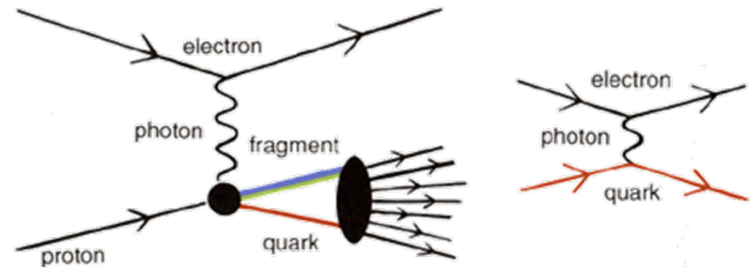
Deep Inelastic Electron Scattering



from Nobel lectures, 1990

energy available to produce particles in final state

$$s = W^2 = \left(E_{beam} + E_{tgt}\right)^2 = \left(E' + \sum_h E_h\right)^2$$

$$\frac{d\sigma}{d\Omega dE'} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \times \left[W_2\left(\nu, Q^2\right) + 2W_1\left(\nu, Q^2\right)\tan^2\tfrac{\theta}{2}\right]$$

these are not the same F's as in elastic scattering

Experimentally, W_2 and W_1 seem to depend on only one variable

$$x = \frac{Q^2}{2M_{tgt}\nu}, \quad 0 < x < 1, \quad \sum x_{partons} = 1$$

$$W_1\left(\nu, Q^2\right) = F_1(x)$$

$$\frac{\nu}{M} W_2\left(\nu, Q^2\right) = F_2(x)$$

$$F_2(x) = 2xF_1(x)$$

"scaling" (anticipated by Bjorken, 1967)

scaling good when $(Q^2,\nu) \rightarrow \infty$, and if the partons have no transverse momentum .

Hadron Physics

Lecture #1: The quark model, QCD, and hadron spectroscopy

Lecture #2: Internal structure of hadrons: momentum and spin

Lecture #3: Internal structure of hadrons: charge, magnetism, polarizability

Lecture #4: Hadrons in nuclei, hadrons as laboratories (and miscellaneous topics)

references

Halzen & Martin: Quarks and Leptons

Xiangdong Ji: Graduate nuclear physics lecture notes
http://www.physics.umd.edu/courses/Phys741/xji/lecture_notes.htm

Review articles:

C.F. Perdrisat, V. Punjabi and M. Vanderhaegen,
Prog. Part. Nucl. Phys. 59 (2007) 694-764, arXiv: hep-ph/0612014.

J. Arrington, C.D. Roberts and J.M Zanotti,
J. Phys. G 34 (2007) S23, arXiv: nucl-th/0611050

Donnelly and Raskin:
T.W. Donnelly and A.S. Raskin, Ann. Phys. 169, 247 (1986).

Properties of Hadrons: charge, magnetism, polarizability

Nucleon electromagnetic form factors

2-γ exchange

Meson form factors

Nucleon polarizabilities (maybe…)

The Proton

$J^P = 1/2^+$; $I_3 = +1/2$ *(see Particle Properties Data Book, http://pdg.lbl.gov)*

charge	$= e$ (to 10^{-21})
r.m.s. charge radius	$= 0.8768 \pm 0.0069$ fm^2
mass	$= 938.27231(28)$ MeV/c^2
μ_p	$= 2.792847337 \pm 0.000000029\ \mu_N$ ($= e\hbar/2m_N c$)
elec. dipole moment	$= (-3.7 \pm 6.3) \times 10^{-23}$ e-cm
electric polarizability	$= (12.0 \pm 0.6) \times 10^{-4}$ fm^3
magnetic polarizability	$= (1.9 \pm 0.5) \times 10^{-4}$ fm^3
mean lifetime	$= > 5.8 \times 10^{29}$ years (any decay mode)

$|P\rangle = |uud\rangle + |uudqq\rangle + |uudg\rangle + |uudqqg\rangle + \ldots$

or

$|P\rangle = |p\rangle + |p\pi^0\rangle + |n\pi^+\rangle + |p\,\pi^+\,\pi^-\rangle + |p\eta\rangle + |\Lambda^0 K^+\rangle + \ldots$

The proton's magnetic moment

Otto Stern

Nobel Prize, 1943: "for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"

μ_p = 2.5 nuclear magnetons, ± 10% (1933)

2002 experiment:

$\mu_p = 2.792847351(28)\ \mu_N$

$\mu_n = -1.91304274(45)\ \mu_N$

2006 theory:

$\mu_p \sim 2.8\ \mu_N$

$\mu_n \sim -1.8\ \mu_N$

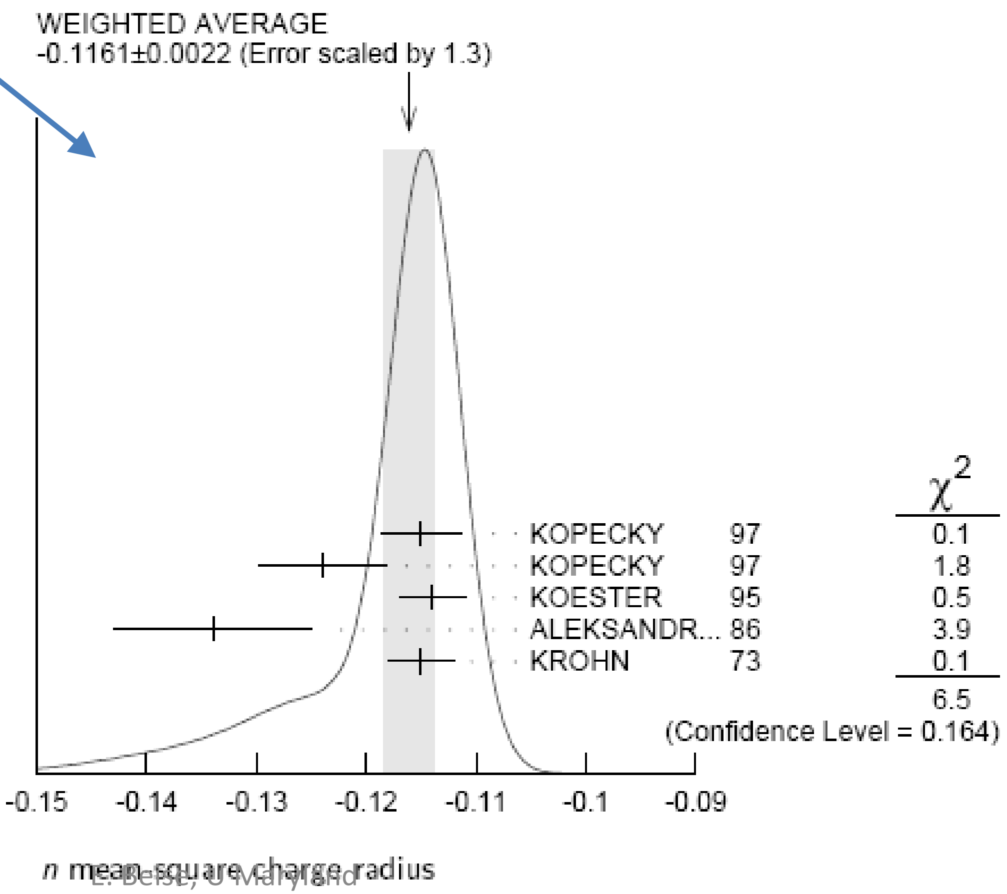
How do the quark contributions add up?

How are charge and magnetism distributed?

The neutron

$J^P = 1/2^+$ $I_3 = -1/2$ *(see Particle Properties Data Book, http://pdg.lbl.gov)*

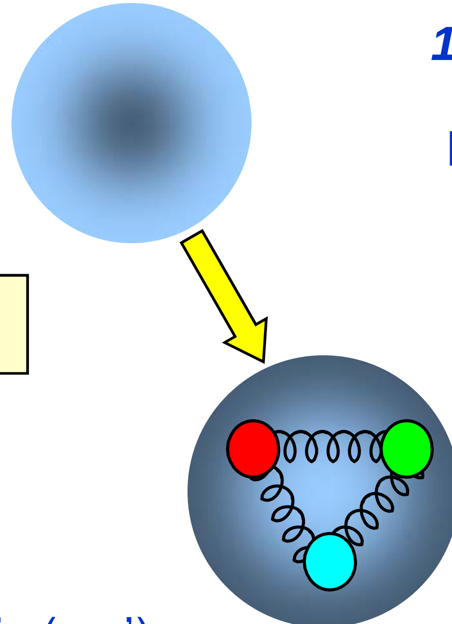
charge	$= -0.41 \pm 1.1 \quad (\times 10^{-21}\, e)$
r.m.s. charge radius	$= -0.1161 \pm 0.0022\ \text{fm}^2$
mass	
μ_n	
elec. dipole moment	
electric polarizability	
magnetic polarizabilit	
mean lifetime	



1930's:

(Chadwick NP 1935)
(Stern NP 1943)

$\mu_p \sim 3\ \mu_N$



1950's:

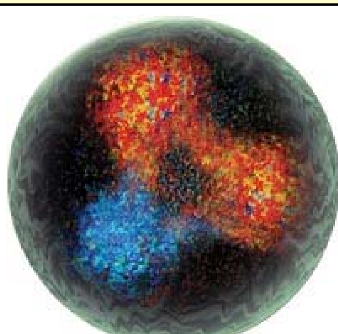
proton charge radius from (e,e')
(Hofstadter NP 1961)

$r_p \sim 1$ fm

1970's:

partons in proton via inelastic (e,e')
(Friedman,Taylor,Kendall, NP 1990)

luminosity:
(SLAC, 1978) ~ 8 x 10^{31} cm^{-2}-s^{-1}
(JLab, 2000) ~ 4 x 10^{38} cm^{-2}-s^{-1}



1990's:

polarized targets/polarimetry
Intense CW electron beams
improvement in polarized e sources
precision Parity Violation exps

SU(3) and hadron structure
advances in Lattice QCD
EFT, Fewbody theory

$$d = 1 \rightarrow 0.1\,\text{fm} \quad \Leftrightarrow \quad Q^2 = 0.1 - 10\ (\text{GeV/c})^2$$

Why study hadron form factors?

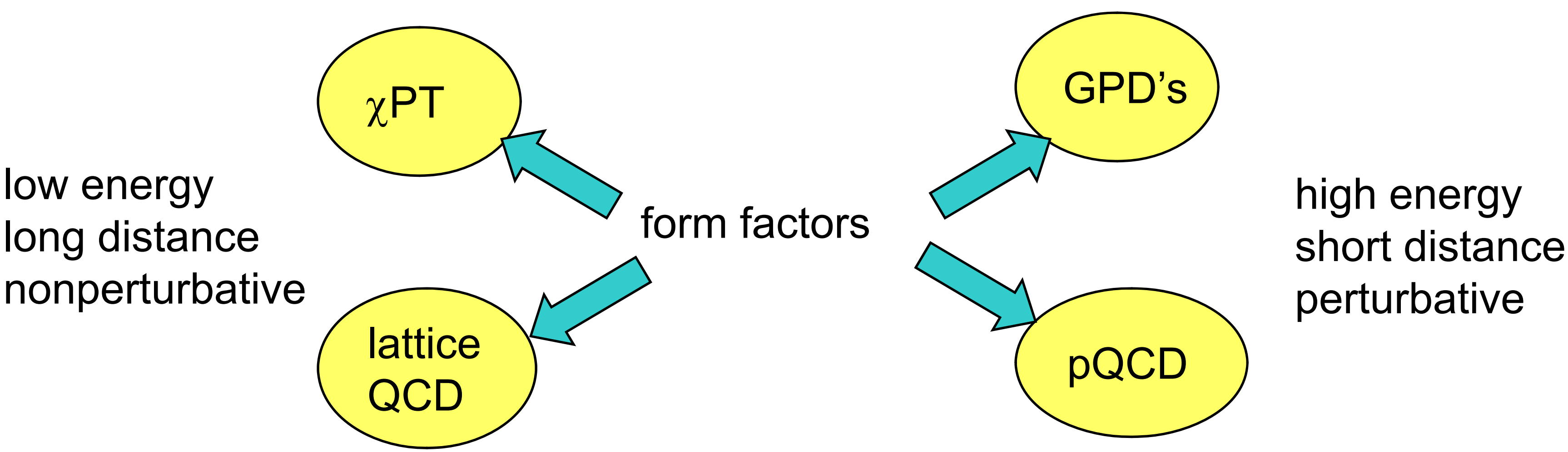
They give us the ground state properties of (visible) matter:

size and shape, charge and magnetism distributions
spin and angular momentum

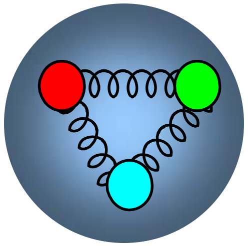
They are required elsewhere

baseline for structure of nuclei at short distances
Proton charge radius → Lamb shift
precision symmetry tests at low Q^2
needed input for ν-N interactions: impact on ν oscillation data

Benchmarks for connecting QCD across energy/distance scales

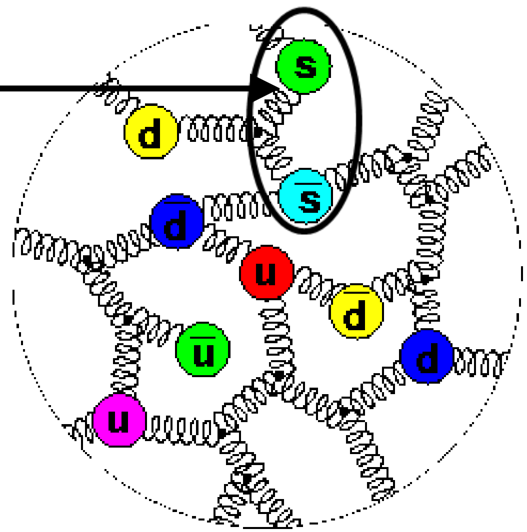


Views of the Nucleon

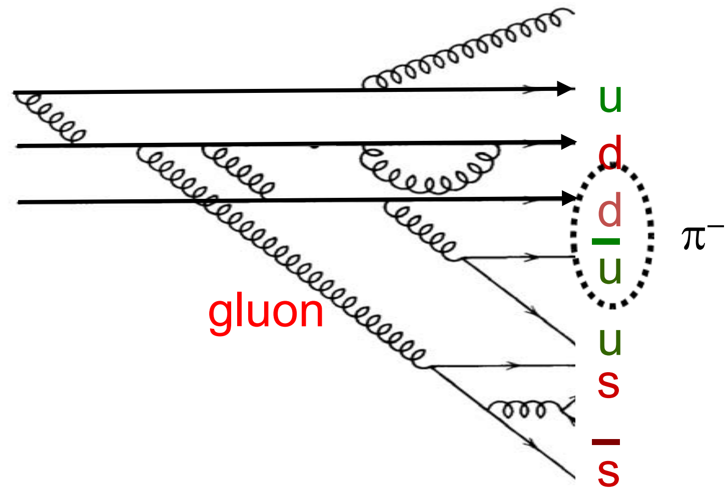


"quark model"

