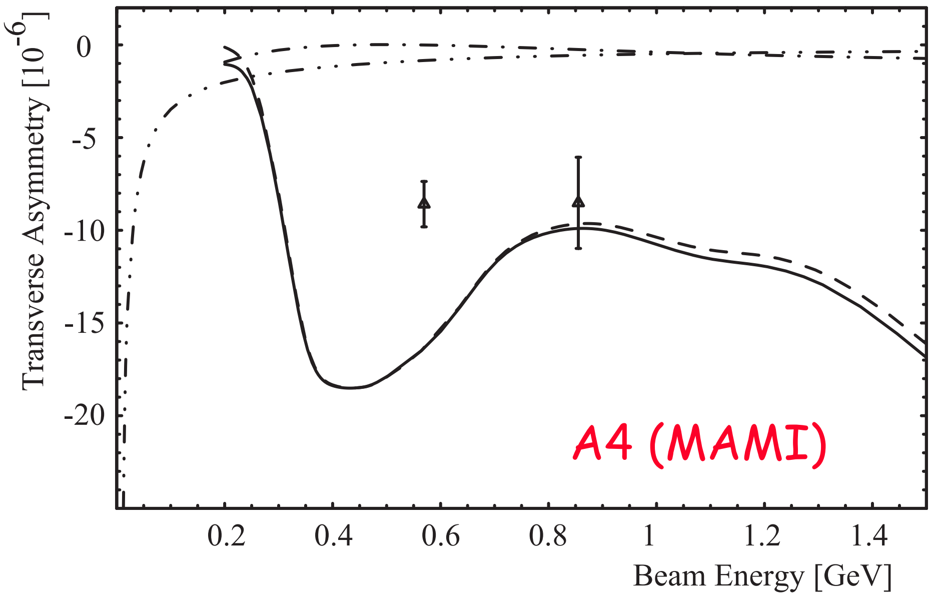
- GPD model allows connection of real and imaginary amplitudes
- Hadronic models sensitive to intermediate state contributions, no reliable theoretical calculations at present
- First data taken late 2008 in QE scattering off polarized ^3He (E05-015)

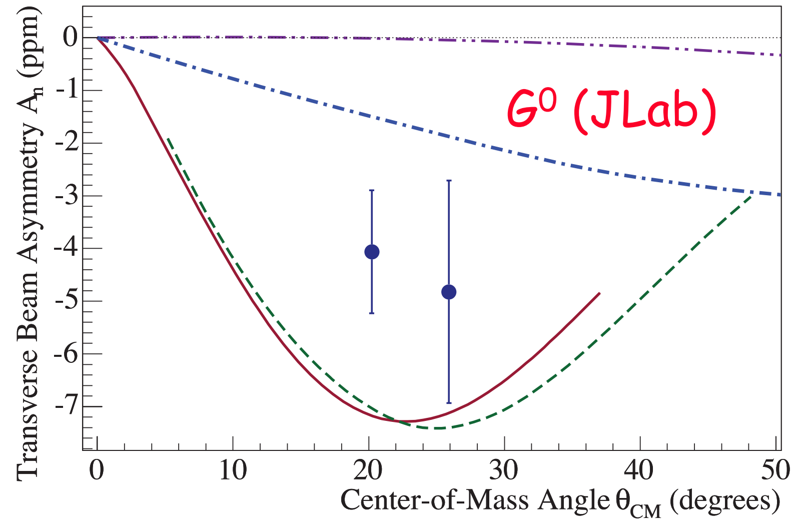
Beam: general formula of order $m_e\, e^2$ (few ppm)

- Measured in PV experiments (longitudinally polarized electrons) at SAMPLE, A4 (Mainz), G^0 and HAPPEx (JLab)
- Only non-zero result so far for TPEX

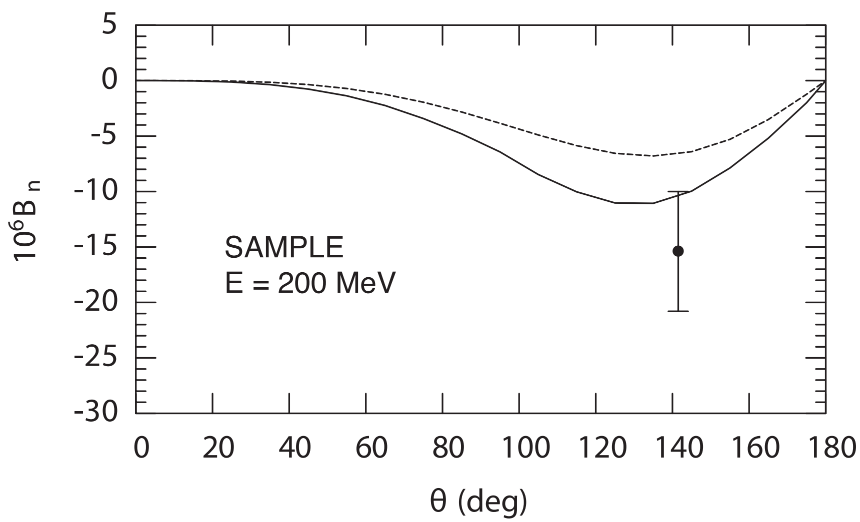
Peter Blunden

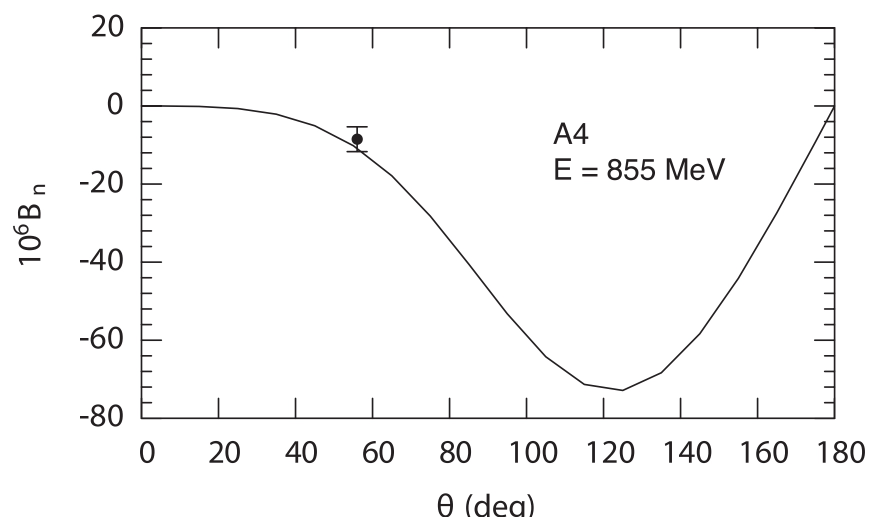
Some available data on SSA



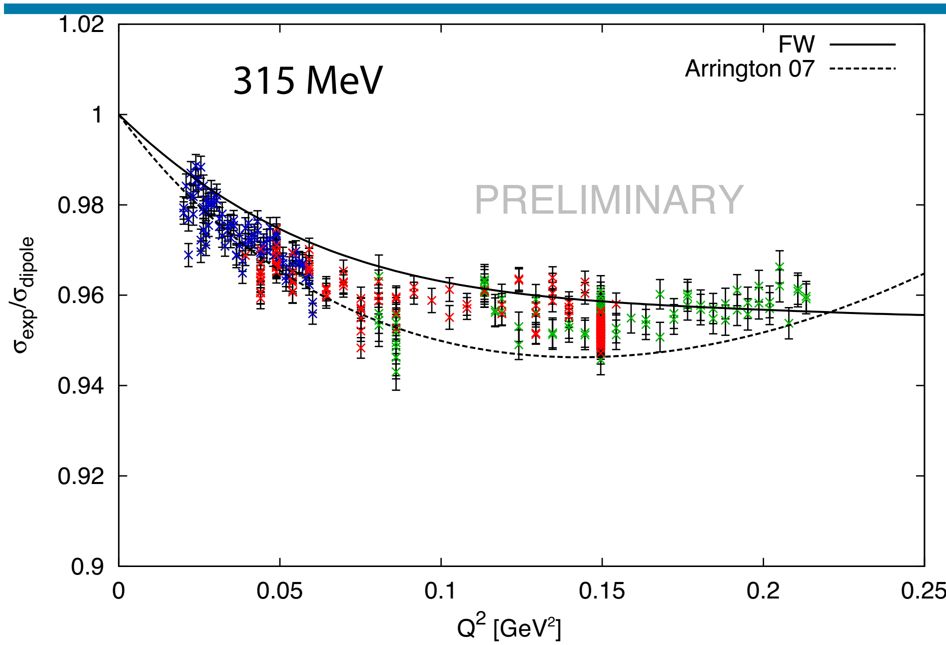


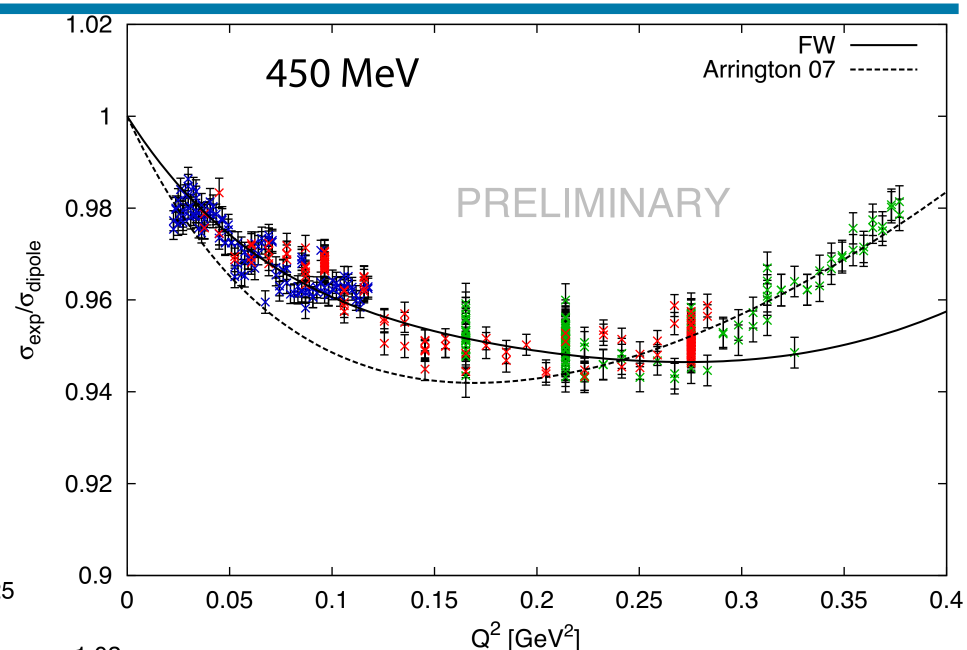
More recent calculations by Borisyuk&Kobushkin (arXiv:0812.0469)

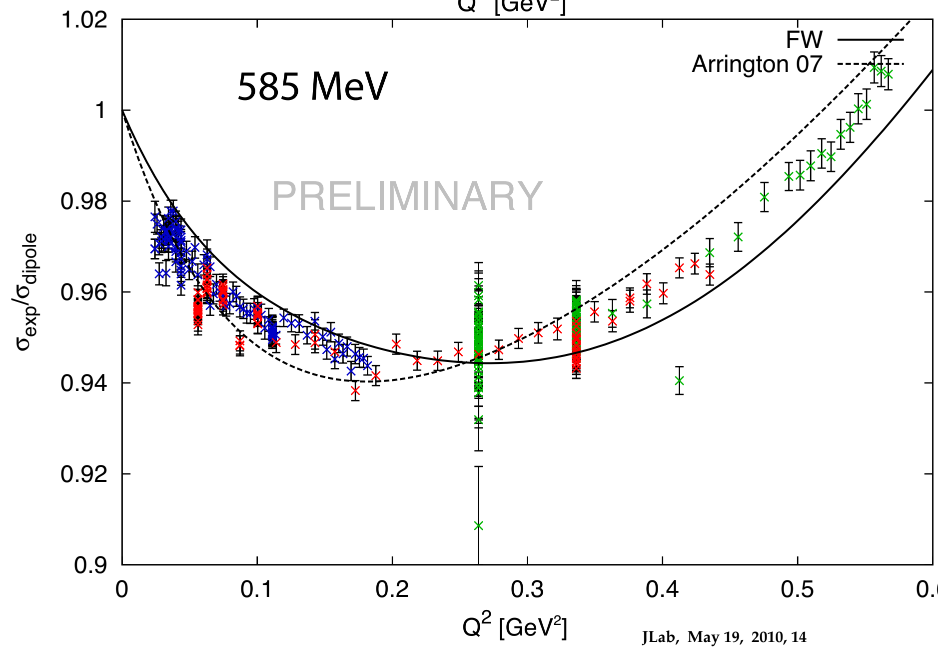




Proton cross-section data from MAMI







- Bernauer et al. collected a large data set using all three A1 spectrometers
- The projected ≤1% accuracy will allow an L/T separation in a Q^2-range of 0.02 to 0.5 GeV^2
- Data analysis has been completed and will be available shortly

Polarization Transfer at low Q^2-values

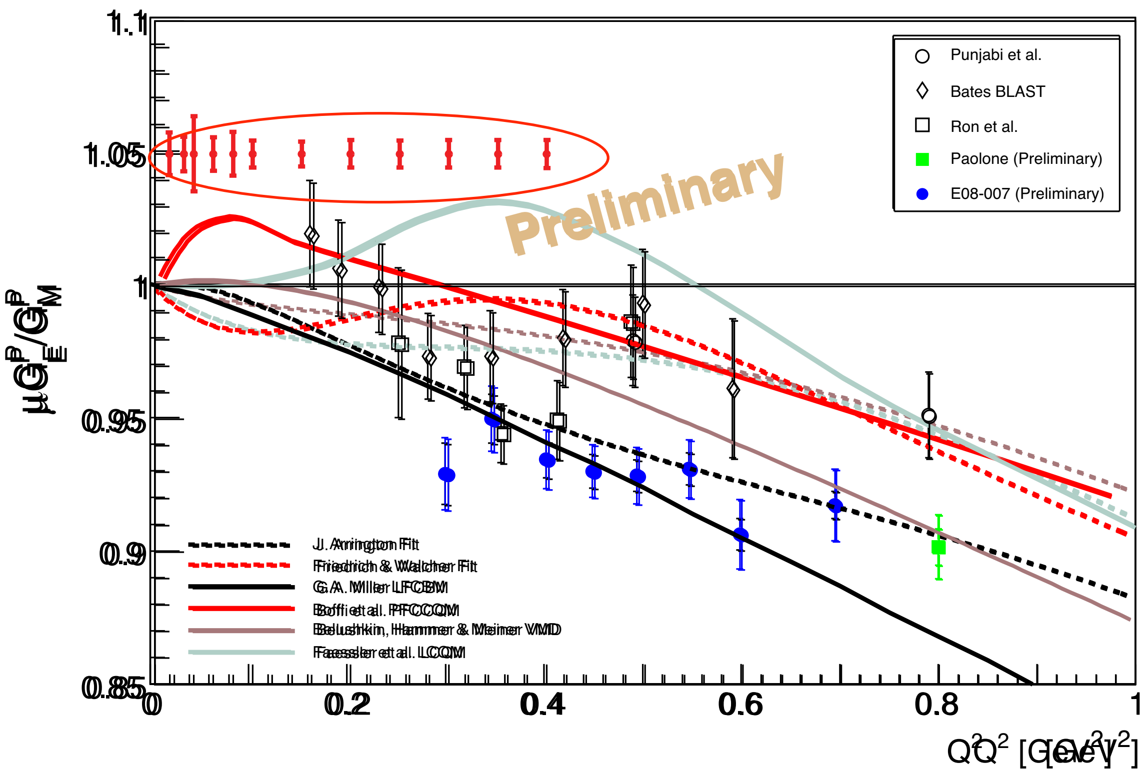
Detailed understanding of Hall A HRS spectrometer optics and availability of BigBite spectrometer has made possible polarization transfer measurements with a ~1% accuracy in a Q^2-range from 0.3 – 0.7 GeV^2

Results are in disagreement (at a better precision) with earlier data

New data analyzed together with new cross-section data set measured at MAMI will allow to set sensitive limits to TPE effects at low Q^2

Xiaohui Zhan
Ph.D. thesis

Further data at Q^2-values down to 0.1 GeV^2 are scheduled for late 2011 with a DNP target



Measuring G^n_M

Old method: quasi-elastic scattering from ^2H
large systematic errors due to subtraction of proton contribution

$$R_D = \frac{\dfrac{d^3\sigma(eD \Rightarrow e'n(p))}{dE'\,d\Omega_{e'}d\Omega_n}}{\dfrac{d^3\sigma(eD \Rightarrow e'p(n))}{dE'\,d\Omega_{e'}d\Omega_p}}$$

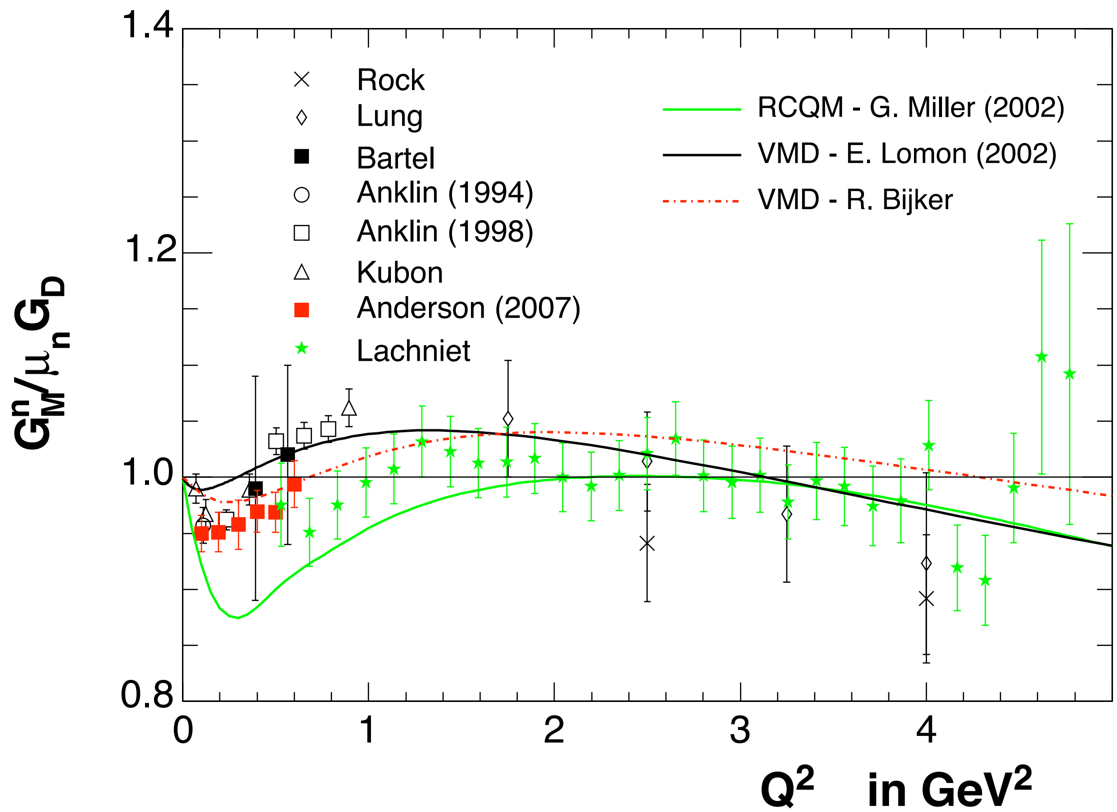
- Measure (en)/(ep) ratio
  Luminosities cancel
  Determine neutron detector efficiency
  - On-line through e+p->e'+π^+(+n) reaction (CLAS)
  - Off-line with neutron beam (Mainz)

- Measure inclusive quasi-elastic scattering off polarized ^3He

$$A = \frac{-\left(\cos\theta^* v_{T'} R_{T'} + 2\sin\theta^* \cos\varphi^* v_{TL'} R_{TL'}\right)}{v_L R_L + v_T R_T}$$

$R_{T'}$ directly sensitive to $(G_M{}^n)^2$

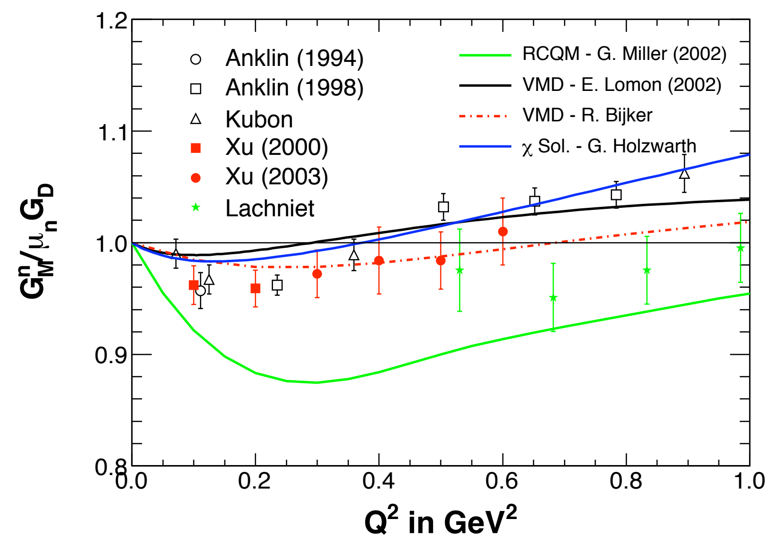
Overview of results for G_M^n



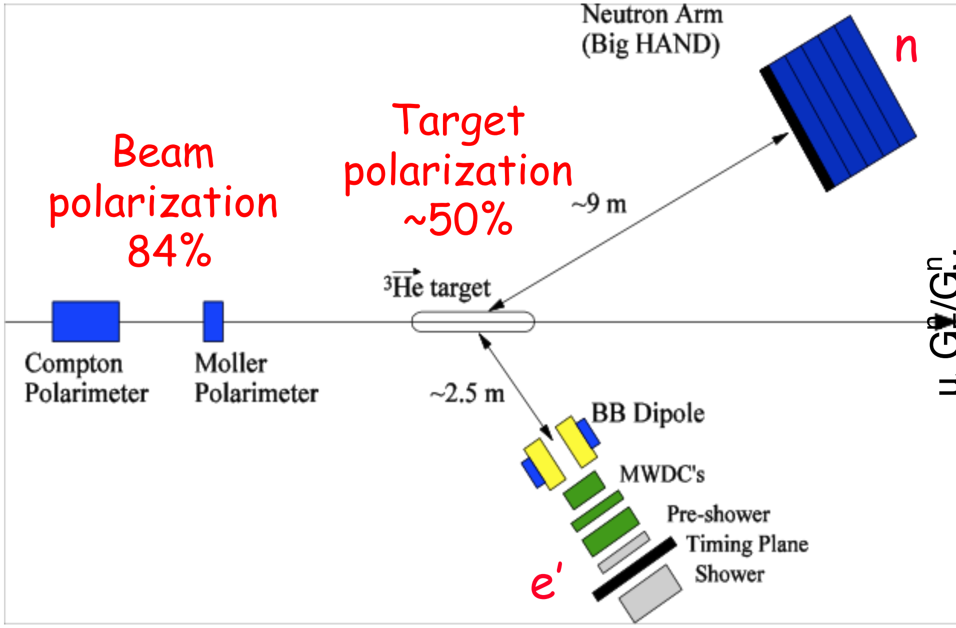
High-quality data set now available up to ~4.5 GeV^2