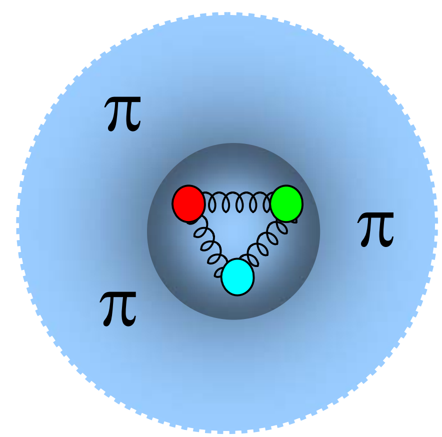
explicit sea quarks



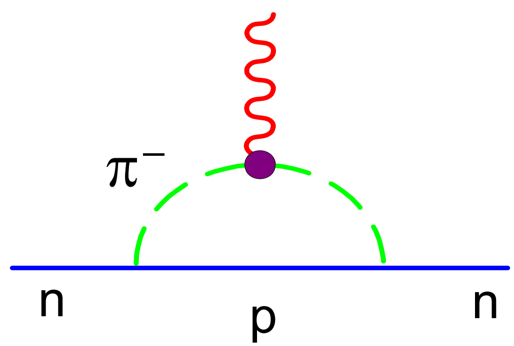
QCD/parton description



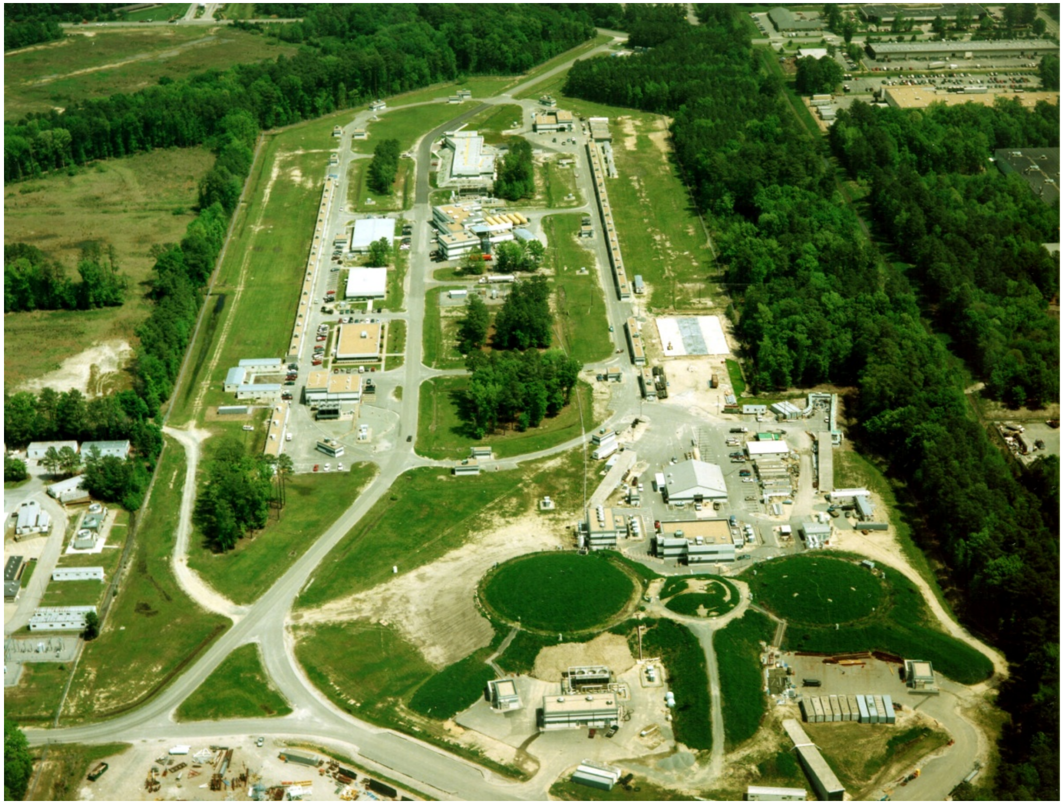
"pion cloud" description



chiral Pert. Theory



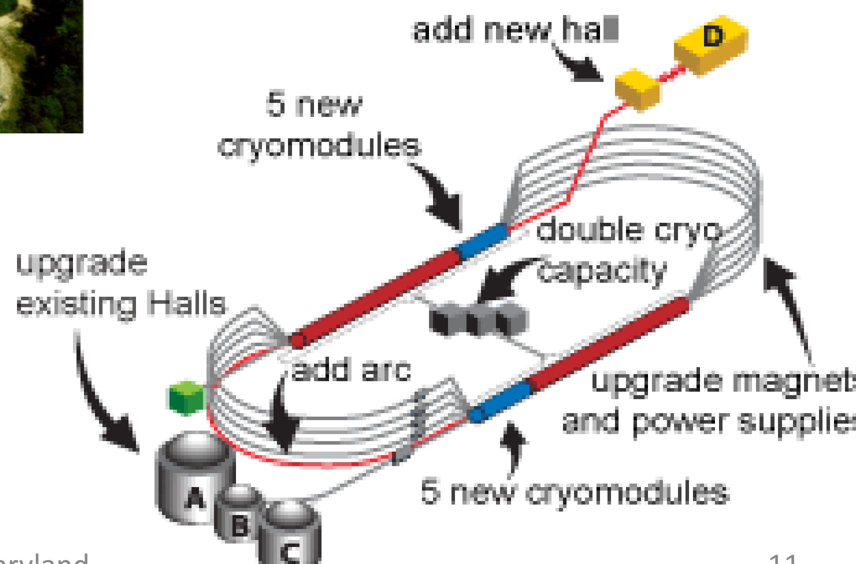
Jefferson Laboratory



E ~ 6 GeV
Continuous Polarized Electron Beam

> 100 μA
up to 80% polarization
concurrent to 3 Halls

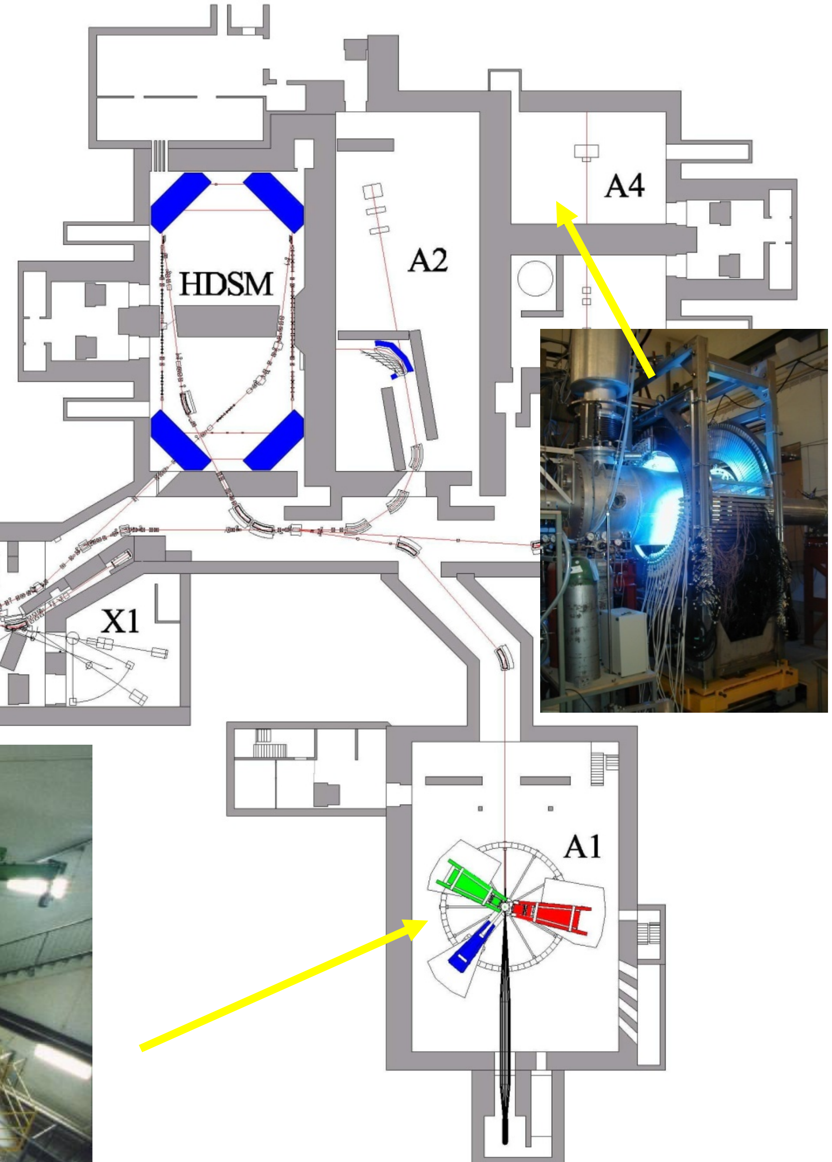
12 GeV Upgrade

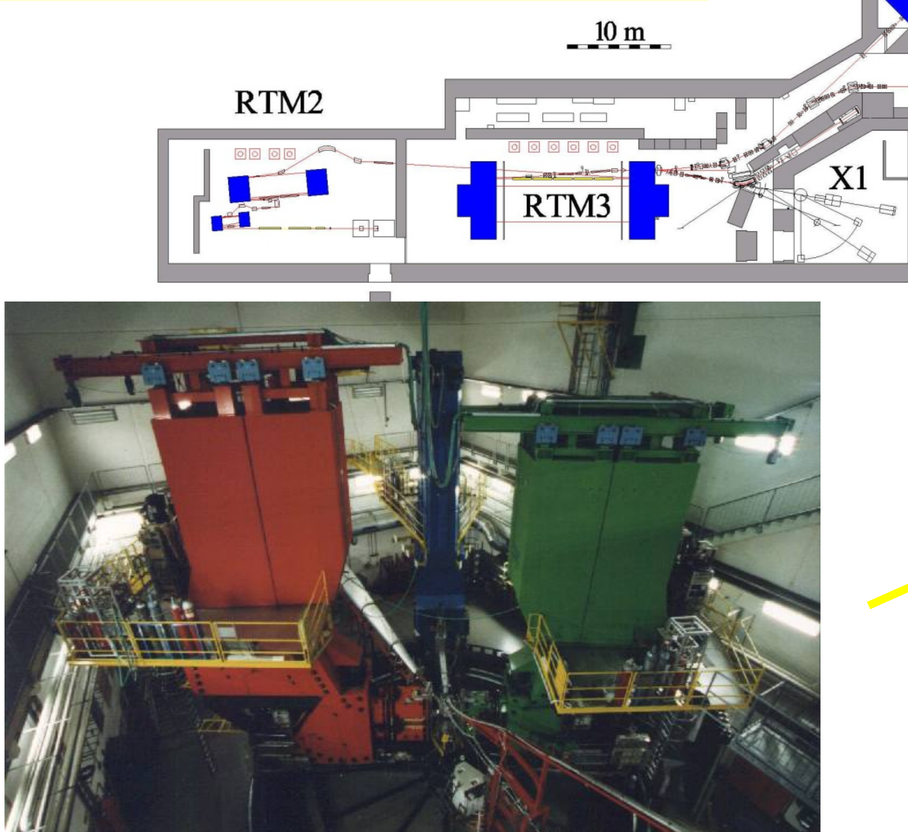


Mainz Microtron

0.8 GeV CW beam, now 1.5 GeV
polarized D/^{3}He external targets

neutron EM form factors at low Q^2
parity violation and Weak form factors





MIT-Bates Laboratory

CW 1 GeV polarized beam

polarized internal H/D/^{3}He targets

***BLAST* program:**

neutron and proton form factors at low Q^2

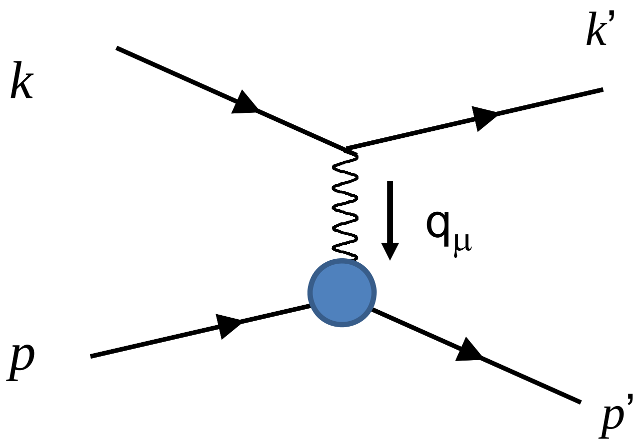
proton charge radius

deuteron structure via vector and tensor polarization

BLAST detector

Kinematics of electron scattering

A common reference frame to work in is the LAB frame with a stationary target:



$$q_\mu^2 = \nu^2 - \vec{q}^{\,2} = -Q^2 (>0)$$

case 1: elastic scattering

$$p = (M, 0) \qquad p' = (E_R, \vec{p}\,')$$
$$k = (E, \vec{k}) \qquad k' = (E', \vec{k}\,')$$
$$\hat{k} \cdot \hat{k}' = \cos\theta$$
$$q_\mu = (\nu, \vec{q}) = k - k'$$

It is common to assume the electron is massless (extreme relativistic limit). In the case of elastic scattering, energy and 3-momentum are each conserved:

$$E + M - E' = \nu + M = E_R \qquad \vec{k} - \vec{k}' = \vec{q} = \vec{p}\,'$$

can usually eliminate the recoiling target variables

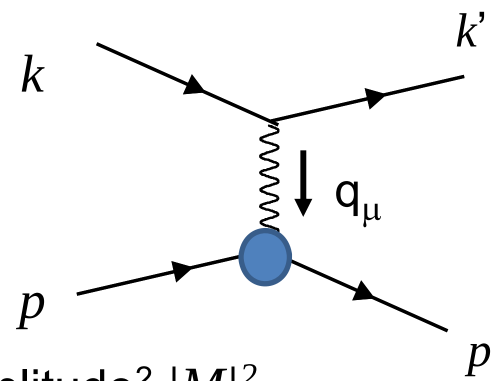
$$Q^2 = 4EE' \sin^2 \theta/2 \qquad E' = \frac{E}{1 + \frac{2E}{M}\sin^2 \theta/2} = E\, f_{rec}$$

in elastic scattering E', θ are 100% correlated

unpolarized cross section

Using Fermi's Golden rule, we integrate over the recoiling target quantities, average over initial spin states, sum over final spin states, and, *for elastic scattering*, integrate over an energy-conserving delta function. This gives:

$$\frac{d\sigma}{d\Omega} = \frac{1}{(2\pi)^2} \frac{1}{2\left(1 + \frac{2E}{M}\sin^2 \theta/2\right)} |M|^2$$



All the details of the interaction are in the invariant amplitude[2] $|M|^2$.

strength and photon propagation

$$|M|^2 = \frac{\alpha^2}{Q^4} l^{\mu\nu} W_{\mu\nu}$$

lepton current

hadron current

pointlike leptons

$$l^{\mu\nu} = \bar{u}(k')\gamma^\mu u(k)\bar{u}(k)\gamma^\nu u(k')$$

$$W_{\mu\nu} = \langle P|J_\mu|P'\rangle\langle P'|J_\nu|P\rangle$$

all the excitement is in

$$J_\mu = \bar{u}(p')[\ ?\ ]u(p)$$

the hadronic current

$$J_\mu = \bar{u}(p')[\,?\,]u(p)$$

In elastic scattering: the target is left intact and we measure its response to the EM current.

$$[\,?\,] = \left[F_1(Q^2)\gamma^\mu + \frac{\kappa}{2M} F_2(Q^2) i\sigma^{\mu\nu} q_\nu \right]$$

κ = anomalous part of magnetic moment

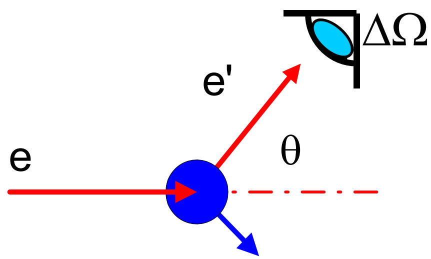
The cross section becomes:

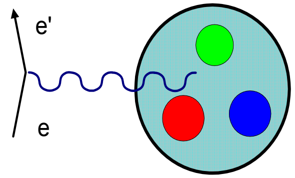
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{E'}{E} \left[\left(F_1^2 + \frac{\kappa^2}{4M^2} F_2^2 \right) + \frac{Q^2}{2M^2} \left(F_1 + \kappa F_2 \right)^2 \tan^2 \theta/2 \right]$$

if the target is spin ½ and has no structure then: $F_1 = 1,\ F_2 = 0$

if the target is spin 0 then it has no magnetic moment so term with $F_2 \rightarrow 0$

Form factors: spin 0 target





$Q = (\nu, \mathbf{q})$

$$\frac{d\sigma}{d\Omega} = \frac{\#counts}{N_e N_{tgt} \Delta\Omega}$$

Rutherford
$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{Z^2\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}}$$

Mott
$$\left(\frac{d\sigma}{d\Omega}\right)_M = \left(\frac{d\sigma}{d\Omega}\right)_0 \cos^2 \frac{\theta}{2} \cdot \frac{E'}{E}$$

Scattering from an extended object:

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_M \cdot \left| F(Q^2) \right|^2$$

form factor

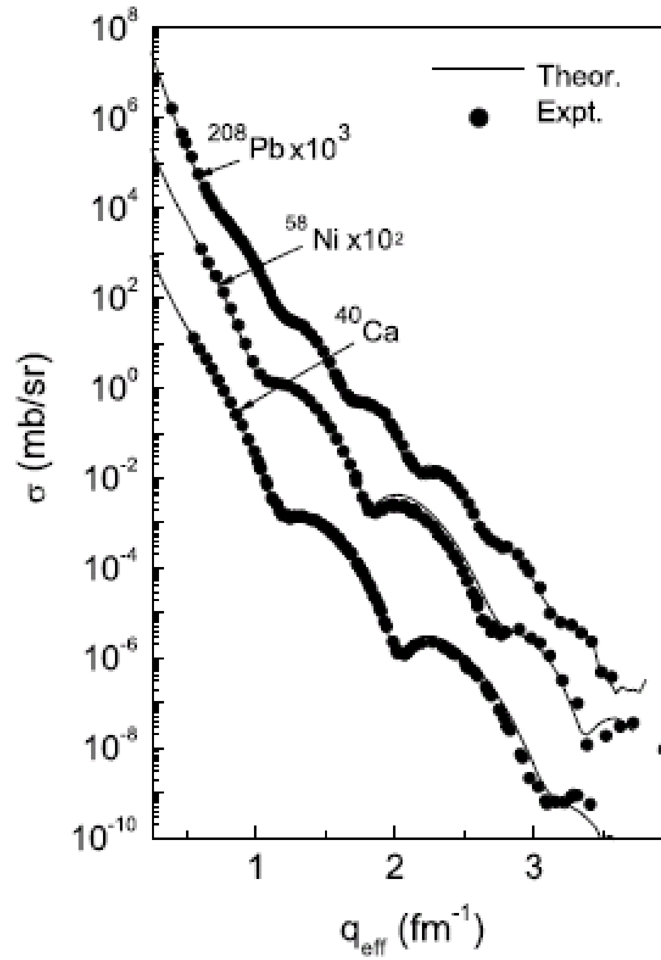
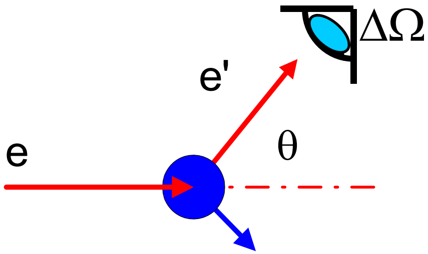
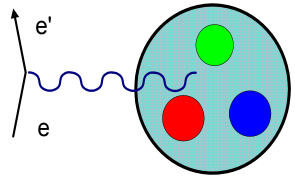


FIG. 3. Comparison of differential cross sections for scattering of 502 MeV electrons by ^{208}Pb, 449.8 Mev electrons by ^{58}Ni, and of 400 MeV electrons by ^{40}Ca. The solid lines are theoretical results from the combination of the relativistic eikonal approximation with the RMF model. The filled circles are experimental data [61].