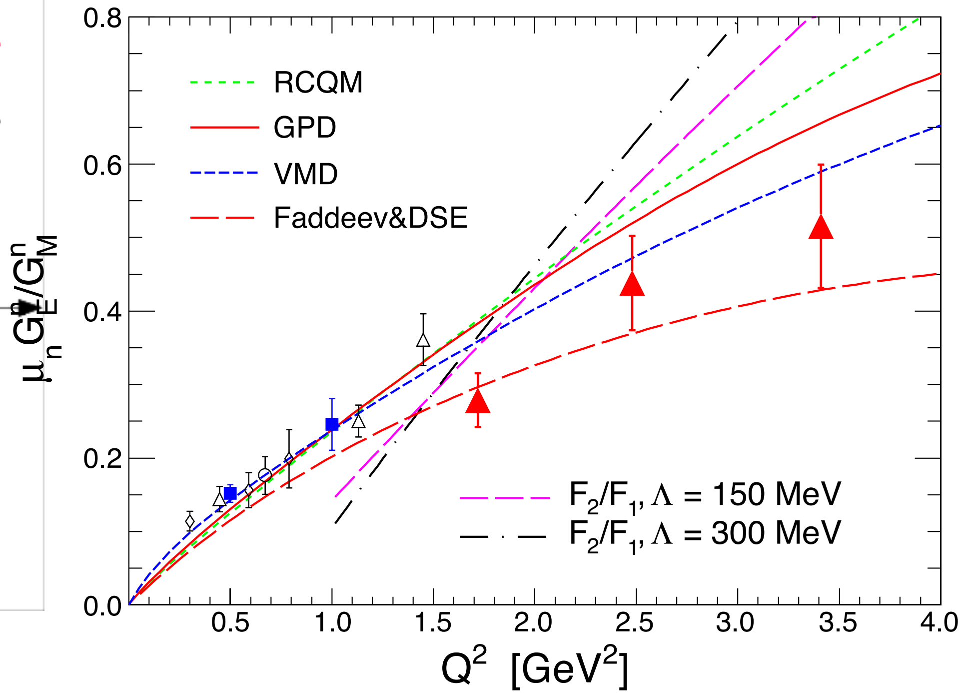
Jerry Gilfoyle

- ➙ A systematic difference of several % between results from JLab and MAMI in Q^2-range 0.4 - 1.0 GeV^2
- ➙ Reminder that at least two independent experiments are always needed



G_E^n from polarized ^{3}He target: $^3\vec{He}(\vec{e},e'n)$



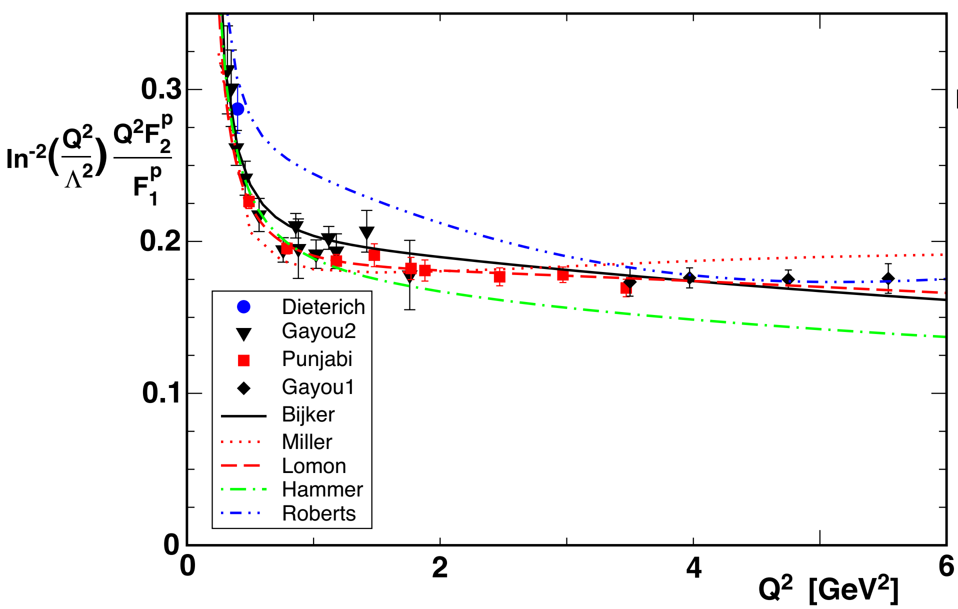


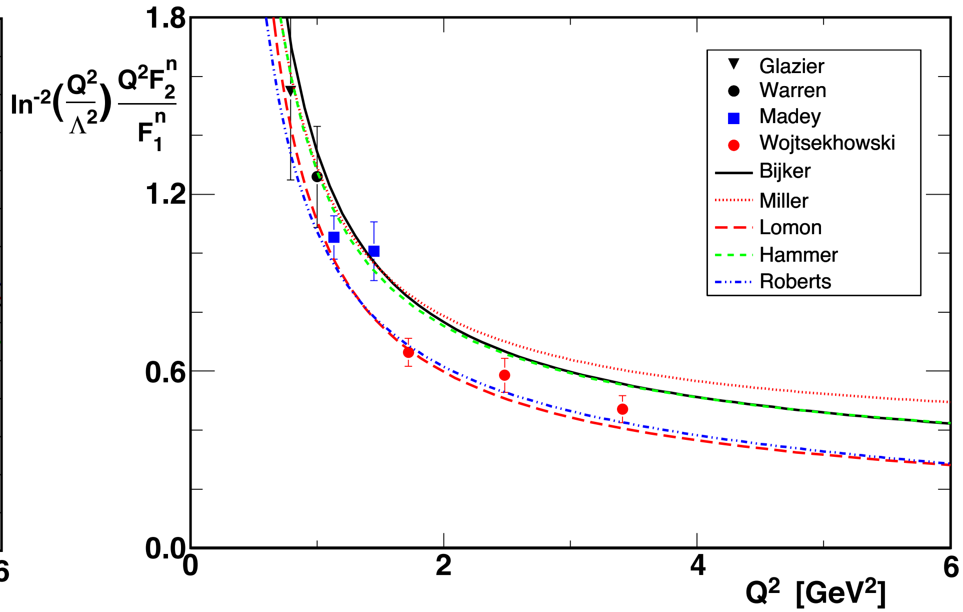
Seamus Riordan

- New data more than double the Q^2-range of the world data set
- Roberts' dressed quark-diquark model using the Dyson-Schwinger and Faddeev equations in good agreement, better than Miller's CQM prediction
- Belitsky/Ji logarithmic scaling does not hold for the neutron in the Q^2-region where it was validated by the proton data
- New data will add significant constraints to GPD modeling

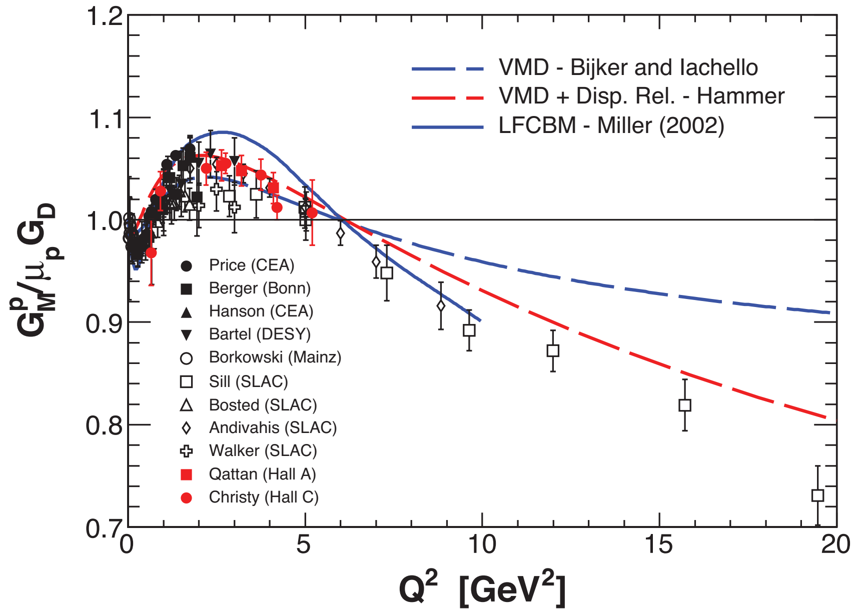
(Logarithmic) Scaling

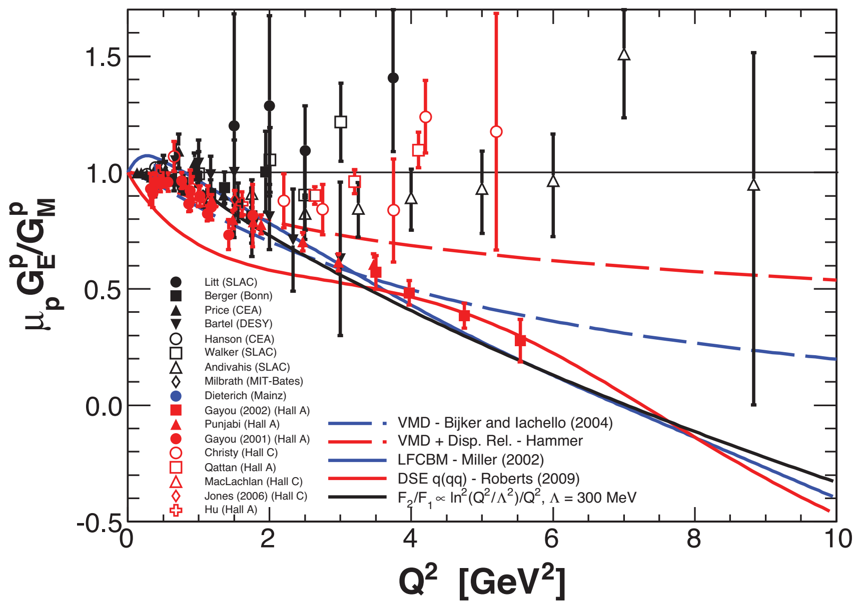
- Basic pQCD scaling predicts $F_1 \propto 1/Q^4$; $F_2 \propto 1/Q^6 \rightarrow F_2/F_1 \propto 1/Q^2$
- Data clearly do not follow this trend (yet?)
- The introduction of a quark orbital angular momentum component results in
  - $F_2/F_1 \propto 1/Q$
- Belitsky et al. have included logarithmic corrections in pQCD limit
- Proton data appear to follow this scaling behaviour, but new neutron data do not