DOI: 10.1103/PhysRevC.71.054323

Form factors: spin 0 target





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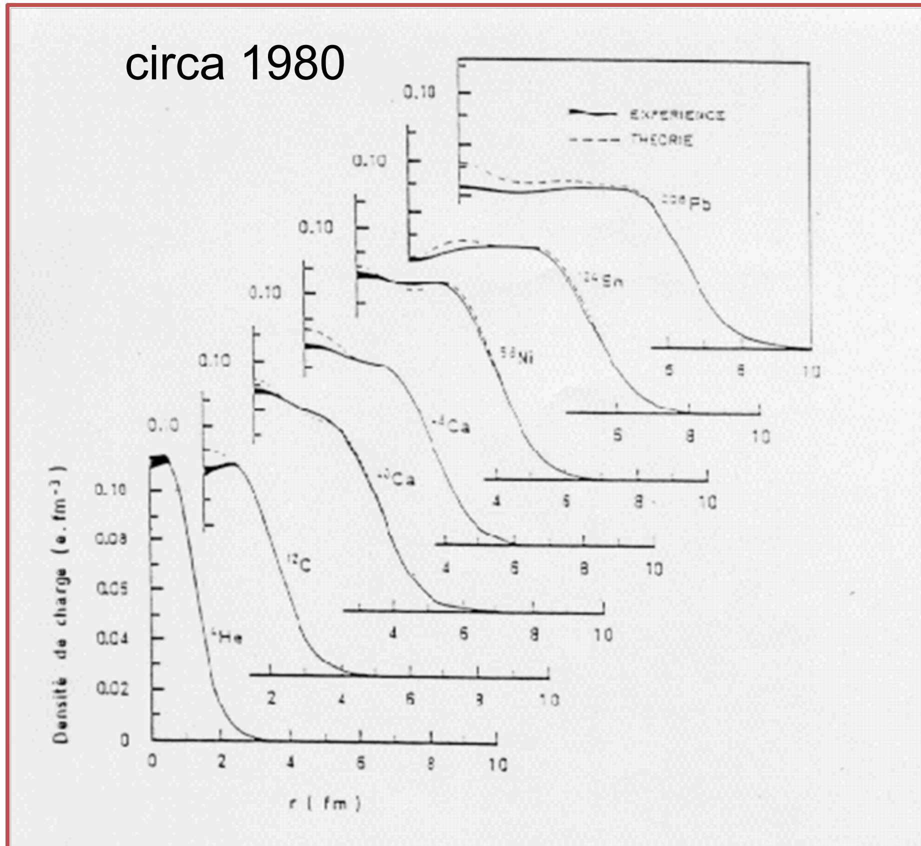
form factor



J.M. Cavedon, PhD thesis, Orsay, France (1980)

$$F(q^2) = \int e^{i\vec{q}\cdot\vec{r}} \rho(\vec{r}) d^3r = 1 - \frac{q^2\langle r^2 \rangle}{6} + \ldots$$

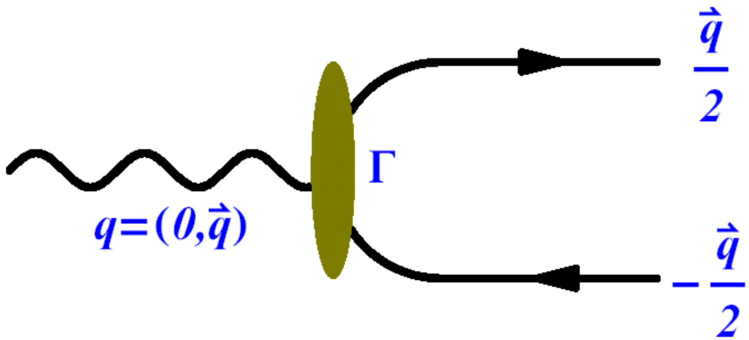
Spin ½ hadrons: Sachs Form Factors

slide from J. J. Kelly

The nucleon e.m. current

$$J^{\mu} = \bar{u}(p)\left[F_1(Q^2) + \kappa F_2(Q^2)\frac{i\sigma^{\mu\nu}q_{\nu}}{2m} \right] u(p)$$

as seen in the Breit frame



$$J^{\mu} = \chi_{s'}^{*}\left(G_E + \frac{i\vec{\sigma}\times\vec{q}}{2m} G_M \right)\chi_s$$

charge and current contributions in this frame are represented by Sachs form factors:

$$G_E = F_1 - \tau\kappa F_2$$
$$G_M = F_1 + \kappa F_2$$

$$G_E^p(0) = 1$$
$$G_E^n(0) = 0$$

$$G_M^p(0) = (1+\kappa_p) = 2.79 = \frac{\mu_p}{\mu_N}$$

$$G_M^n(0) = \kappa_n = -1.91 = \frac{\mu_n}{\mu_N}$$

$$\tau = \frac{Q^2}{4M_N^2}$$

"Rosenbluth" Separation

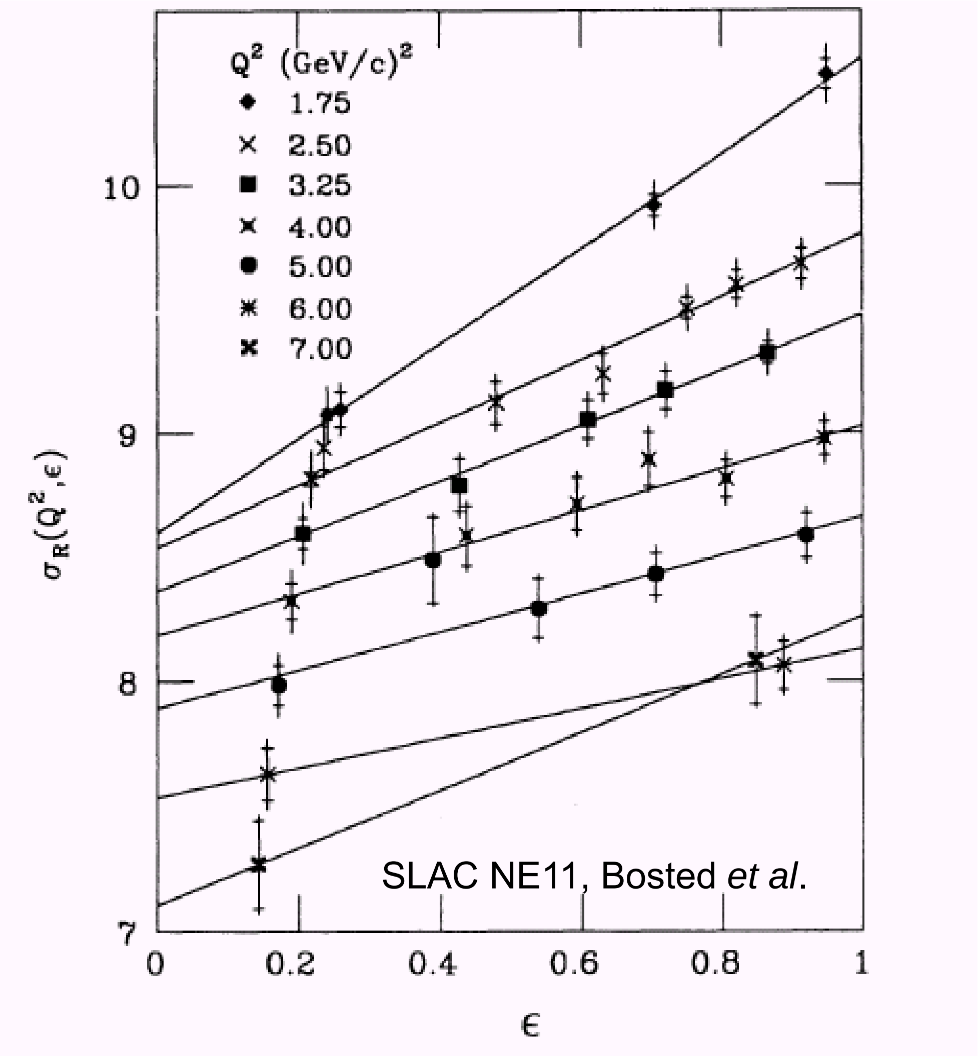
slide from J. J. Kelly

$$\frac{\varepsilon(1+\tau)}{\sigma_M}\frac{d\sigma}{d\Omega} = \tau G_M^2 + \varepsilon G_E^2$$

intercept (τG_M^2) slope (G_E^2)

$$\tau = \frac{Q^2}{4M^2}, \quad \varepsilon = \frac{1}{\left[1+2(1+\tau)\tan^2 \theta/2\right]}$$

- G_M dominates for large τ.
- Must control kinematics, acceptances, and radiative corrections very accurately because coefficient is strong function of angle.
- As Q^2 increases, the contribution from εG_E^2 gets very small (even for the proton)



proton form factors

using the Rosenbluth technique only here

from
J. Arrington, Phys. Rev. C 69 (2001) 022201

$$F(Q^2) \to \varepsilon G_E(Q^2) + \tau G_M(Q^2)$$

τ, ε depend on scattering angle

Nonrelativistically, as with nuclei, the textbook description is

$$\rho(r) = \rho_0 e^{-(r/r_0)}$$

↕ *"dipole"*

$$G_D(Q^2) = \frac{1}{\left(1 + Q^2 r_0^2\right)^2}$$

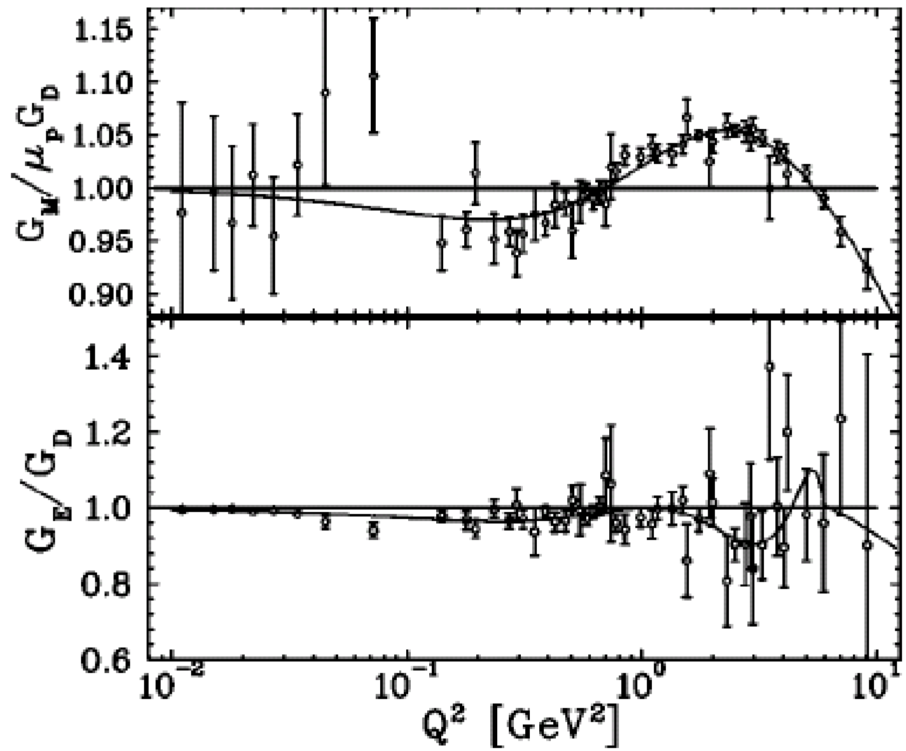


FIG. 2. G_M (top) and G_E (bottom) from direct Rosenbluth separation utilizing normalization factors from the global fit.

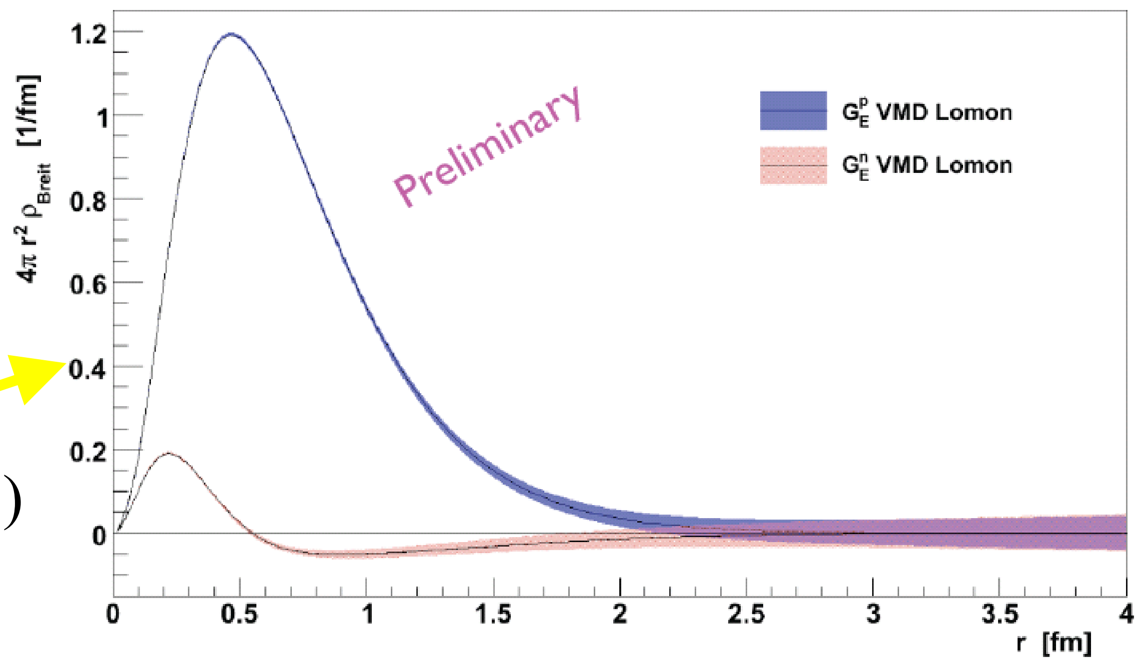
BUT quarks are highly relativistic: this is reference frame dependent, and thus can't be interpreted as a 3-D charge distribution

charge and magnetism distributions

These are ***at best*** *qualitative, and are reference frame dependent.*
But we can correctly call them "Breit frame distributions"

Reference frame independent approach:
Look only at the transverse dimensions, which are the same in all frames.

BLAST fit from D. Hasell, CIPANP 2009



$$\rho_{chg}(r) = \int \frac{d^3 r}{(2\pi)^3} e^{-i\vec{q}\cdot\vec{r}} G_E(q^2)$$

$$r = \sqrt{b^2 + z^2}$$

$$\int_{-\infty}^{\infty} dz\, \rho_{chg}(\sqrt{b^2 + z^2}) = \int \frac{d^2 b}{(2\pi)^2} e^{-i\vec{q}\cdot\vec{b}} \widetilde{G}_E(q_\perp{}^2) = \rho(b)$$

see G. Miller, PRL 99 (2007)112001

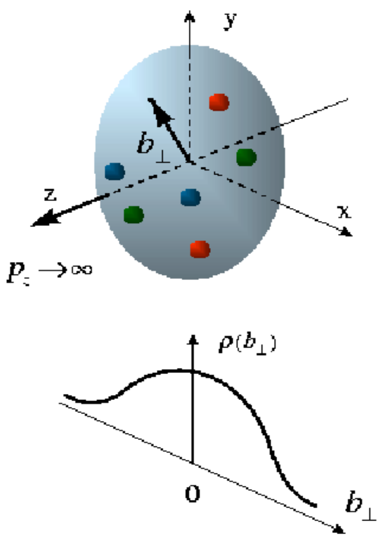
Generalized Parton Distributions

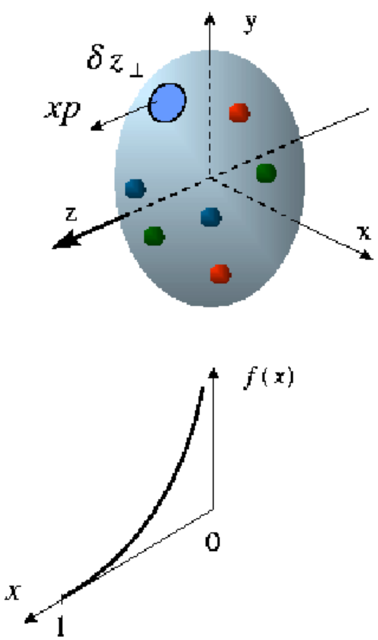
GPDs yield 3-dim quark structure of the nucleon

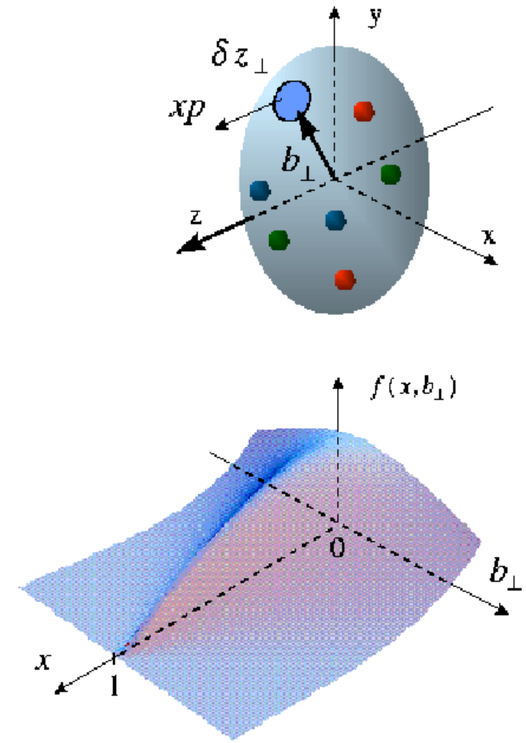
Burkardt (2000, 2003)

Belitsky, Ji, Yuan (2003)

slide from F. Sabatie, CIPANP 2009







Elastic Scattering

transverse quark **distribution** in coordinate space

DIS

longitudinal quark **distribution** in momentum space

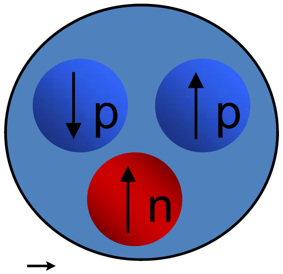
DES (GPDs)

fully-correlated quark distribution in both coordinate and momentum space

Polarized e-N scattering

- Polarized beam + polarized target:

Donnelly + Raskin, Ann. Phys. 169 (1986)247

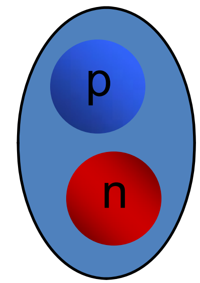


$^3\vec{He}$

$$A = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\uparrow\downarrow}} \propto \frac{a(\theta^*)G_M^2 + b(\theta^*)G_M G_E}{\sigma_{unpol}}$$

$\vec{e} + \vec{d} \rightarrow e + n + p$ → neutron charge

$\vec{e} + ^3\vec{He} \rightarrow e + n + \ldots$ → neutron magnetism



$\vec{d}$

- Polarized beam + polarization of recoil nucleon:

$$\frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{(E_e + E_e^{'})}{2M_p}\tan\frac{\theta_e}{2}$$

Akhiezer+Rekalo, Sov.JPN 3 (1974) 277
Arnold,Carlson+Gross, PRC 21 (1980) 1426

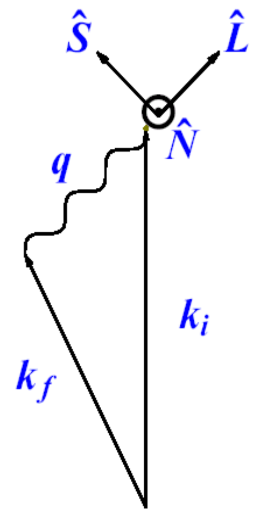
$d(\vec{e}e'\vec{n})$ neutron charge

$p(\vec{e}e'\vec{p})$ proton G_E/G_M

Proton recoil polarization experiments

$$\frac{d\sigma}{dp_N d\Omega_N d\Omega_e} = \bar{\sigma}\left(1 + \vec{S}\cdot\vec{P} + h(A + \vec{S}\cdot\vec{P}')\right)$$

electron helicity

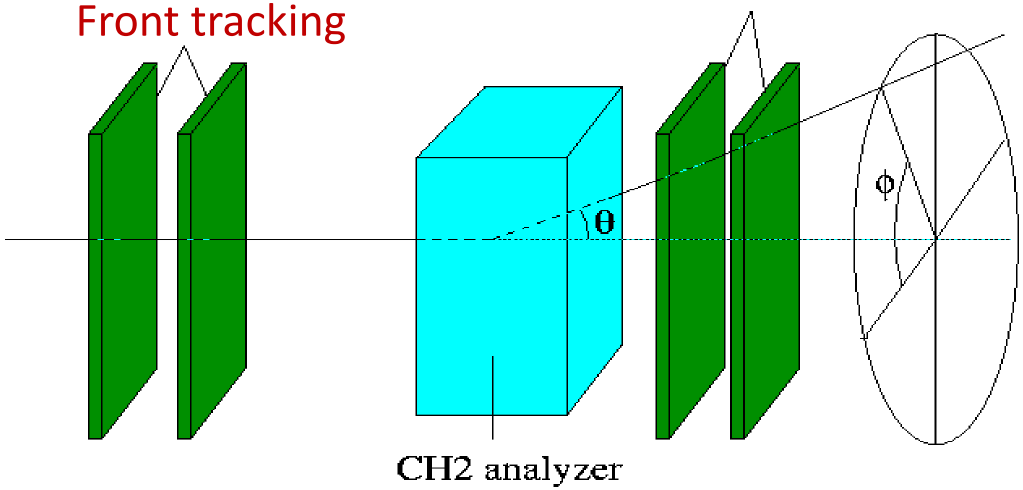


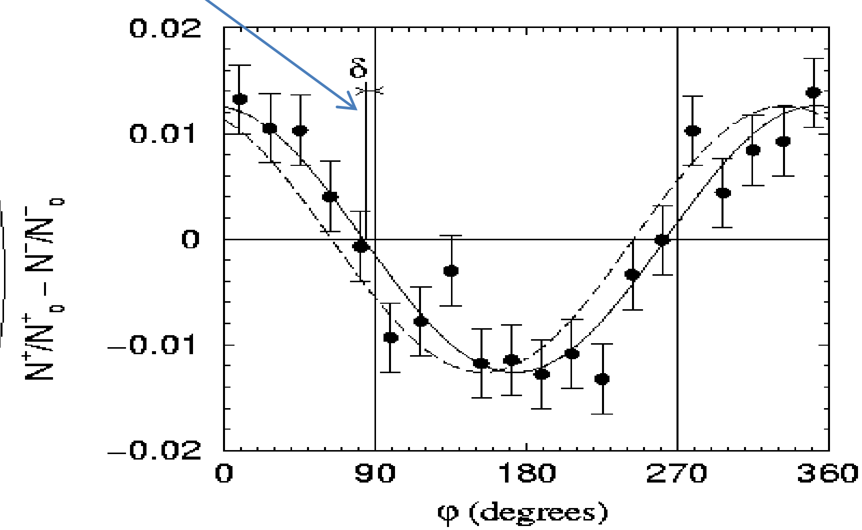
$$\frac{G_E}{G_M} = -\frac{P'_S}{P'_L}\frac{\left(E_e + E_e^{'}\right)}{2M}\tan\left(\theta_e/2\right)$$

Measure direction of proton polarization by looking for small phase shift in rotation of proton's polarization vector through a polarimeter

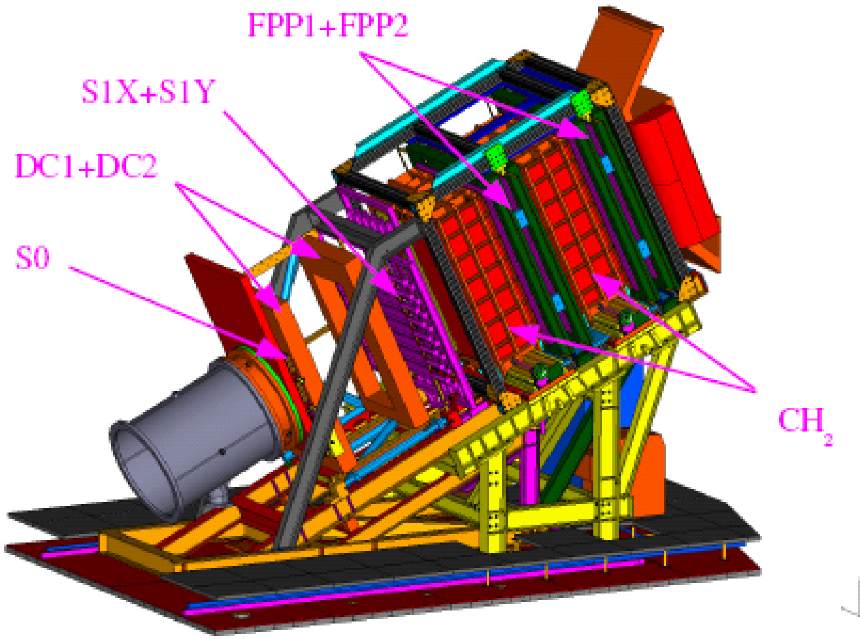
Rear tracking

Front tracking





example of Focal Plane polarimeter (Hall C, Jlab)

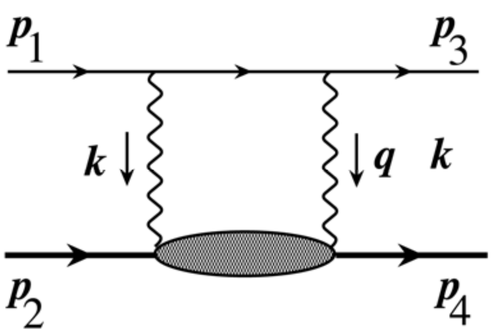


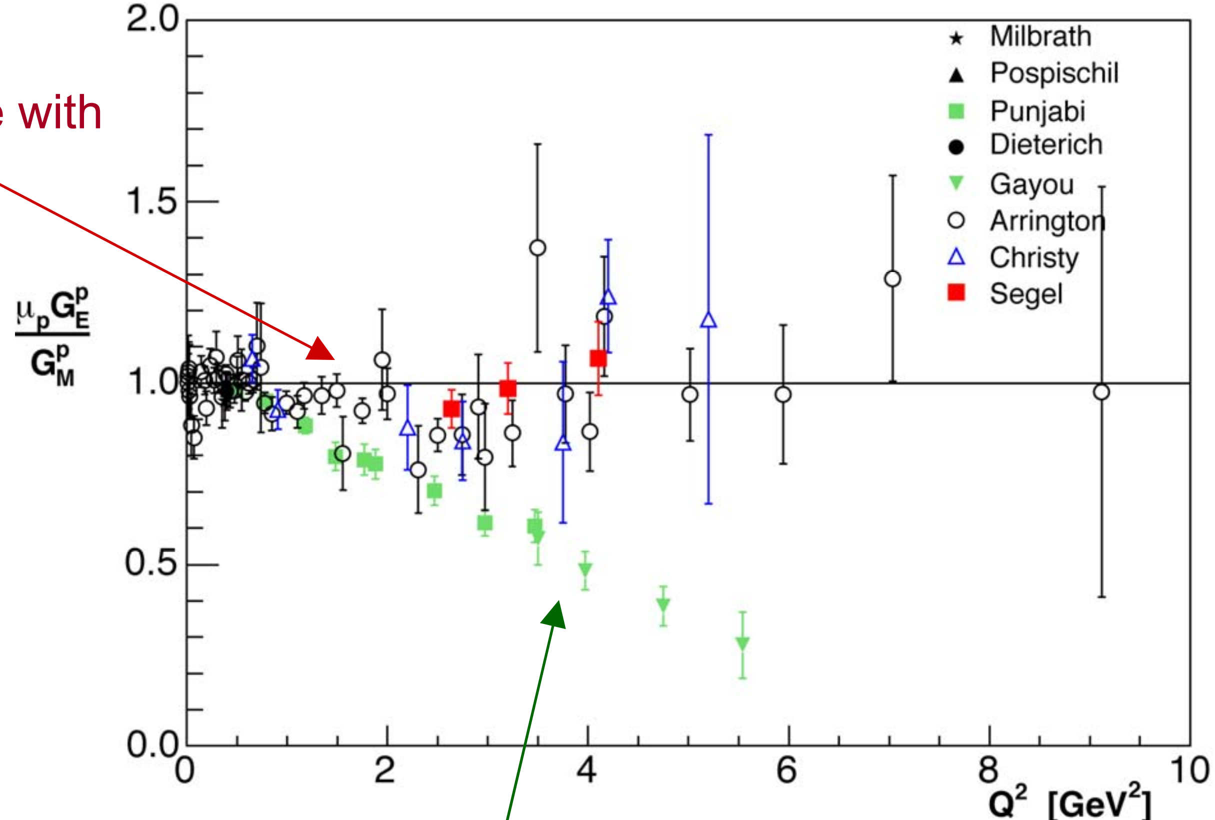
Detect electrons with magnetic spectrometer (GEP-I, GEP-II) or with a calorimeter (GEP-III): this determines all the kinematics of the scattering reaction. Measure the polarization with polarimeter behind a magnetic spectrometer. Need also to worry about g-2 precession in the spectrometer magnets!