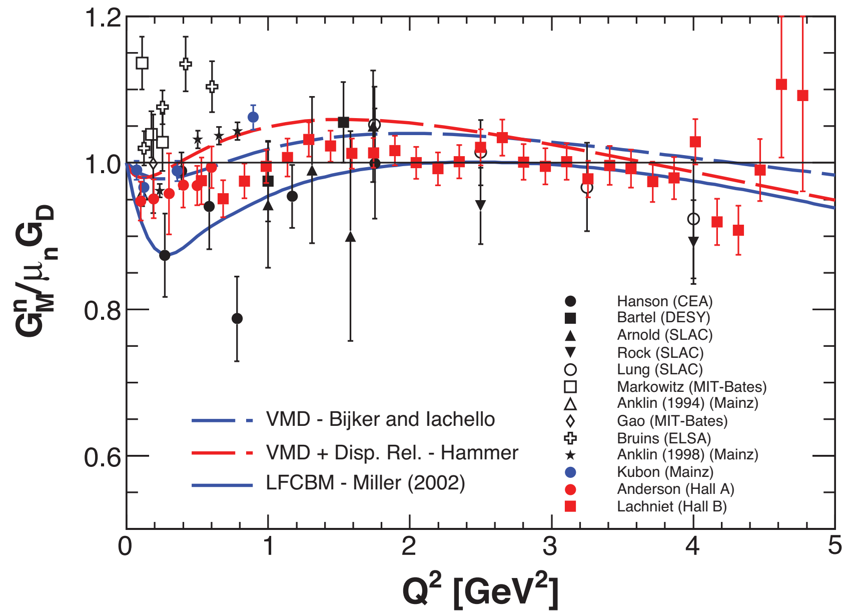


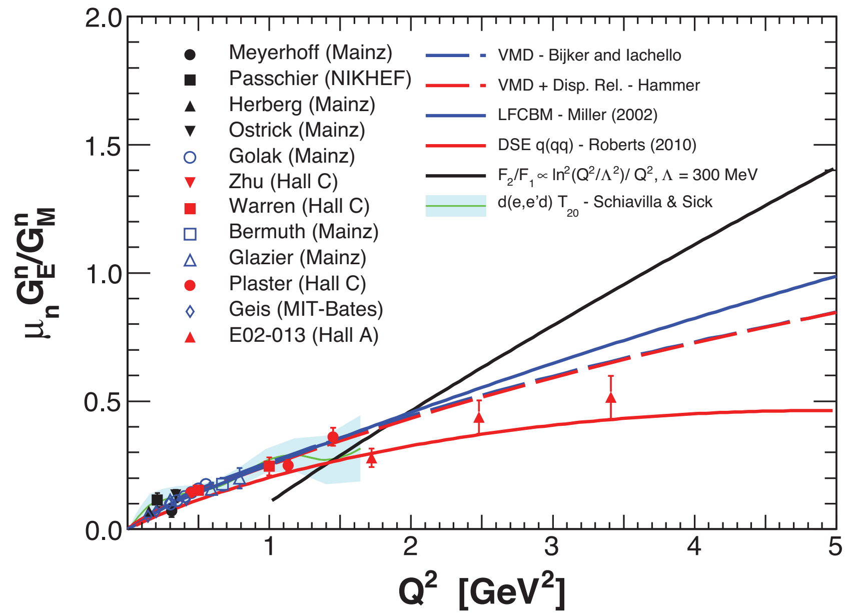


Comparison with Theory

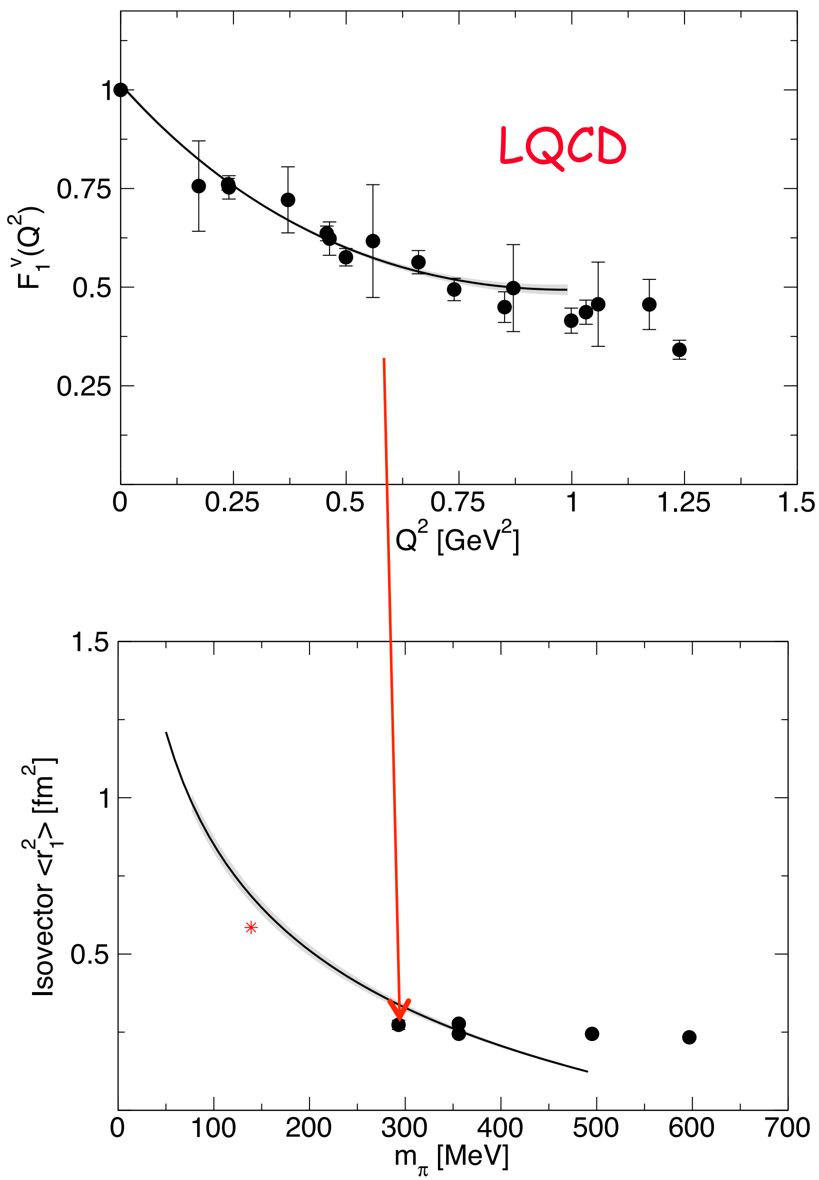


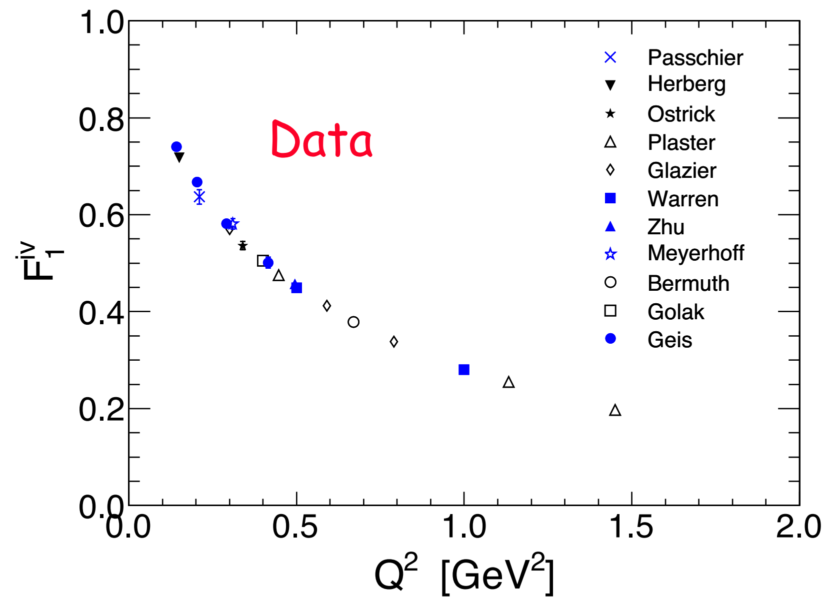






Status of Lattice QCD





Significant progress in LQCD, but still limited to $m_\pi \geq 300$ MeV and neglect of disconnected diagrams, resulting in large underestimates of e.g. isovector charge radius

Bratt et al., arXiv: 1001.3620

Nucleon densities and relativity

$$\rho(r) = \frac{2}{\pi}\int_0^\infty dk\, k^2\, j_0(k\,r)\, \tilde{\rho}(k)$$

rest frame

rest frame density

intrinsic FF

Q^2-evolution of quark mass (nucl-th/9812063)

- non-relativistic limit: $\tilde{\rho}(k) = G(Q^2)$

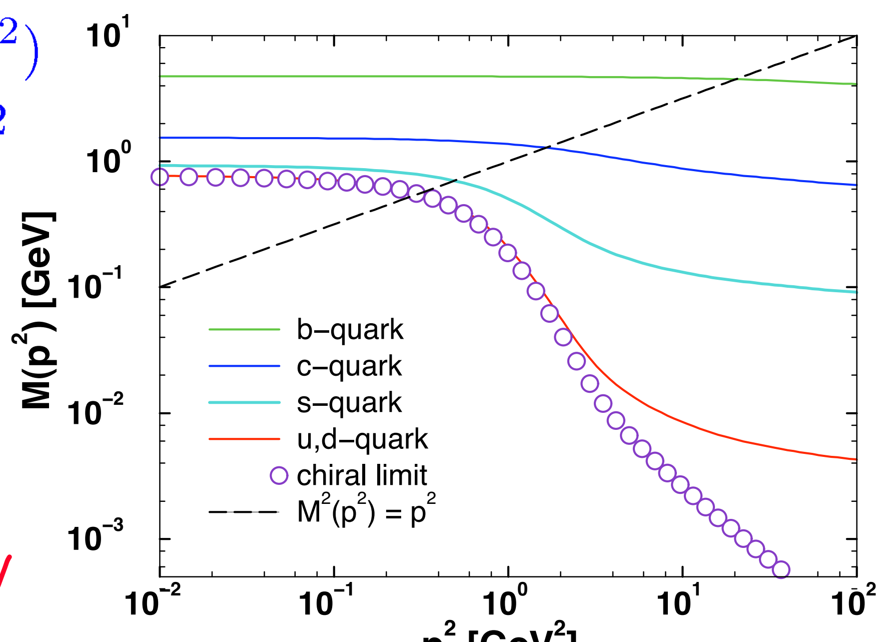
- importance of relativity (with increasing Q^2) :
  Lorentz contraction of spatial distributions in Breit frame

$$k^2 = Q^2/(1+\tau) \qquad \tau = Q^2/(4M^2)$$

$$\tilde{\rho}_{E,M}(k) = G_{E,M}(Q^2)(1+\tau)^2$$

- limit : k = 2 M (Compton wavelength)
  Thus, Fourier transform remains
  valid for $r > r_{min} \approx 0.3$ fm

At Q ≈ 0.6 GeV (r ≈ 0.3 fm) $m_{u/d} \approx 0.3$ GeV

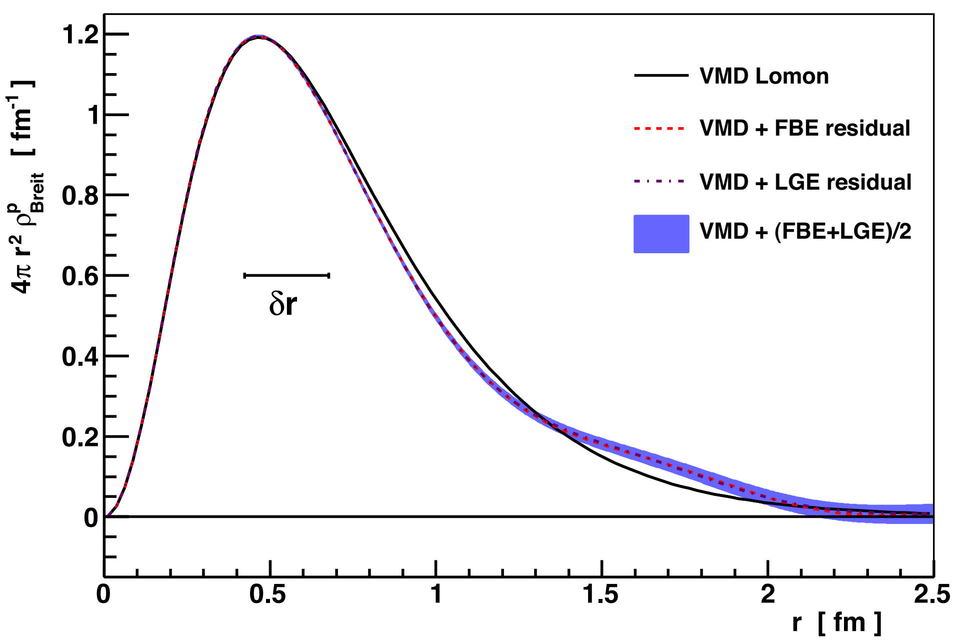


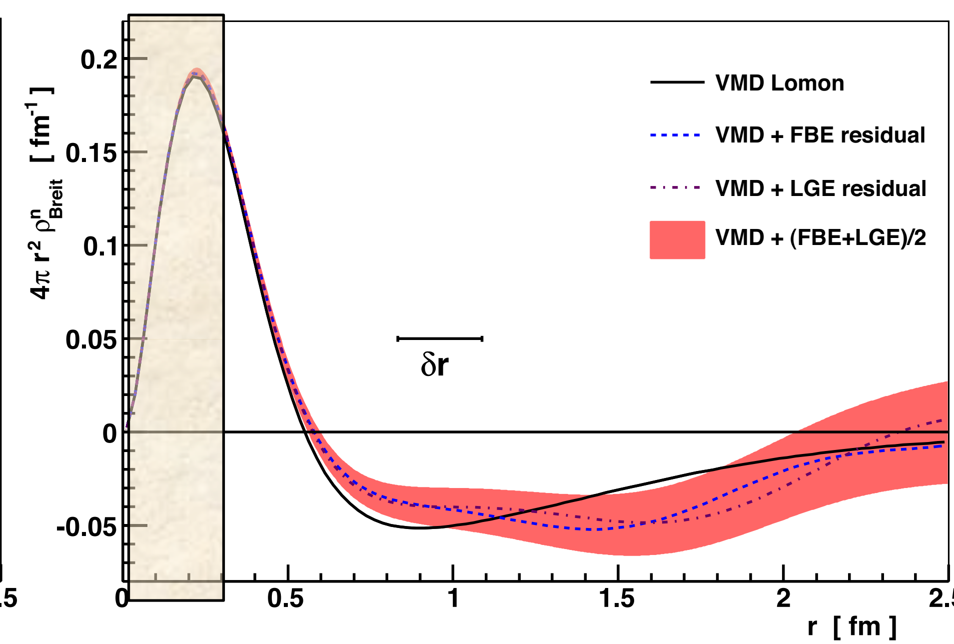
Pion Cloud

No information extractable

- Kelly and Friedrich and Walcher have performed simultaneous fit to all four EMFF in coordinate space. Both observe a structure in the proton and neutron densities at ~0.9 fm which they assign to a pion cloud
- Crawford et al. performed a global fit to all four EMFF within the framework of Lomon's VMD parametrization, including an estimate of the unmeasured high-Q^2 region with either a Fourier-Bessel or a Laguerre expansion. A straight-forward transformation to coordinate space is shown below.

C. Crawford et al., arXiv:1003.0903

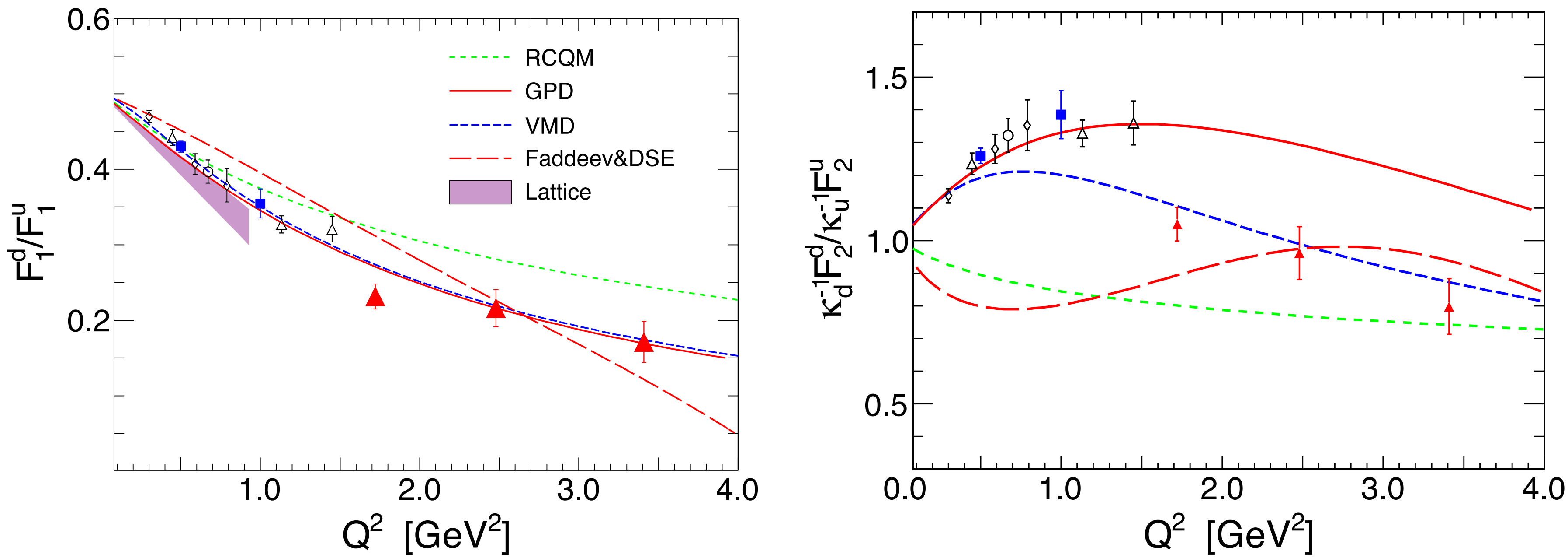




$F_{1,2}$ form-factor decomposition

$$F_{1,2}^{p} = \frac{2}{3}F_{1,2}^{u} - \frac{1}{3}F_{1,2}^{d}; \qquad F_{1,2}^{n} = \frac{2}{3}F_{1,2}^{d} - \frac{1}{3}F_{1,2}^{u}$$

assuming isospin symmetry: $F_{1,2}^{u,p} = F_{1,2}^{d,n}$ and $F_{1,2}^{d,p} = F_{1,2}^{u,n}$

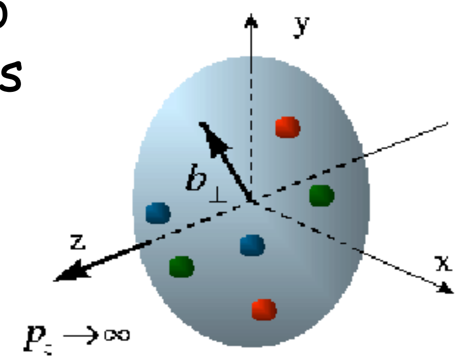


- New data have been used to flavor separate the Pauli and Dirac FFs
- Assuming that the s-quark contribution is negligible (based on the HAPPEx plus G0 results)
- Clearly, the F_2 ratio provides a sensitive test for theoretical predictions

Nucleon transverse charge density

Light Front Kinematics

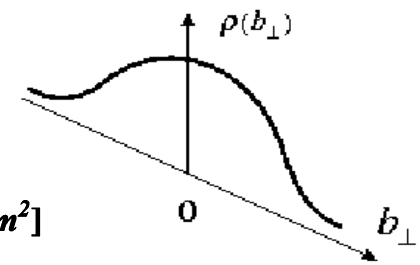
photon only couples to forward moving quarks



⇨ Transverse (Dirac) charge density of unpolarized nucleon

$$\rho_0^N(\vec{b}) \equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2} e^{-i\vec{q}_\perp \cdot \vec{b}} \frac{1}{2P^+} \left\langle P^+, \frac{\vec{q}_\perp}{2}, \lambda \,|\, J^+(0) \,|\, P^+, -\frac{\vec{q}_\perp}{2}, \lambda \right\rangle$$

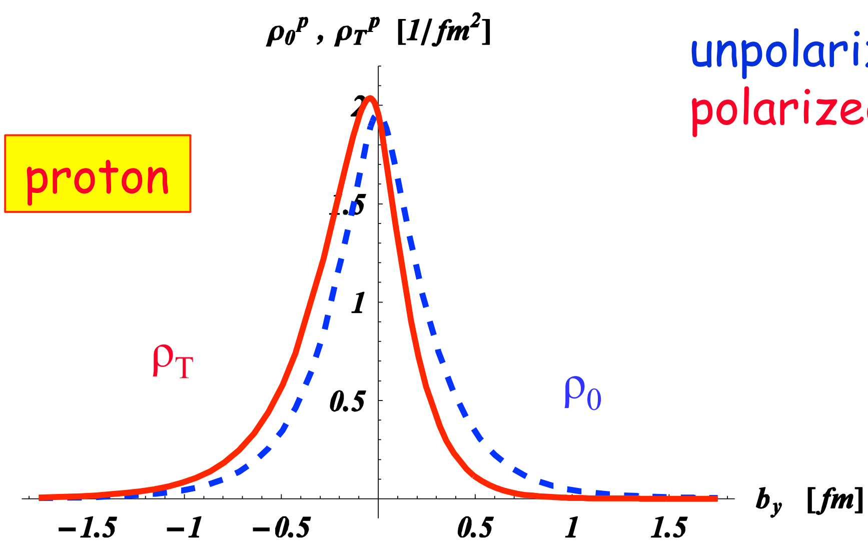
$$= \int_0^\infty \frac{dQ}{2\pi} Q J_0(bQ) F_1(Q^2)$$