The proton: recoil polarization vs. cross sections

Cross section data disagree with polarization data:

Looks like 2-γ exchange is important in the cross section data



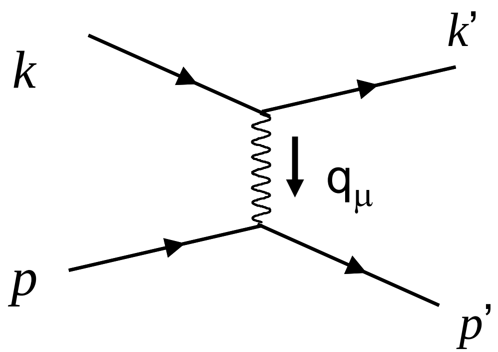


Pol'n data indicate BIG differences charge and magnetism distributions

In pQCD description, seems to be that orbital motion of quarks is important in G_E^P (Belitsky, Ji + Yuan PRL 91 (2003) 092003)

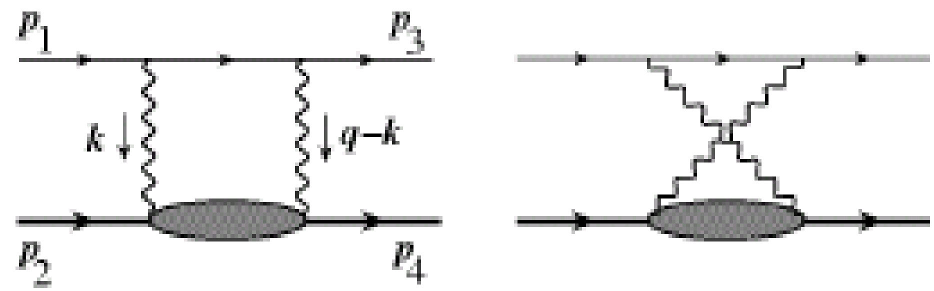
2-photon exchange

the scattering *amplitude* goes like



"Born" term

+



the *cross section* goes like:

$$\frac{\sigma(e^\pm)}{d\Omega} \propto \left|A_{born} + A_{2\gamma} + \ldots\right|^2$$

$$\propto \left|A_{born}\right|^2 \pm 2A_{born}\,\mathrm{Re}(A_{2\gamma})$$

In terms of *form factors*:
additional terms add corrections of a few %
→comparable to size of the G_E^P term of the cross section

these are now complex

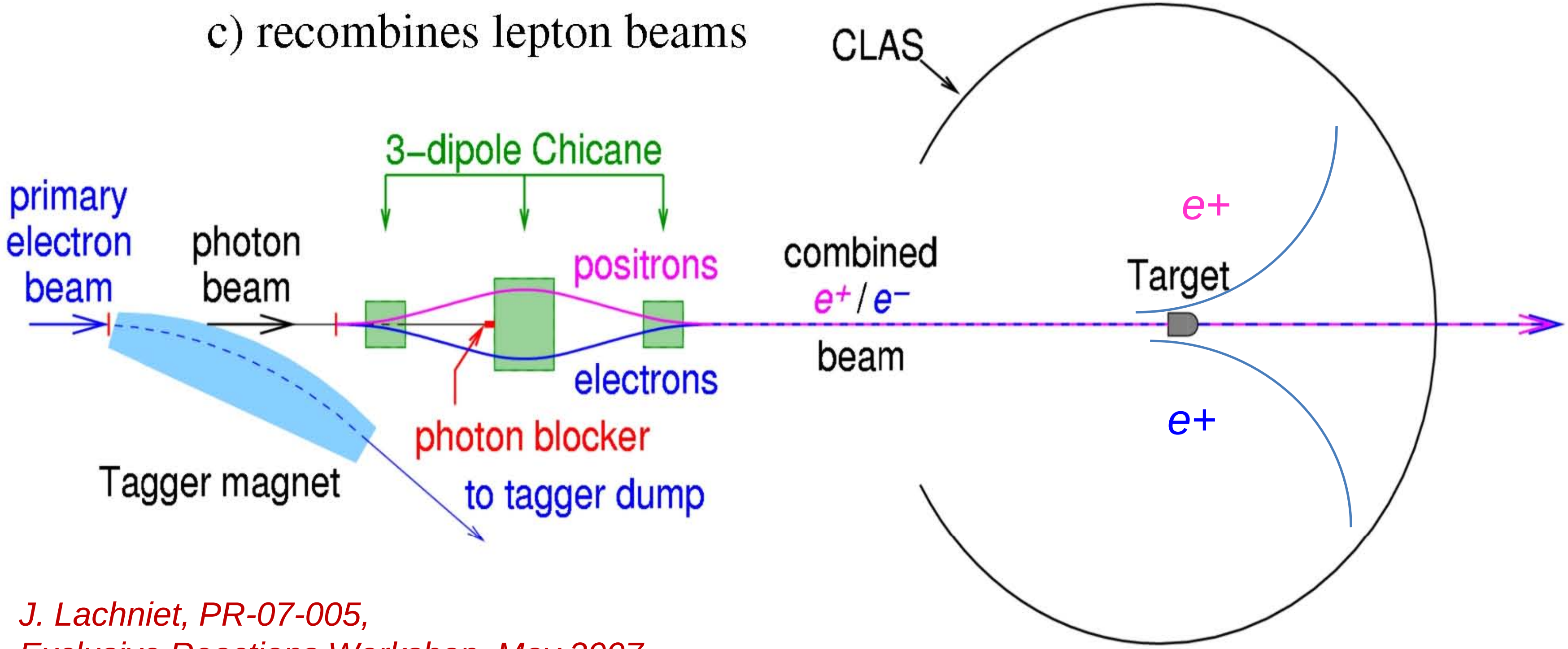
2γ only

$$\frac{d\sigma}{d\Omega} \propto \frac{\left|\widetilde{G}_M\right|^2}{\tau}\left\{\tau + \varepsilon\frac{\left|\widetilde{G}_E\right|^2}{\left|\widetilde{G}_M\right|^2} + 2\varepsilon\left(\tau + \varepsilon\frac{\left|\widetilde{G}_E\right|}{\left|\widetilde{G}_M\right|}\right)\mathrm{Re}\left(\frac{\nu\widetilde{F}_3}{M^2\left|\widetilde{G}_M\right|}\right)\right\}$$

Making Positrons in Hall B at JLab

1. Electron beam hits radiator foil, producing photon beam
2. Photon beam strikes converter foil. e-/e+ pairs are produced.
3. Magnetic chicane:
   a) separates lepton beams
   b) blocks photon beam
   c) recombines lepton beams

Also plans for positron exps at Novosibirsk, Siberia and with BLAST at DESY

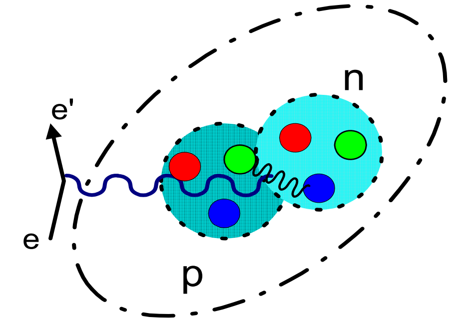


J. Lachniet, PR-07-005,
Exclusive Reactions Workshop, May 2007

the neutron

no free neutron targets exist! Must use a nucleus

simplest case → unpolarized elastic e-d scattering
-- need to know n-p wave function very well
-- not too bad for magnetism, but charge is *hugely* dominated by the proton

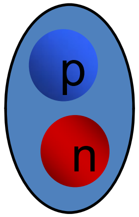


next simplest case → unpolarized *quasielastic* e-d scattering
-- direct interaction with nucleon, don't need to know so much about n-p interaction
-- Better than above for *magnetism*, especially if can detect the outgoing neutron
-- *but,* knowledge of efficiency of neutron detector is very important

$$\frac{d\sigma}{d\Omega dE} \propto \left[\sigma_T + \varepsilon\sigma_L + \ldots\right]$$

$$\sigma_T \propto \left(G_M^p\right)^2 + \left(G_M^n\right)^2 \xrightarrow[Q^2 \to 0]{} \mu_p^2 + \mu_n^2$$

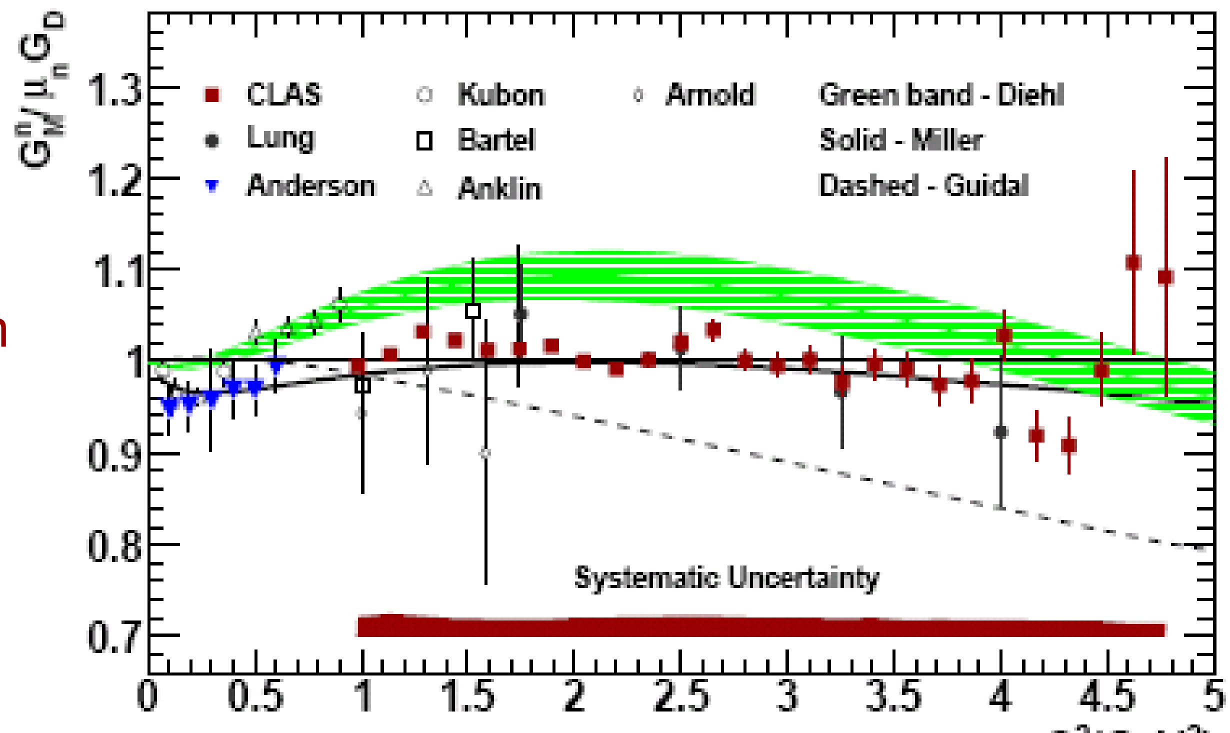
$$\sigma_L \propto \left(G_E^p\right)^2 + \left(G_E^n\right)^2 \xrightarrow[Q^2 \to 0]{} (1)^2 + (0)^2$$



the neutron in deuterium

$$\frac{d(e,e'n)}{d(e,e'p)}$$

$\rightarrow$ neutron magnetism



Lachniet et al, arXiv:0811.1716

$$\vec{e} + \vec{d} \rightarrow e + n + p$$

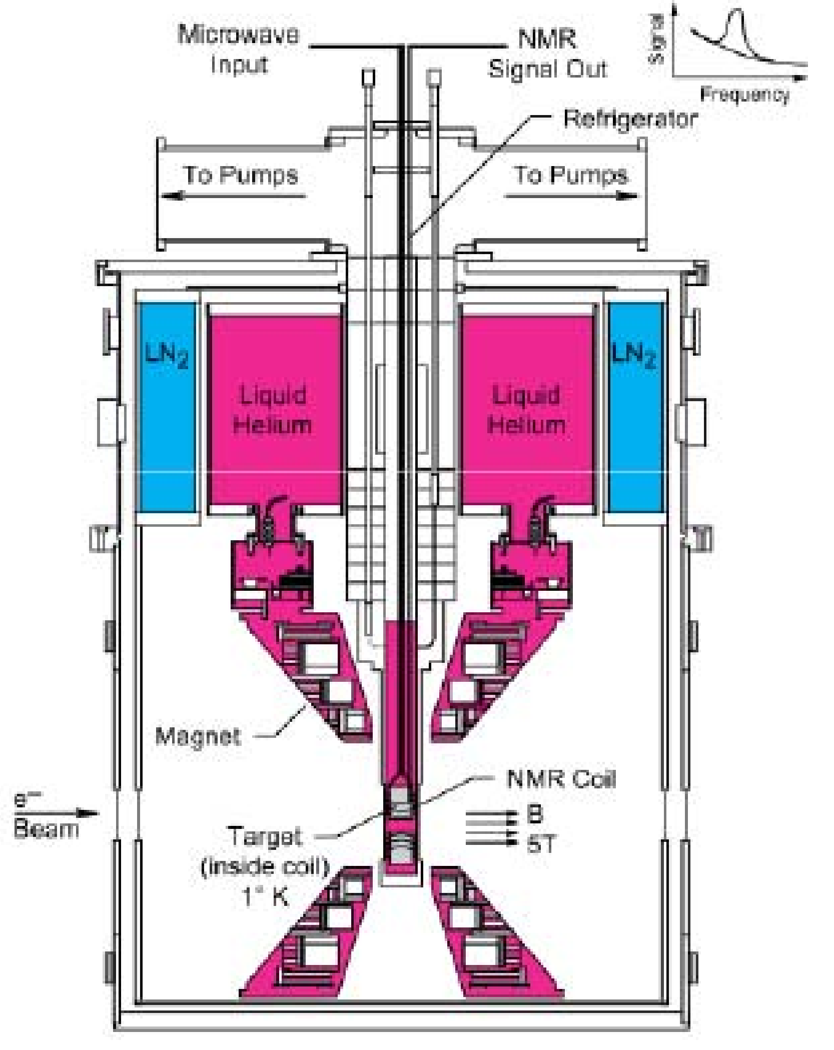
$$\vec{e} + d \rightarrow e + \vec{n} + p$$

$\rightarrow$ double polarization needed to measure the neutron charge distribution

$\rightarrow$ helps to detect the neutron – identifies the nucleon involved in the scattering

Polarized deuteron or proton target

- ❑Helmholtz coils produce field of 5T
- ❑Target material frozen ammonia ($^{14}ND_3$ or $^{14}NH_3$). Needs to be irradiate to produce unpaired electrons.
- ❑Helium refrigerator (helium bath with pumps to produce low pressure) cools target to 1 K
- ❑140 GHz microwaves irradiate target and dynamically polarize the target. The unpaired electrons are 100% polarized which is transferred to the H or D
- ❑Produce proton polarized to 70-90% and deuterons polarized to 20-40%
- ❑Only low 100nA currents possible. Beam heating destroys the polarization of the material

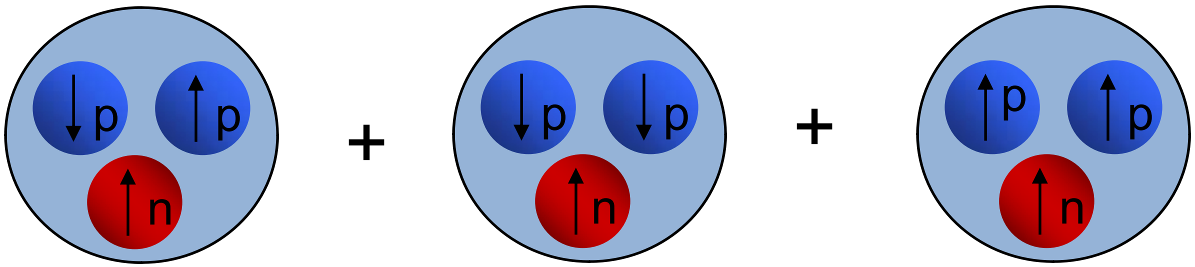


from M. Jones, HUGS 2009

D. Crabb and D. Day, NIM A356, 9 (1995)

the neutron in ^{3}He

$^3\vec{He}$



“S” 88.2%

“S-prime” 1.5%

“D” 9.8%

$$P_n = 86\%$$

$$P_p = -3\%$$

$^3\vec{He}(\vec{e},e')$ OK for neutron magnetism → proton is small correction

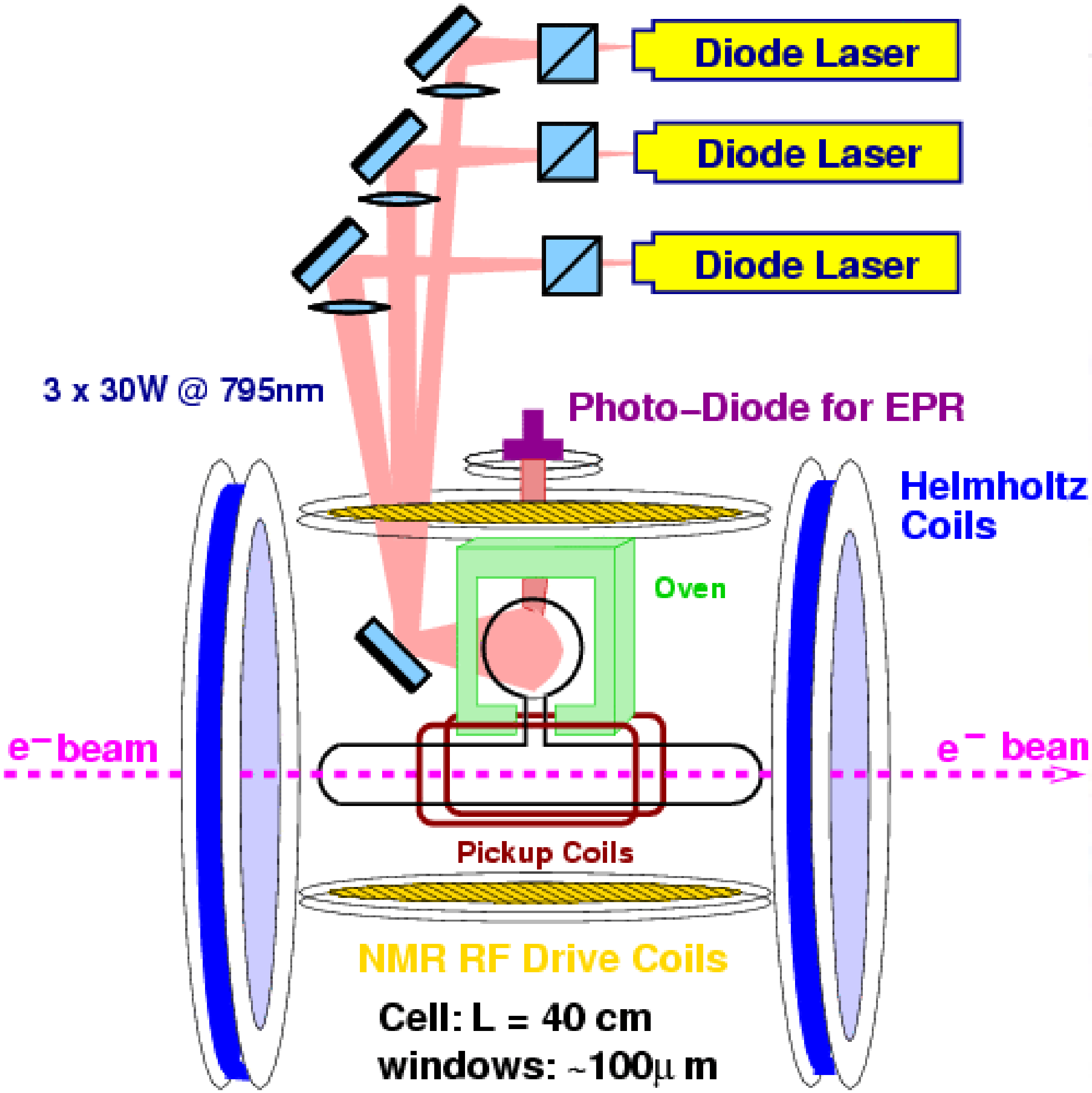
$^3\vec{He}(\vec{e},e'n)$ need to detect the neutron

measure asymmetry → don’t need detection efficiency (much)

$$A = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\uparrow\downarrow}} \propto \frac{a(\theta^*)G_M^2 + b(\theta^*)G_M G_E}{\sigma_{unpol}}$$