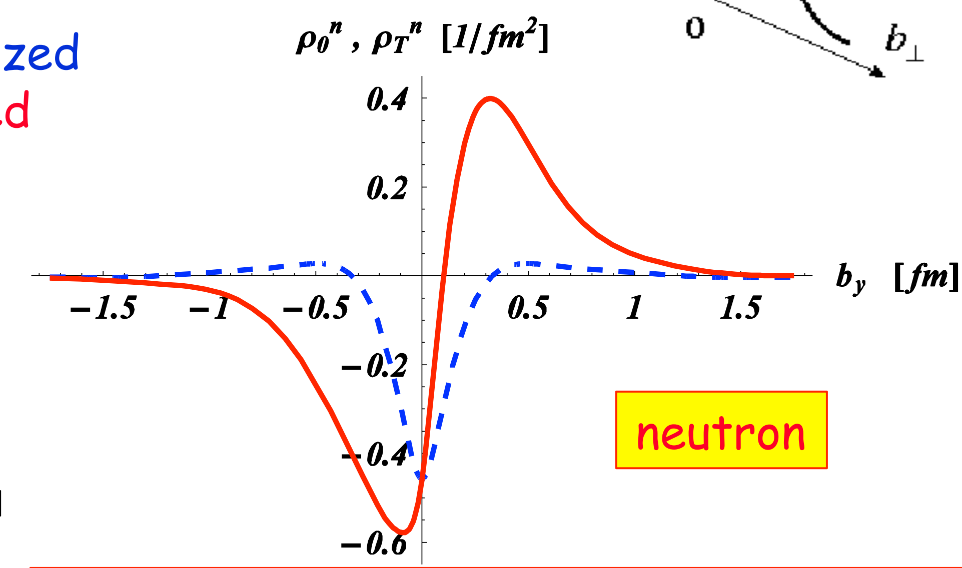


unpolarized

polarized

proton





neutron

J. Miller; C. Carlson & M. Vanderhaegen

Unrelated to rest-frame charge density

Mapping of nucleon constituents (in the proton)

impact parameter *b*
is defined relative to
the transverse center of
the quark's longitudinal
momentum fractions

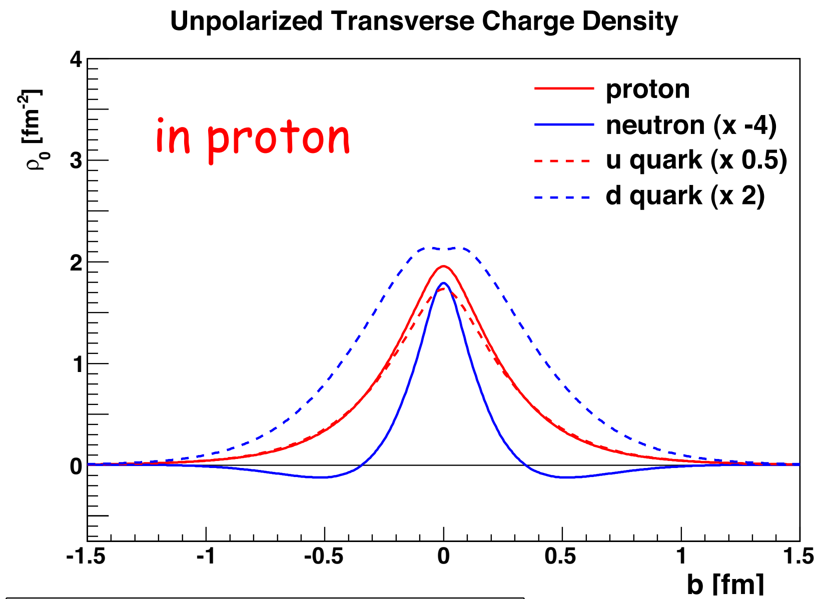
$$R = \sum x_i r_i$$

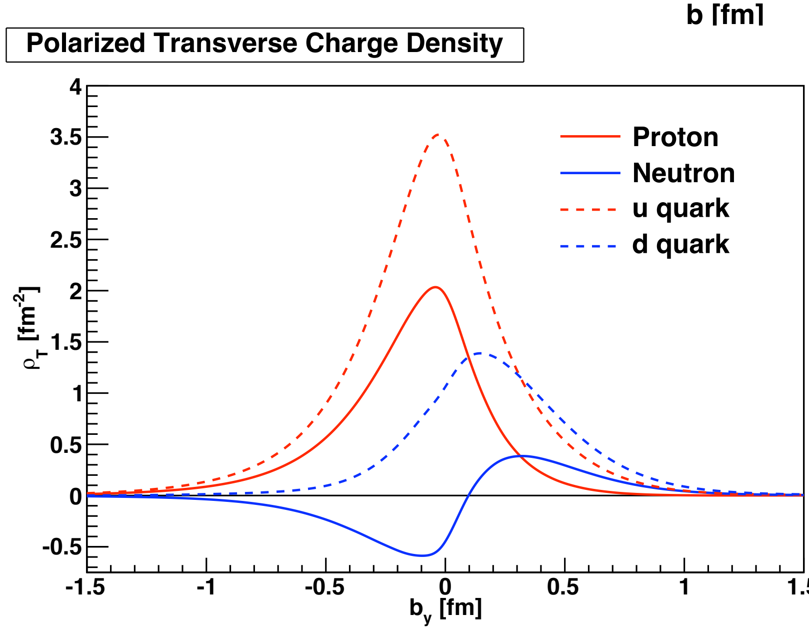
$$\rho_{Dirac}(b) = \int_0^\infty \frac{QdQ}{2\pi} J_o(bQ) F_1(Q^2)$$

$$\rho_{Pauli}(b) = \int_0^\infty \frac{Q^2dQ}{4\pi M} J_1(bQ) F_2(Q^2)$$

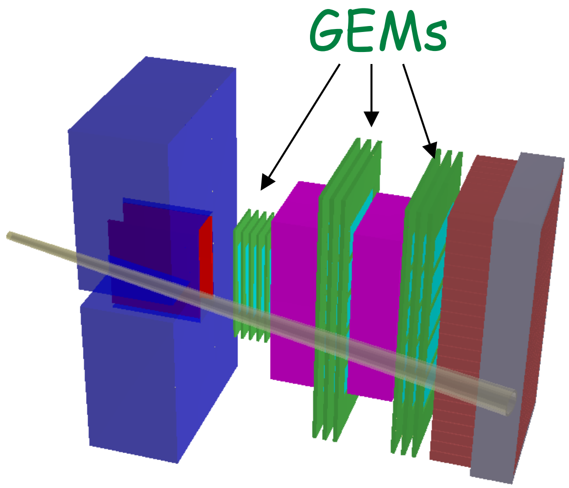
- The flavor-separated F_1 and F_2 ratios were then used to extract the transverse densities for the u- and d-quark (in the proton).

→ Why is the d-quark so much wider?

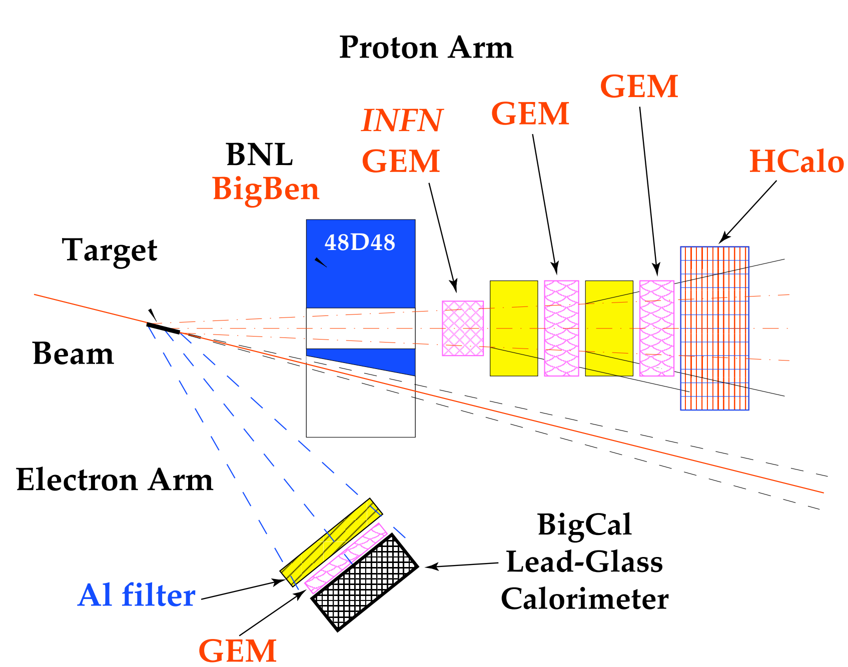




The SuperBigbite project



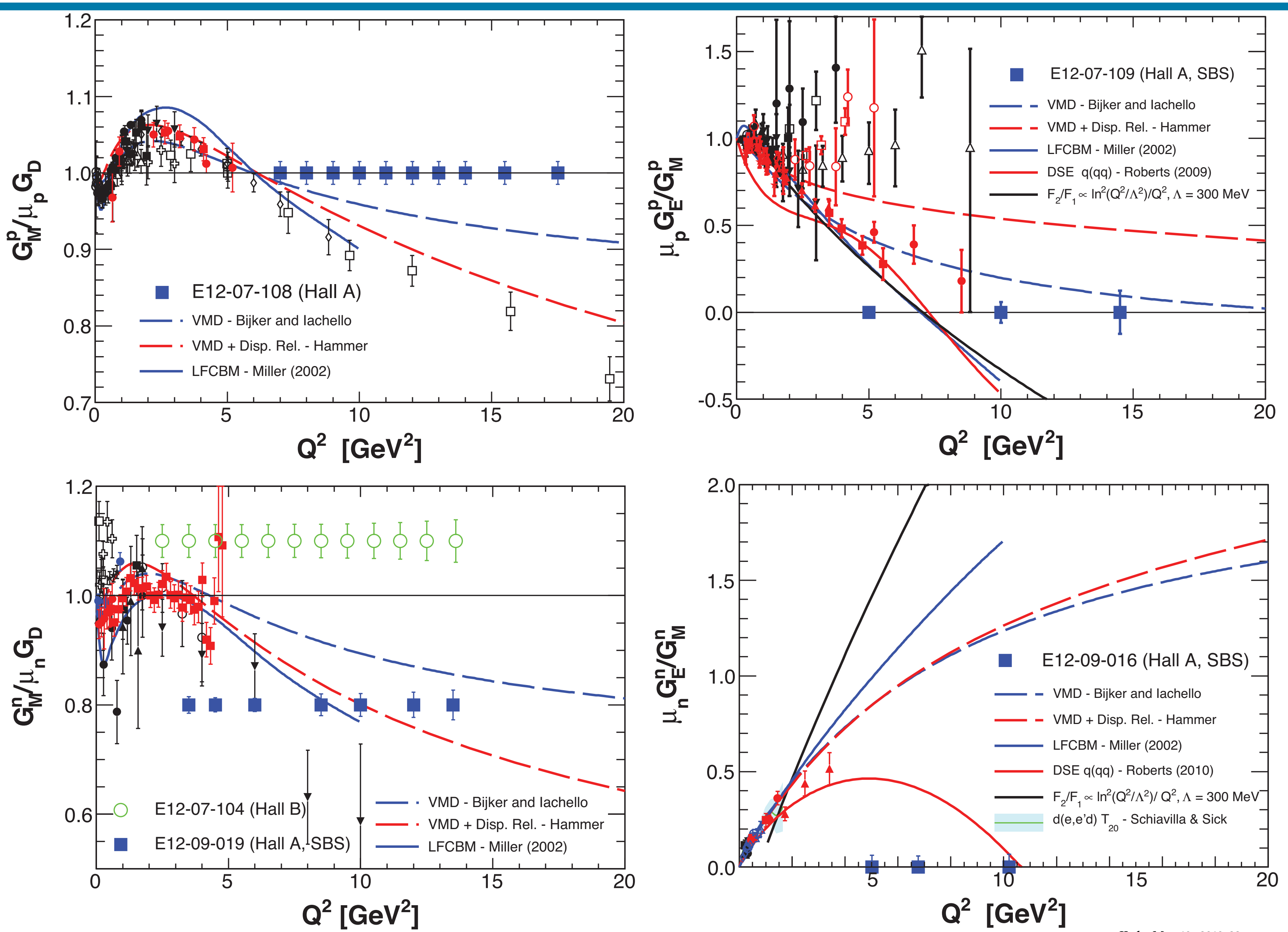
Proton form factors ratio, GEp(5) (E12-07-109)