Polarized ^{3}He

from W. Korsch, U Ky



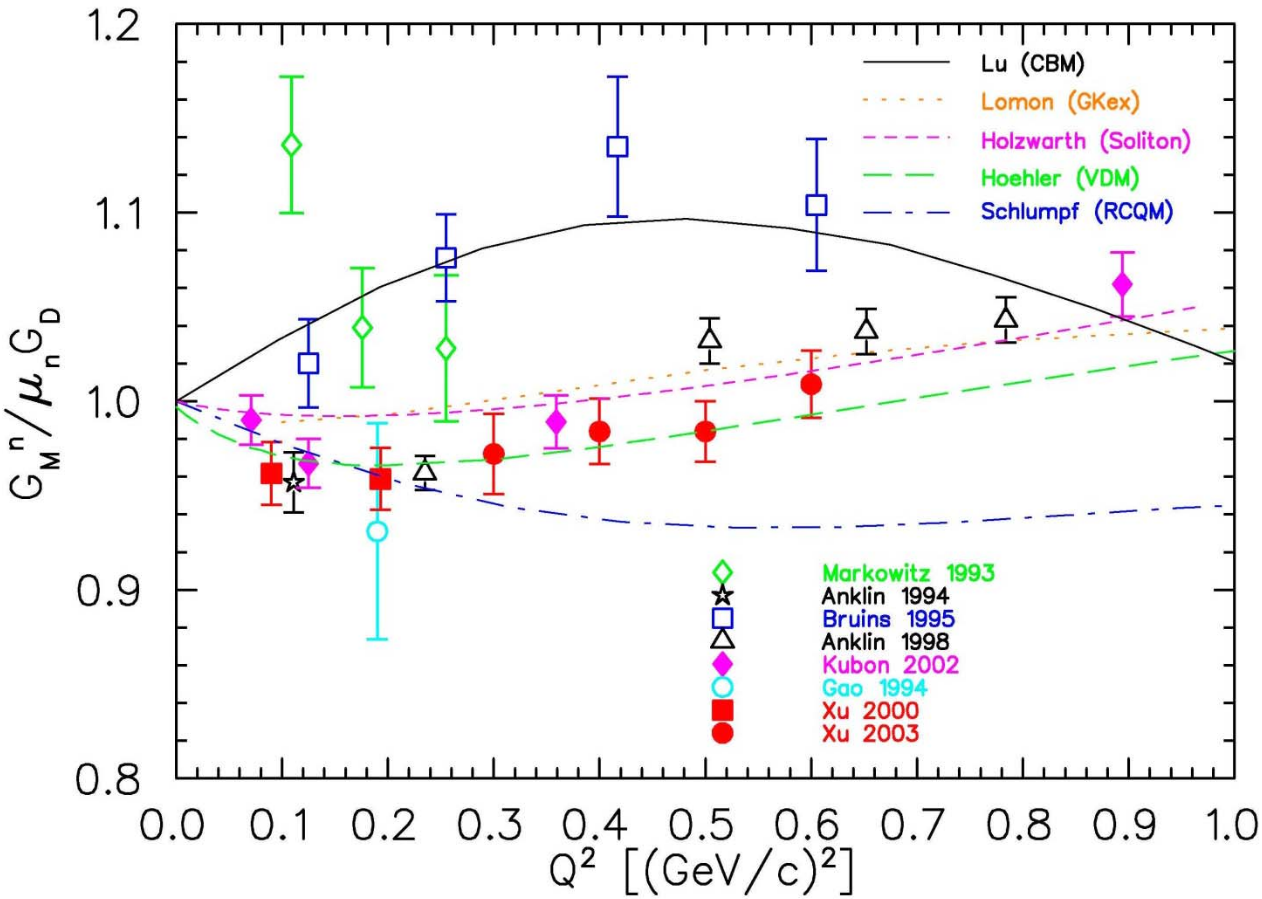
Jlab Hall A target, from A. Kelleher

The neutron magnetic form factor: low Q^2

- $\dfrac{d(e,e'n)}{d(ee'p)}$

Kubon et al, PLB 524 (2002) 26.

requires precise determination of neutron detection efficiency.



- $^3\vec{He}(\vec{e},e')$

Xu et al, PRC 67 (2003) 012201

$Q^2 < 0.3$ (GeV/c)^2: need Fadeev calc of ^{3}He wave fn, including MEC/FSI

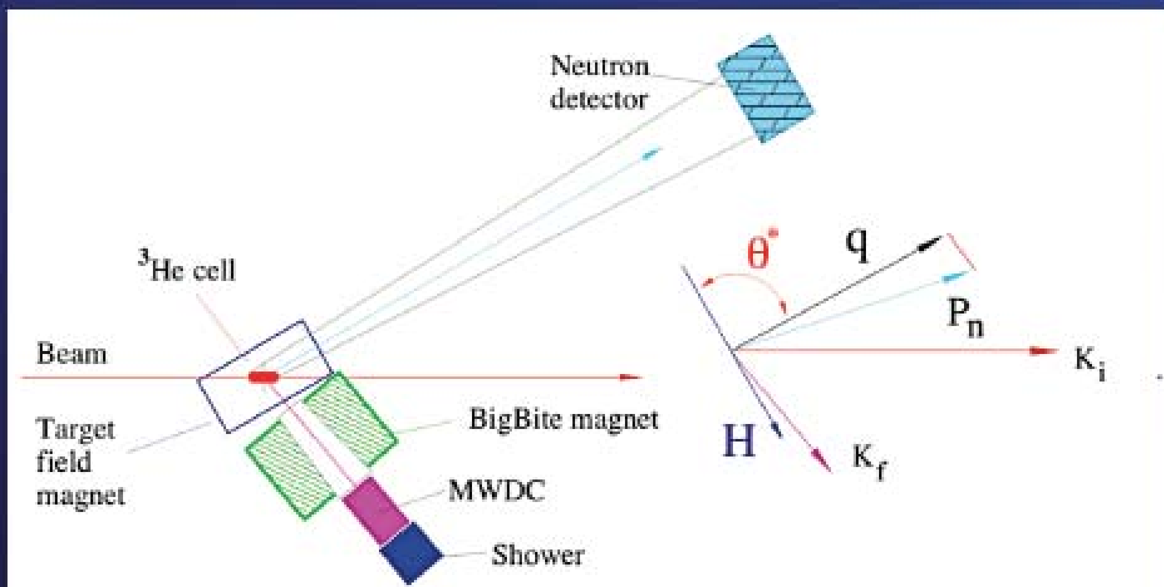
$Q^2 > 0.3$ (GeV/c)^2: PWIA works well, relativity important

example: Jlab Hall A experiment

E02-013 Method for measuring G_E^n

- measure coincidences using reaction: $^3\vec{\mathrm{He}}(\vec{e}, e'\, n)$
- Align polarization perpendicular to q
- Asymmetry $\propto G_E^n/G_M^n$

G. Cates, CIPANP 2009



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

Here a, b and c are solely functions of kinematic factors (and not θ^* or Φ^*)

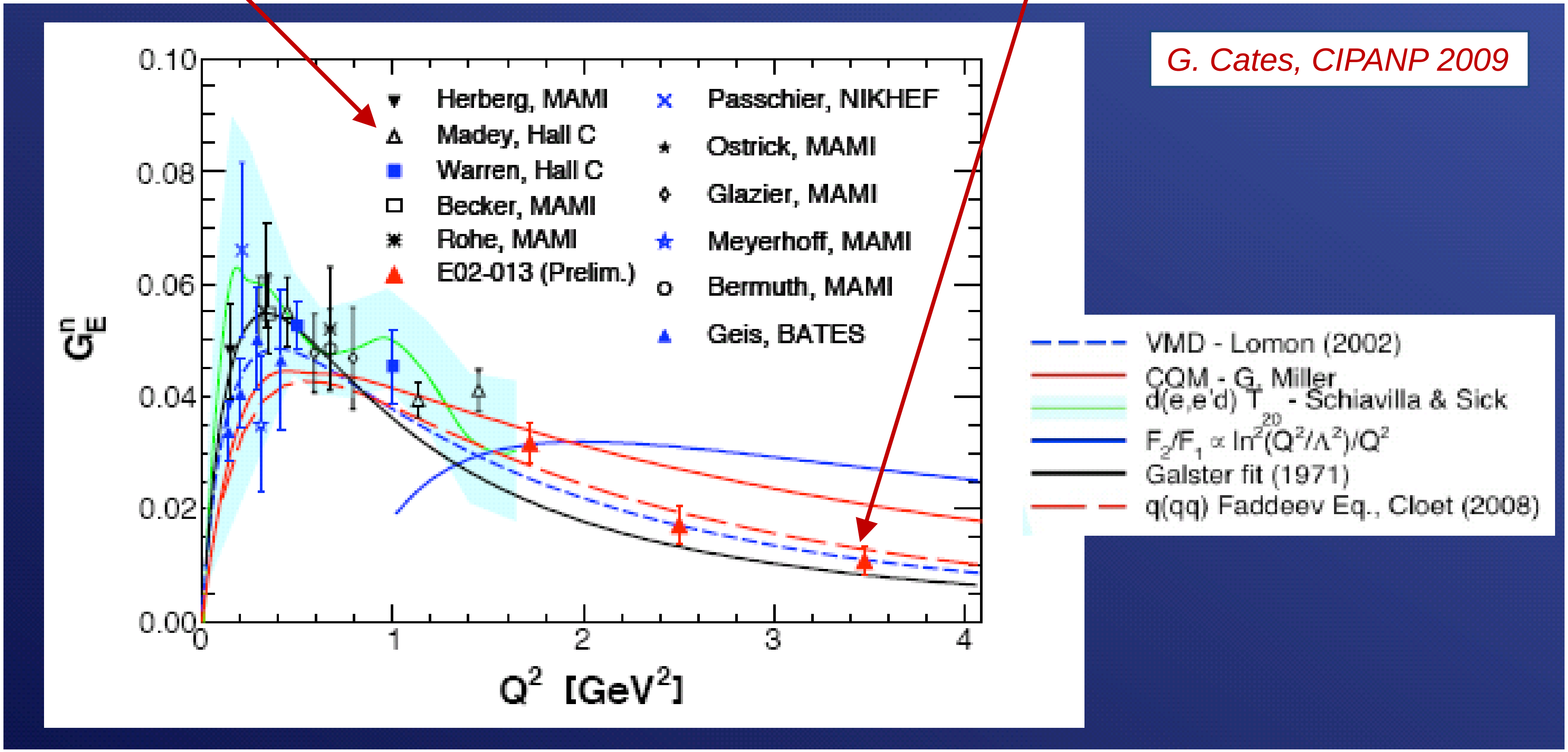
neutron's charge form factor (high Q^2)

$d(\vec{e},e'\vec{n})$

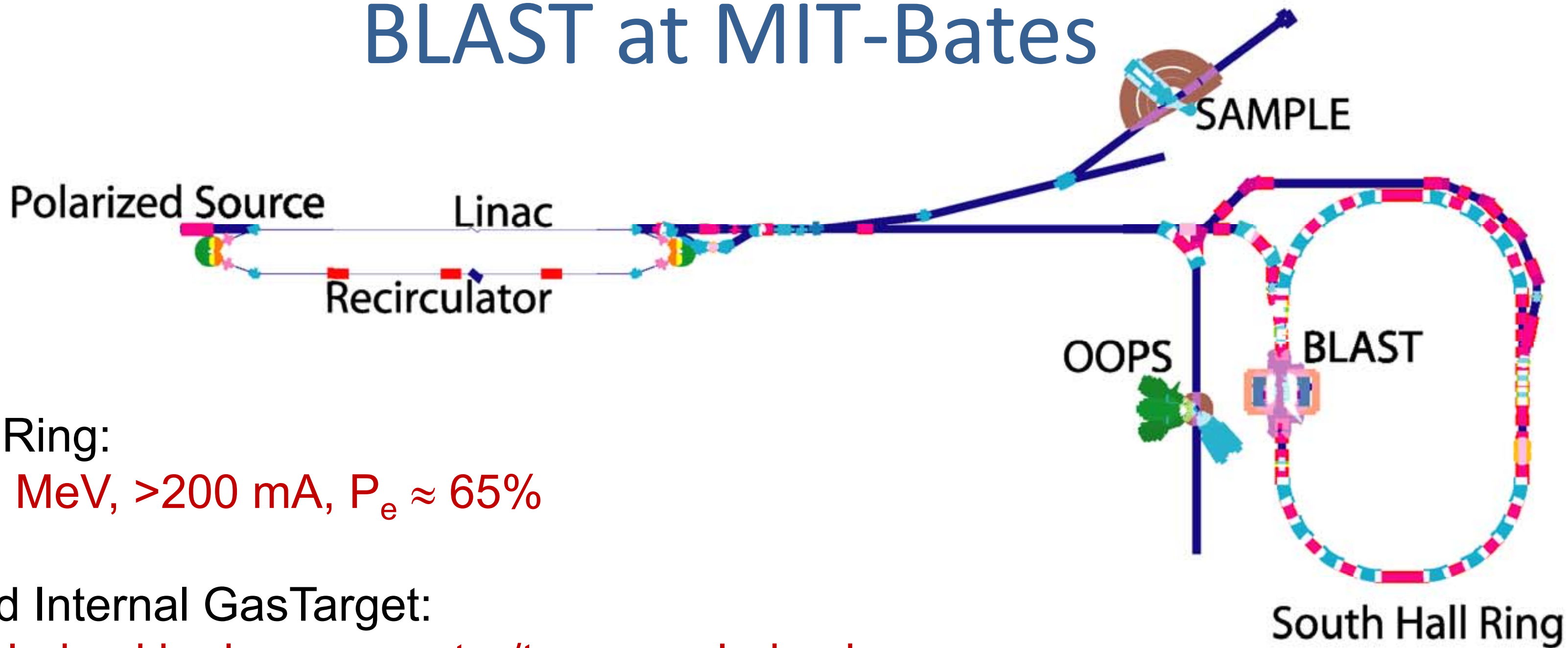
B. Plaster, et al.,
PRC **73**, 025205 (2006)

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

preliminary results
(don't quote these)



BLAST at MIT-Bates



Storage Ring:

50 MeV, >200 mA, $P_e \approx 65\%$

Polarized Internal GasTarget:

Polarized hydrogen, vector/tensor polarized deuterium

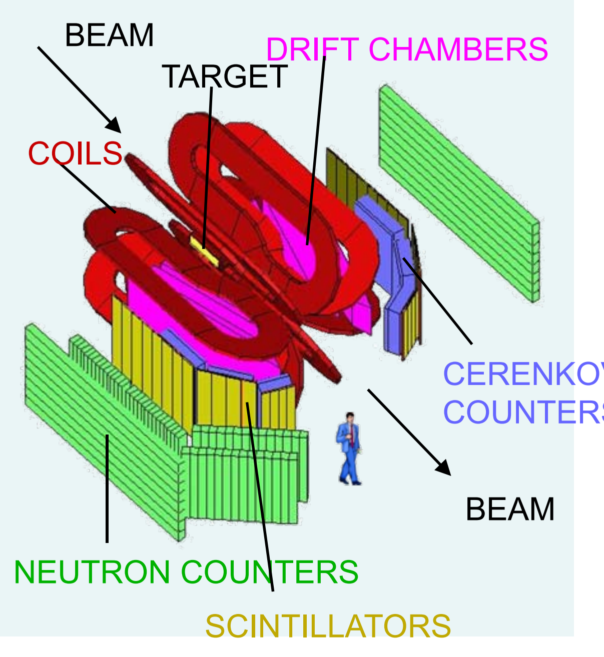
Large Detector acceptance:

$0.1 < Q^2/(GeV/c)^2 < 0.8$

$20^o < \theta < 80^o$, $-15^o < \phi < 15^o$

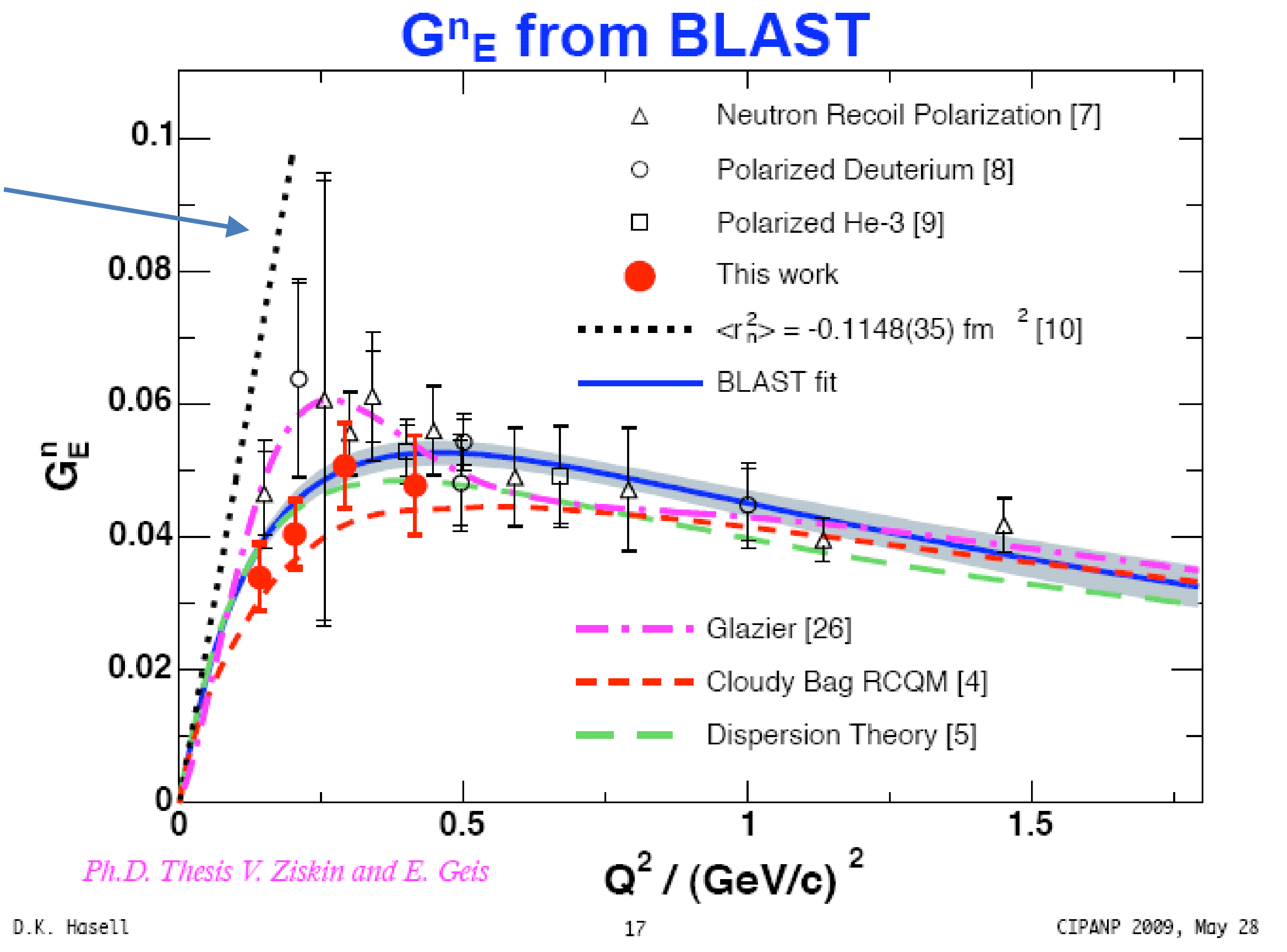
Simultaneous detection of $e^\pm$, $\pi^\pm$, *p*, *n*, *d*

http://mitbates.lns.mit.edu/bates/control/main



neutron charge at low Q^2

constraint from charge radius measurements



INTERLUDE: the NEUTRON CHARGE RADIUS from NEUTRON-ELECTRON SCATTERING

$$\langle r_n^2 \rangle = \frac{3 m_e a_0}{m_n} b_{ne},$$

$<r_n^2>$ - neutron mean squared charge radius

b_{ne} - neutron-electron scattering length (related to phase shift upon scattering)

Nuclear scattering length $b_c >> b_{ne}$, so rely on interference term and high Z:

$$\sigma_{ne} = -4\pi\{2 b_c b_{ne}[Z - f(Z,E)]\},$$

b_{ne} = 1.33 ± 0.27 ± 0.03 fm (^{208}Pb)

yields $<r_n^2>$ = –0.115 fm^2

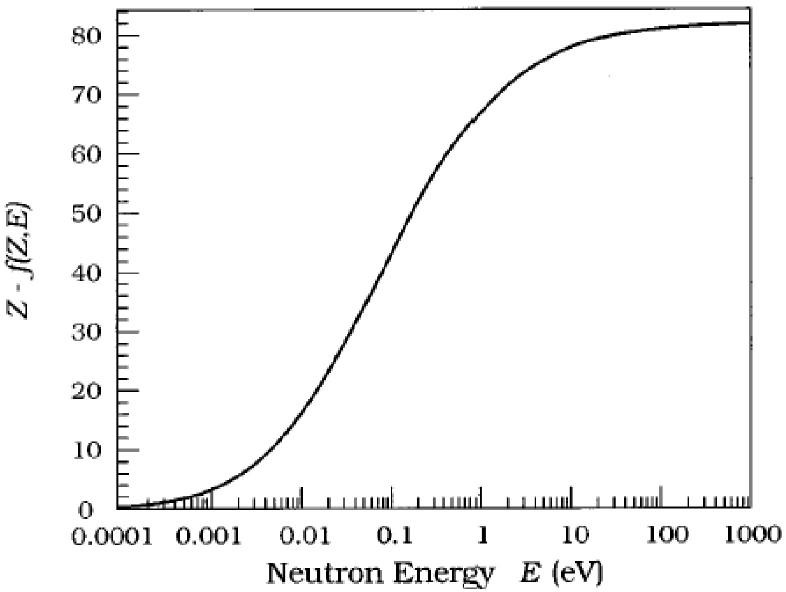
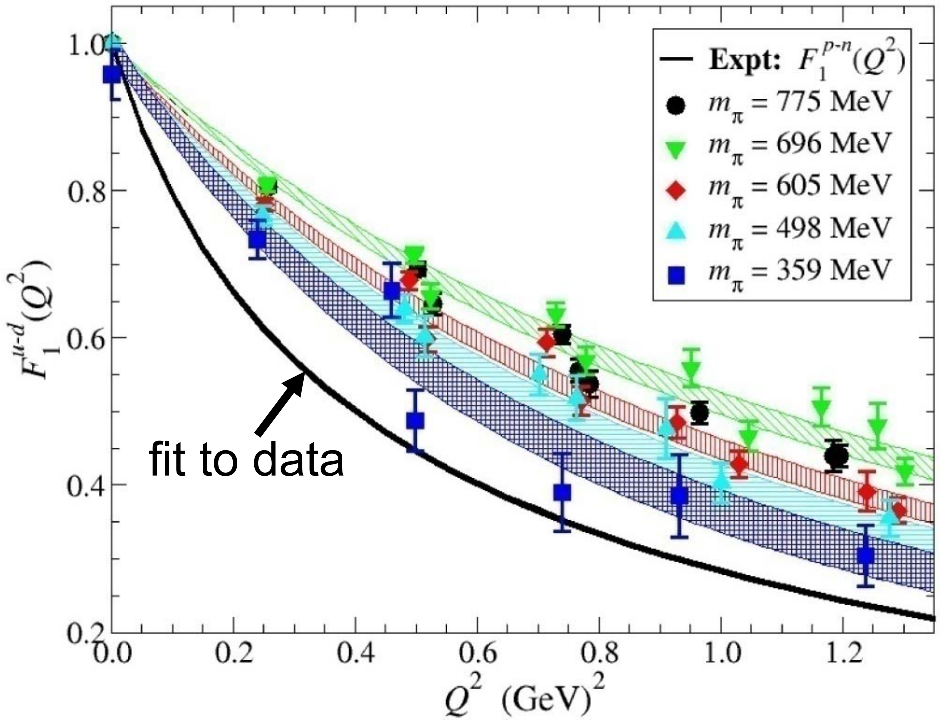


FIG. 1. Illustration of $Z-f(Z,E)$, the atomic charge density of Pb for neutron energies E between 10^{-4} and 10^{3} eV.

S. Kopecky *et al*, Phys Rev. C **56**, 2229 (1997)

Form Factors in Lattice QCD (a sampling)

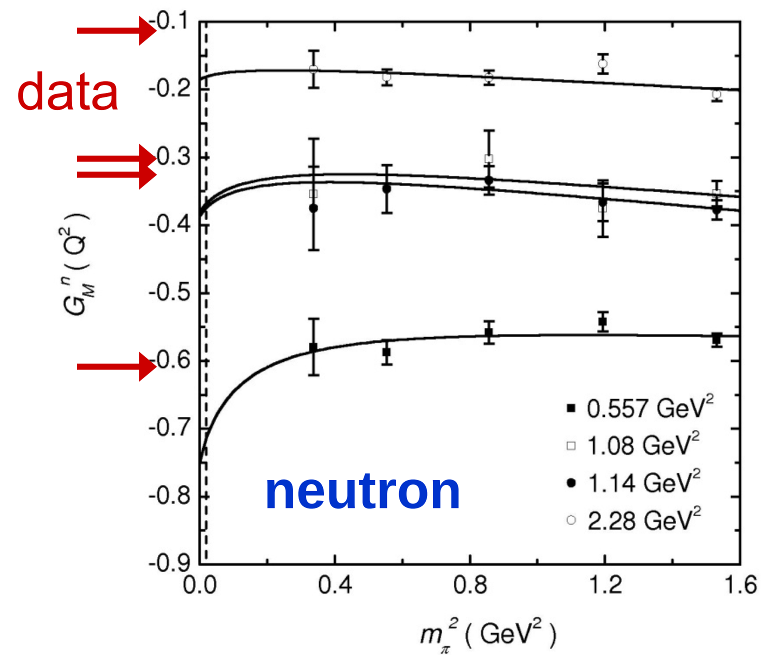


LHPC collab.: (hep-lat/0610007)

$(p - n)$: lattice calculation approaches data as pion mass approaches physical value

Wang, etal, Phys.Rev.D75:073012,2007:

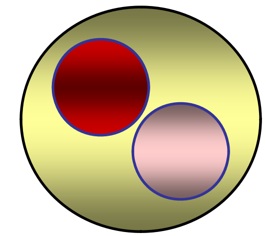
Extrapolate lattice-determined magnetic moments and $G_M{}^{p,n}$ using guidance from chiral effective theory



Spin 0: π and K Electromagnetic Form Factors

Charge radii are known
from π-e and K-e scattering

$$r_\pi^2 = 0.44 \pm 0.01\ \mathrm{fm}^2$$
$$r_{K^+}^2 = 0.34 \pm 0.05\ \mathrm{fm}^2$$



Light mesons important in nucleon structure

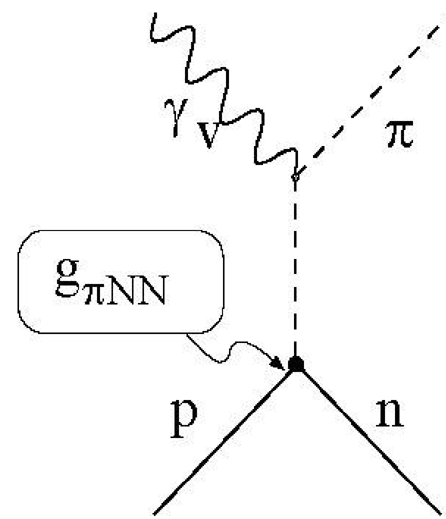
Theoretically "clean"…

$$F_\pi(Q^2) \underset{Q^2\to\infty}{\longrightarrow} \frac{8\pi\alpha_s f_\pi^2}{Q^2}$$

Experimentally "unclean": moving target…

$$2\pi\frac{d\sigma}{dt\,d\phi} = \varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

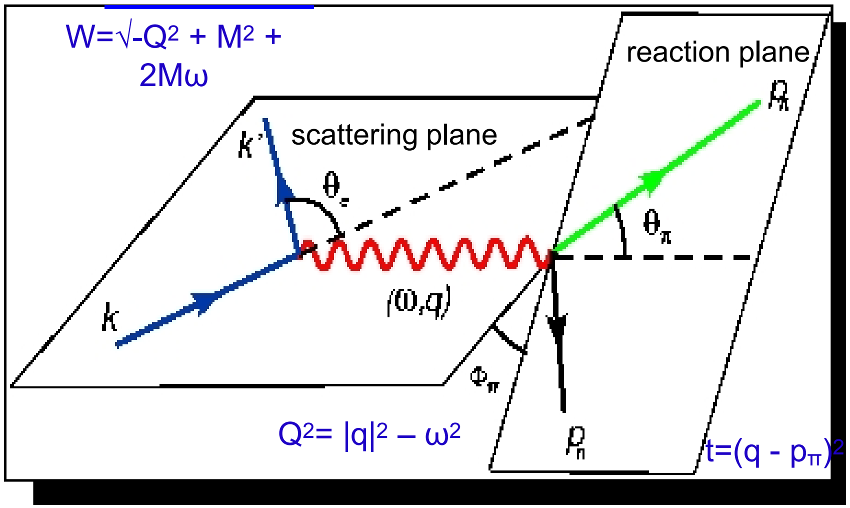
$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)}\, g_{\pi NN}^2(t)\, F_\pi^2(Q^2,t)$$