- The Super Bigbite project:
  - → large dipole magnet
  - → GEM trackers (~100,000 channels)
  - → hadron and EM calorimeter
  - → Trigger and DAQ
- operating in open geometry at a luminosity of 10^{38} $cm^{-2}s^{-1}$
- will extend measurements of EMFFs to double the existing Q^2-range
- Included in the JLab long-term capital funding request to DOE

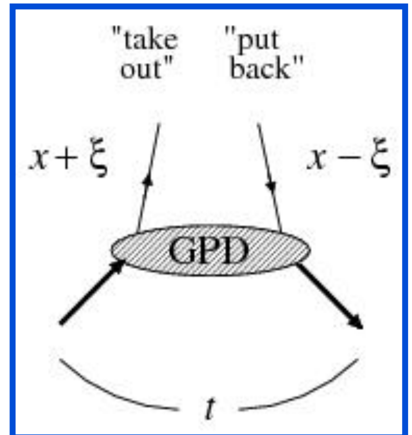
Mahbub Khandaker

Projected EMFF data with SBS @ 12 GeV

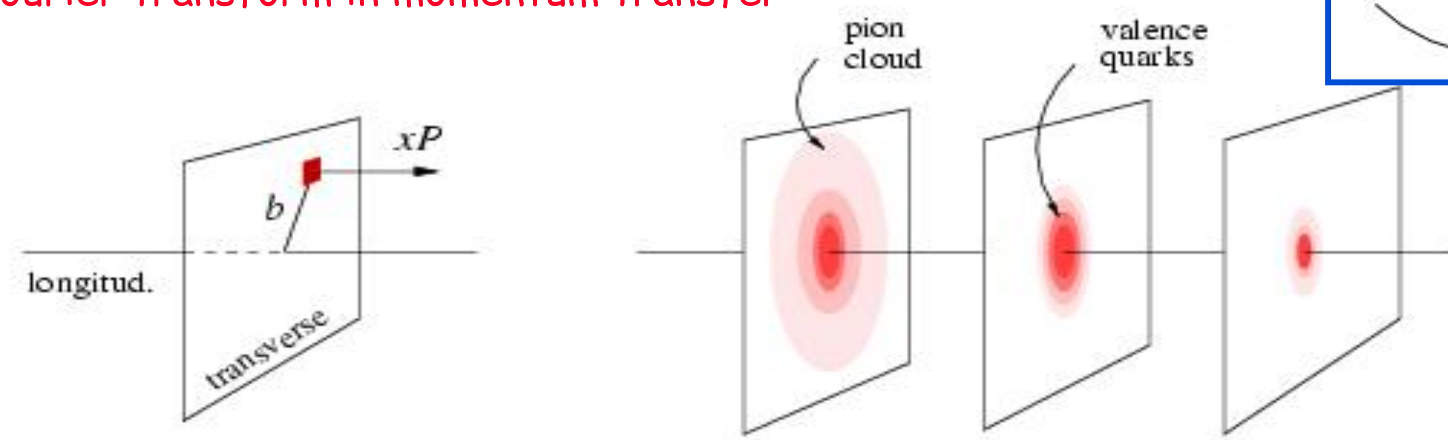


Impact of EMFF on GPDs

1. Allows for a unified description of form factors and parton distributions
2. Describes correlations of quarks/gluons
3. Allows for Transverse Imaging



Fourier transform in momentum transfer



x < 0.1 x ~ 0.3 x ~ 0.8

gives transverse spatial distribution of quark (parton) with momentum fraction x and related to EMFFs through first moments

$$\sum_q e_q \int_{-1}^{1} dx H^q(x,\xi=0,Q^2) = F_1(Q^2); \quad \sum_q \kappa_q \int_{-1}^{1} dx E^q(x,\xi=0,Q^2) = F_2(Q^2)$$

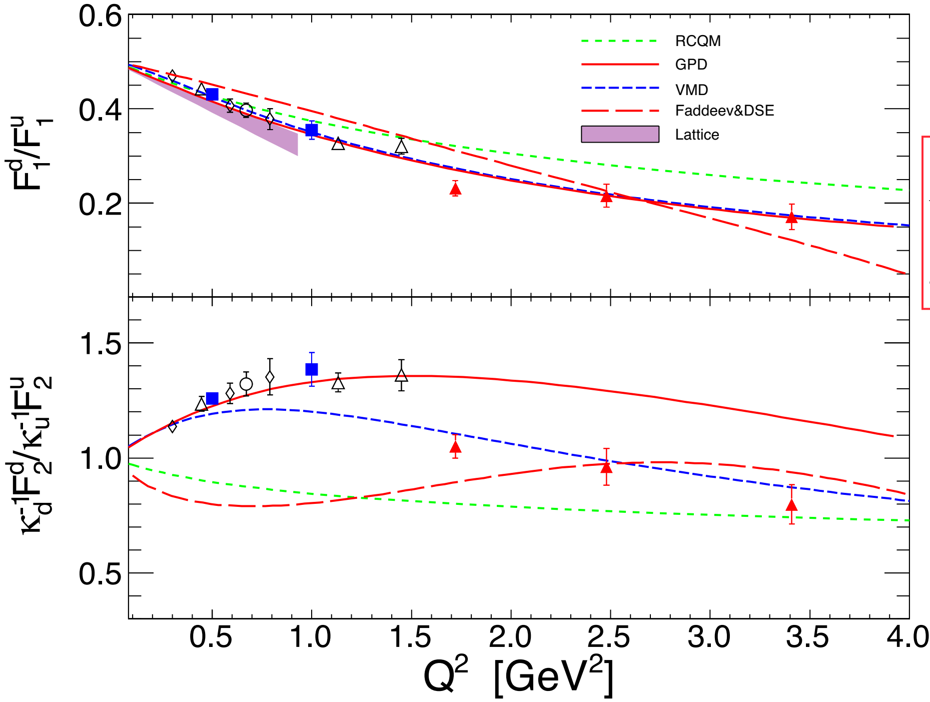
4. Allows access to quark angular momentum (in model-dependent way)

Summary and Outlook

- Very active experimental program on nucleonelectro-magnetic form factors thanks to development of polarized beam (> 100 μA, > 85 %), polarized targets and polarimeters with large analyzing powers
  - ➙ G_E^p discrepancy between Rosenbluth and polarization transfer not an experimental problem, but probably caused by TPE effects.
  - ➙ Broad ongoing program to obtain quantitative information on TPE.
  - ➙ Observation of linear decrease with Q^2 of G_E^p/G_M^p established role of quark Orbital Angular Momentum (OAM) in nucleon
  - ➙ G_M^n precise data up to Q^2 = 4.5 GeV^2, but inconsistency at ~ 1 GeV^2
  - ➙ G_E^n precise data up to Q^2 = 3.5 GeV^2 provides strong indication that OAM has different effect on neutron than on proton
  - ➙ The SuperBigBite project, to be implemented once the JLab 12 GeV upgrade has been completed, will extend the present knowledge of the nucleon EMFF G_E^p, G_E^n and G_M^p to double or triple the Q^2-range covered by existing data
  - ➙ It is imperative that this experimental program is accompanied by a similar progress in our theoretical understanding of the nucleon

THANK YOU !