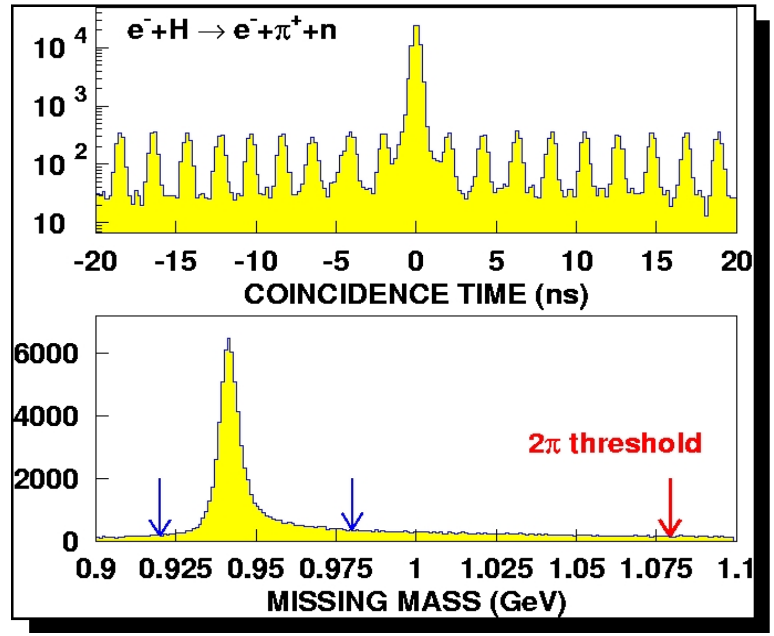


pion electroproduction

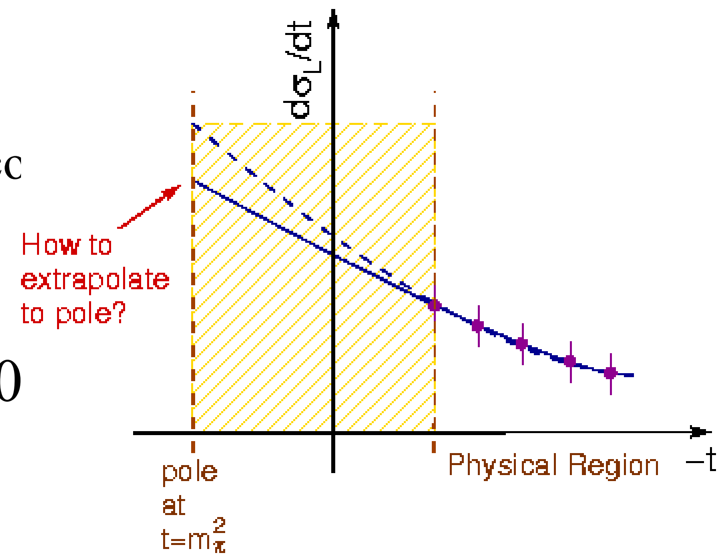
slide from T. Horn, JLab

$$e + p \rightarrow e' + \pi + n$$





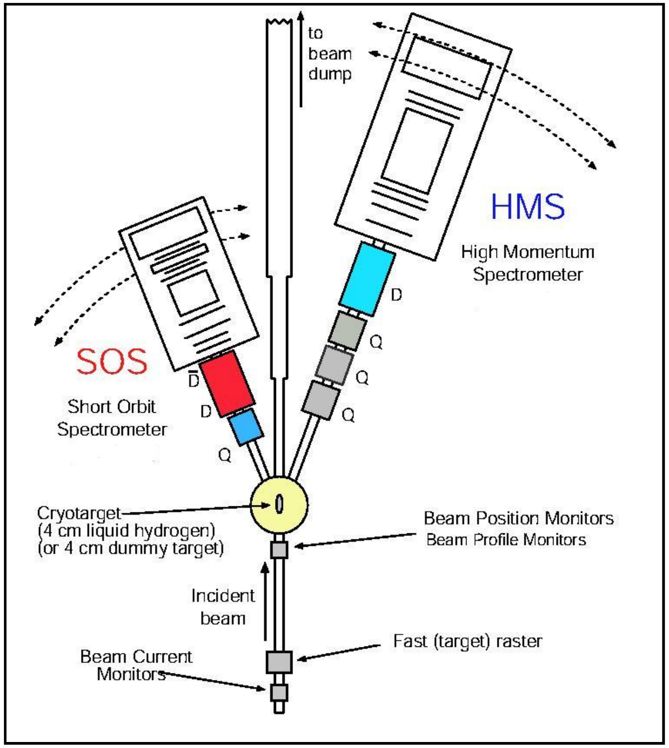
$$2\pi \frac{d\sigma}{dt d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)} \frac{d\sigma_{LT}}{dt} \cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt} \mathrm{cc}$$



$$t = (q - p_\pi)^2 = (E_\pi - \nu)^2 - |p_\pi|^2 - |q|^2 + 2\vec{p}\cdot\vec{q} < 0$$

Need to extrapolate to $t = m_\pi^2$, the “pion pole”

Measurement of F_π (in Hall C, Jlab)

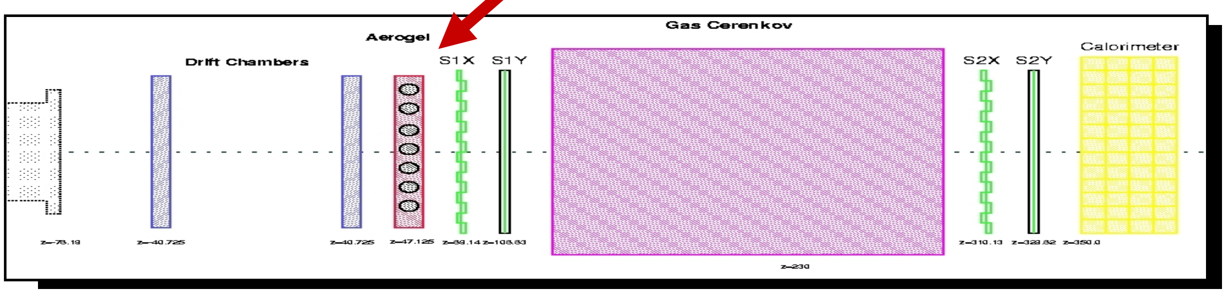


- Hall C spectrometers
  - Coincidence measurement
  - SOS detects e^-
  - HMS detects π^+
- Targets
  - Liquid 4-cm H/D cells
  - Al (dummy) target for background measurement
  - ^{12}C solid targets for optics calibration

HMS Aerogel

- Improvement of $p/\pi^+/K^+$ PID at large momenta, first use in 2003
- Built by Yerevan group

[Nucl. Instrum. Meth. A548(2005)364]



slide from T. Horn, JLab

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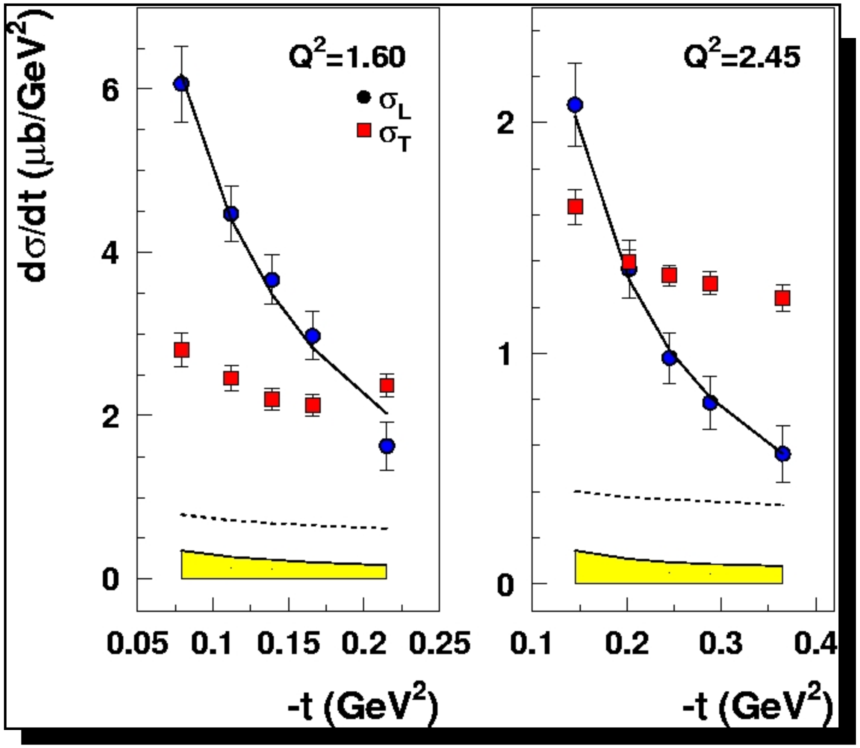
JLab Experimental Equipment

Hall C:
two spectrometers
one suited for K detection
floor space for addt'l detectors
polarized d target

Pion form factor

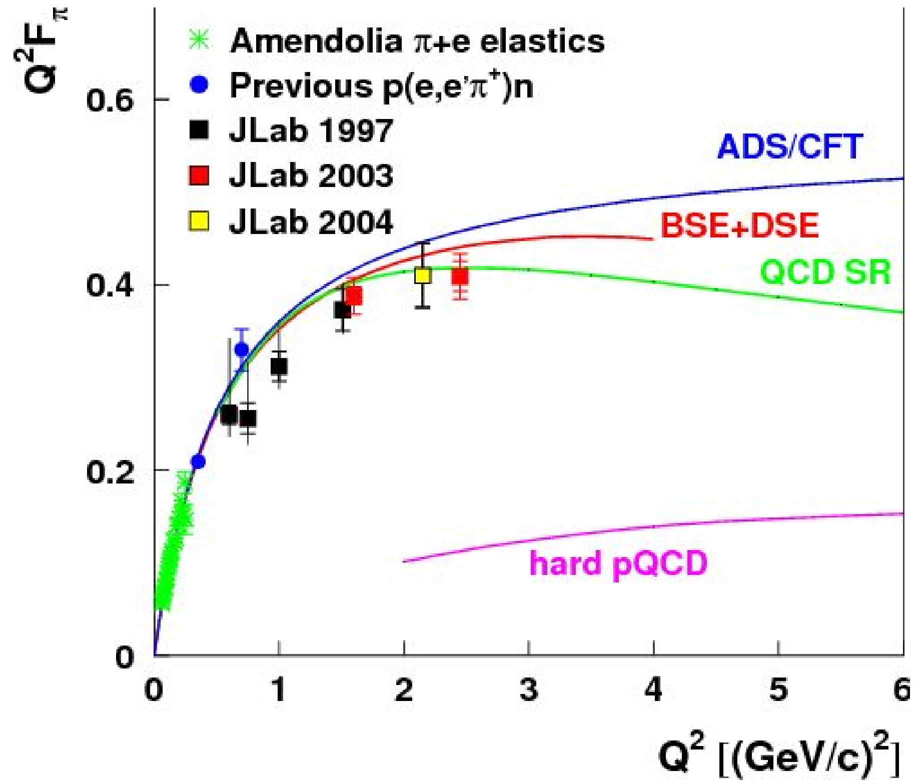
Slides from T. Horn

The part needed for F_π is well-described by model calculation, can be used to extra the form factor



calculation is Vanderhaeghen, Guidal, Laget, PRC 57 (1998), 1454

T. Horn et al., PRL 97 (2006)192001
T. Horn et al., PRC 78 (2008) 058201
V. Tadevosyan et al., nucl-ex/0607007



S. R. Amendolia et al., Nucl. Phys. B277 (1986) 168
H. Ackermann et al., Nucl. Phys. B137 (1978) 294
P. Brauel et al., Z. Phys. C3 (1979) 101

Weak nucleon form factors

pointlike fermions:

$$\text{EM}: \quad ieQ_f\gamma_\mu$$

$$\text{Weak}: \; i\frac{gM_Z}{4M_W}\gamma_\mu\left(g_V^f + g_A^f\gamma_5\right)$$

	Q_f	g_V^f	g_A^f
ν	0	1	−1
e,μ⁻	−1	$-1 + 4\sin^2\theta_W$	+1
u,c,t	+2/3	$1 - 8/3\sin^2\theta_W$	−1
d,s,b	−1/3	$-1 + 4/3\sin^2\theta_W$	+1

nucleons:

$$\langle N'|J_\mu^\gamma|N\rangle = \bar{u}_N\left[F_1^\gamma(q^2)\gamma_\mu + \frac{i\sigma_{\mu\nu}q^\nu}{2M_N}F_2^\gamma(q^2)\right]u_N$$

$$\left[\ldots + \frac{1}{M_N^2}F_A(q^2)(q^2\gamma_\mu - q^\nu\gamma_\nu q_\mu)\gamma_5 - \frac{\sigma_{\mu\nu}q^\nu\gamma_5}{2M_N}F_E(q^2)\right]u_N$$

time reversal violating

$$\langle N'|J_\mu^Z|N\rangle = \bar{u}_N\left[F_1^Z(q^2)\gamma_\mu + \frac{i\sigma_{\mu\nu}q^\nu}{2M_N}F_2^Z(q^2)\right]u_N$$

$$\langle N'|J_{\mu 5}^Z|N\rangle = \bar{u}_N\left[G_A^Z(q^2)\gamma_\mu + \frac{1}{M_N}G_P(q^2)q_\mu\right]\gamma_5 u_N$$

ignore

polarizabilities

proton

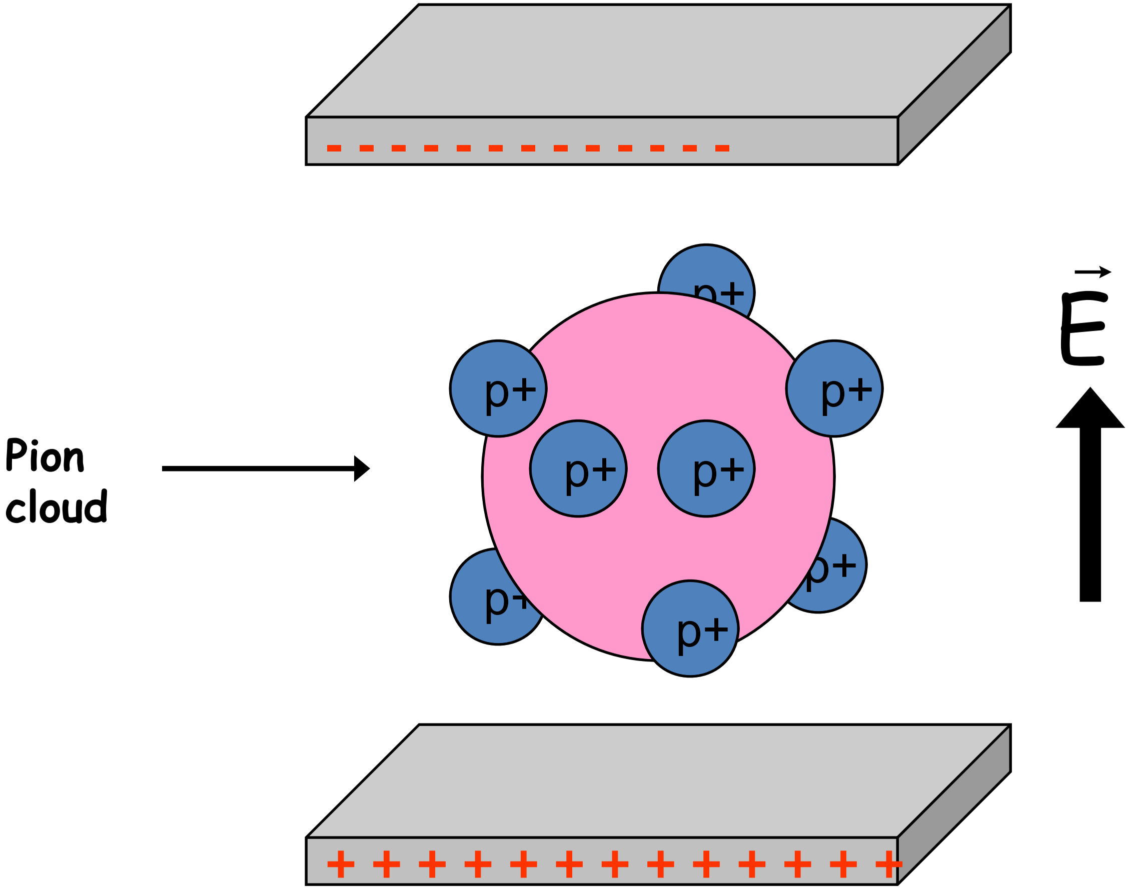
charge	$= e$ (to 10^{-21})
r.m.s. charge radius	$= 0.8768 \pm 0.0069$ fm^2
mass	$=$ 938.27231(28) MeV/c^2
μ_p	$= 2.792847337 \pm 0.000000029\ \mu_N$ $(= e\hbar/2m_N c)$
elec. dipole moment	$= (-3.7 \pm 6.3) \times 10^{-23}$ e-cm
electric polarizability	$= (12.0 \pm 0.6) \times 10^{-4}$ fm^3
magnetic polarizability	$= (1.9 \pm 0.5) \times 10^{-4}$ fm^3
mean lifetime	$= > 5.8 \times 10^{29}$ years (any decay mode)

neutron

charge	$= -0.41 \pm 1.1$ ($\times 10^{-21}$ e)
r.m.s. charge radius	$= -0.1161 \pm 0.0022$ fm^2
mass	$=$ 939.565346(23) MeV/c^2
μ_n	$= -1.913042793 \pm 0.000000023\ \mu_N$ $(= e\hbar/2m_N c)$
elec. dipole moment	$= < 0.29 \times 10^{-25}$ e-cm (90% C.L.)
electric polarizability	$= (11.6 \pm 1.5) \times 10^{-4}$ fm^3
magnetic polarizability	$= (3.7 \pm 2.0) \times 10^{-4}$ fm^3
mean lifetime	$= 885.7 \pm 0.8$ sec

Proton electric polarizability