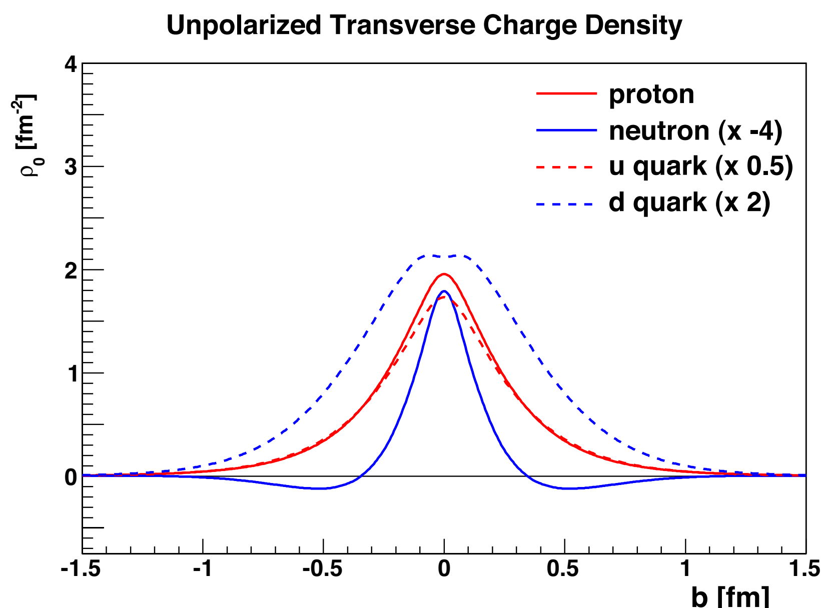
Flavor separation

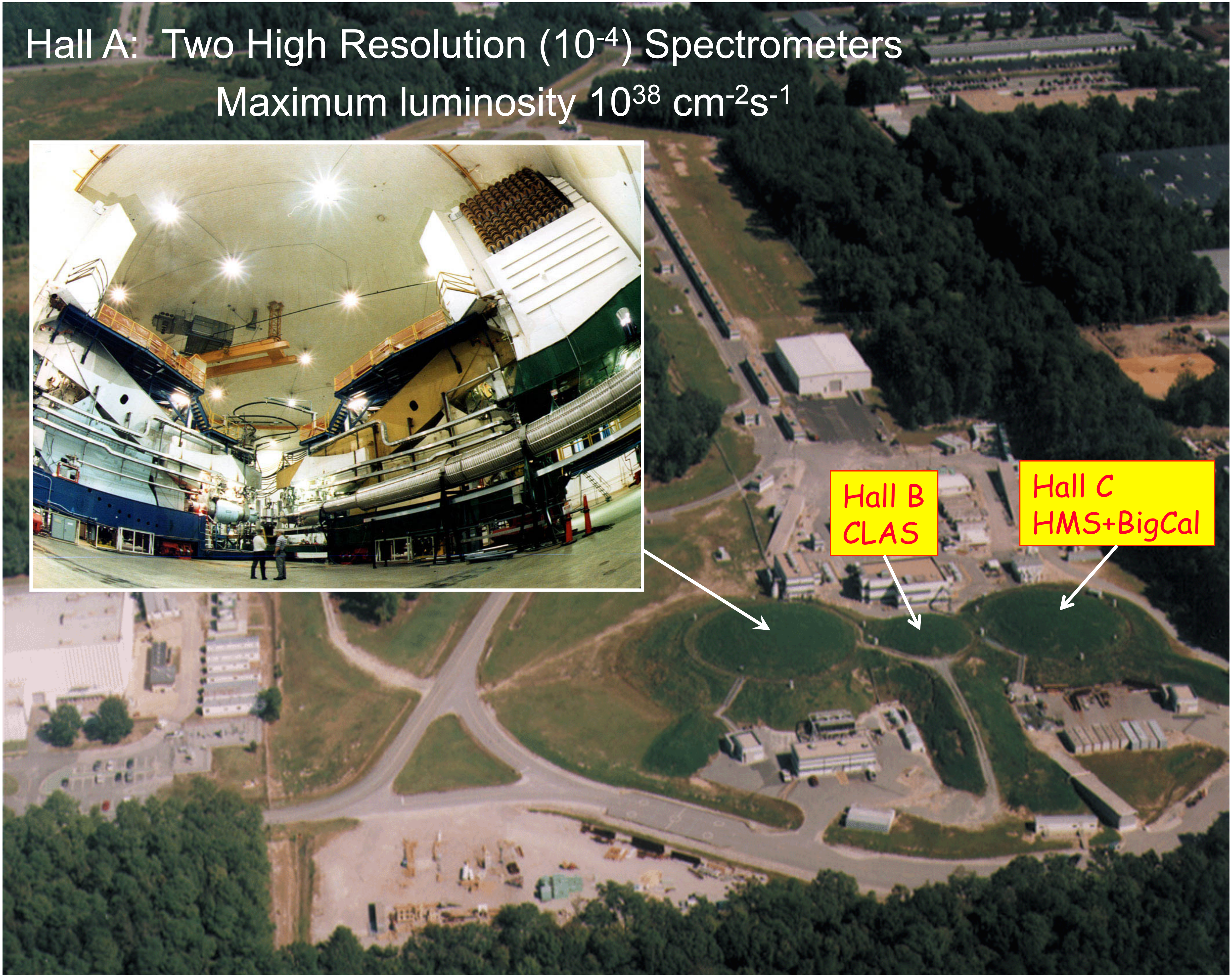


$$F_{1,2}^{p} = \frac{2}{3}F_{1,2}^{u} - \frac{1}{3}F_{1,2}^{d}; \qquad F_{1,2}^{n} = \frac{2}{3}F_{1,2}^{d} - \frac{1}{3}F_{1,2}^{u}$$

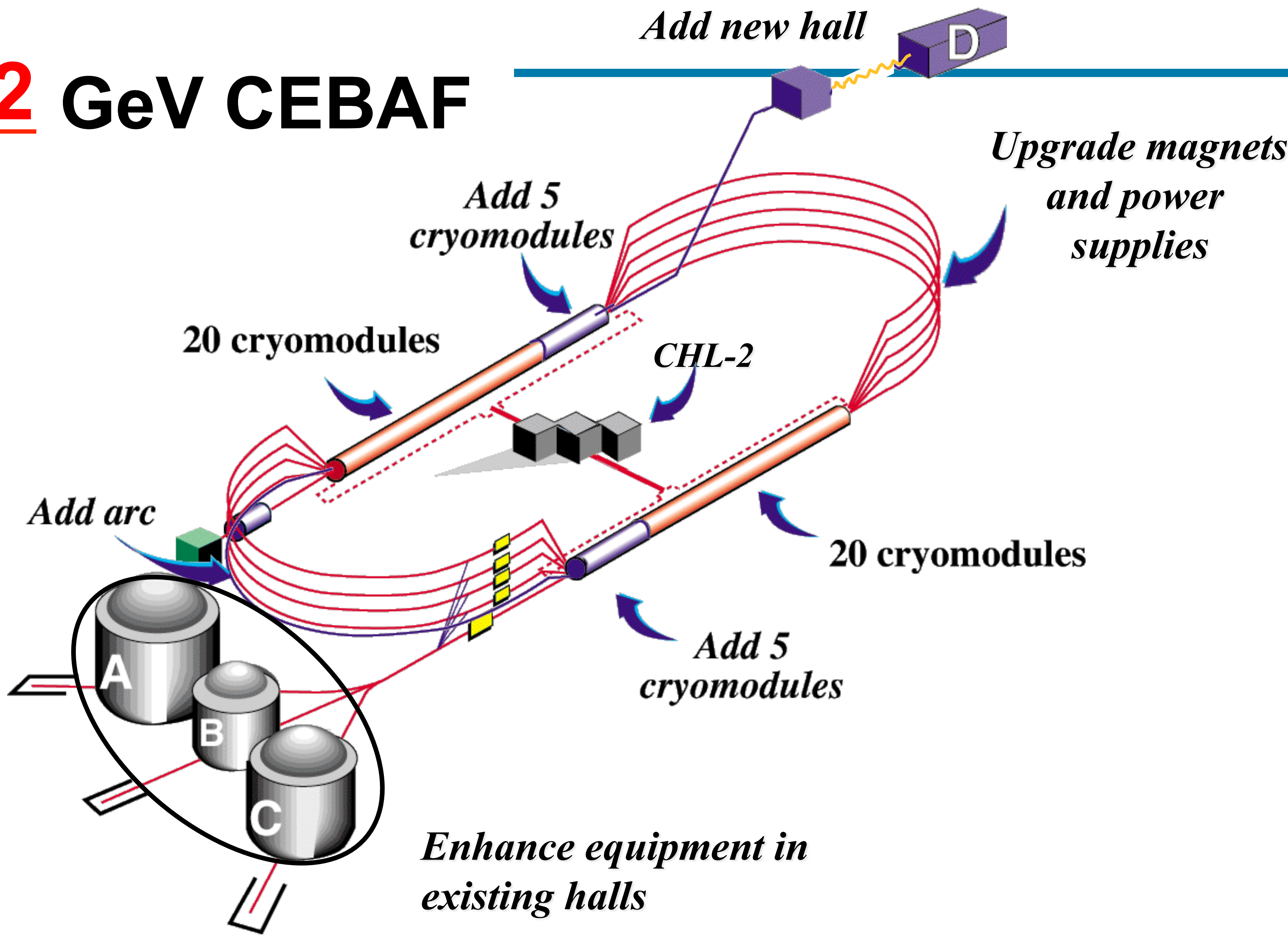
assuming isospin symmetry: $F_{1,2}^{u,p} = F_{1,2}^{d,n}$ and $F_{1,2}^{d,p} = F_{1,2}^{u,n}$

- Especially F_2 ratio sensitive test of predictions (RCQM, GPDs)
- Transverse charge densities shown for proton, d-quark much more spread out than u-quark (large x-behaviour?)




Hall A: Two High Resolution (10^{-4}) Spectrometers
Maximum luminosity 10^{38} cm^{-2}s^{-1}
Hall B
CLAS
Hall C
HMS+BigCal

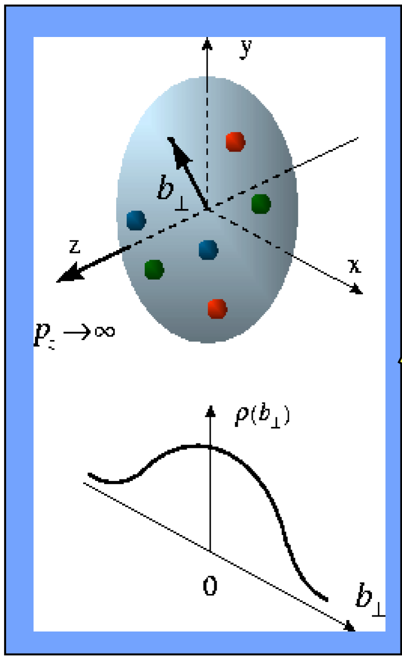
12 GeV CEBAF

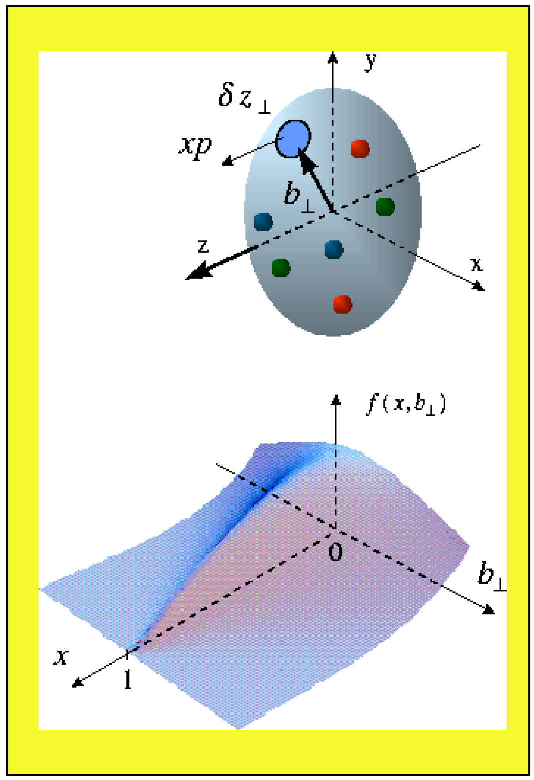

Add new hall
D
Upgrade magnets
and power
supplies
Add 5
cryomodules
20 cryomodules
CHL-2
Add arc
20 cryomodules
Add 5
cryomodules
A
B
C
Enhance equipment in
existing halls

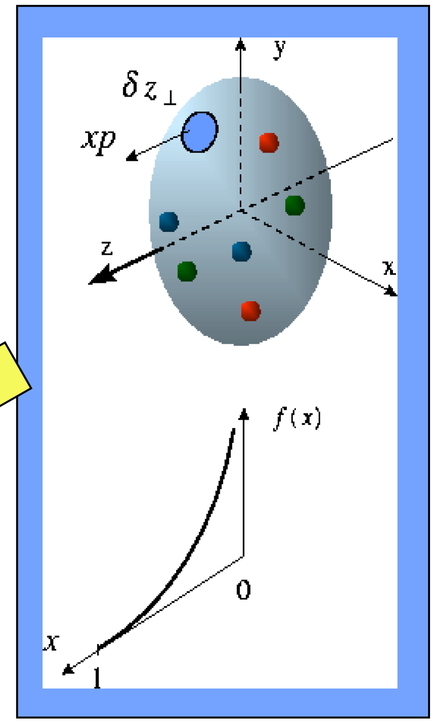
Beyond form factors and quark distributions

Generalized Parton Distributions (GPDs)

X. Ji, D. Mueller, A. Radyushkin (1994-1997)







Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions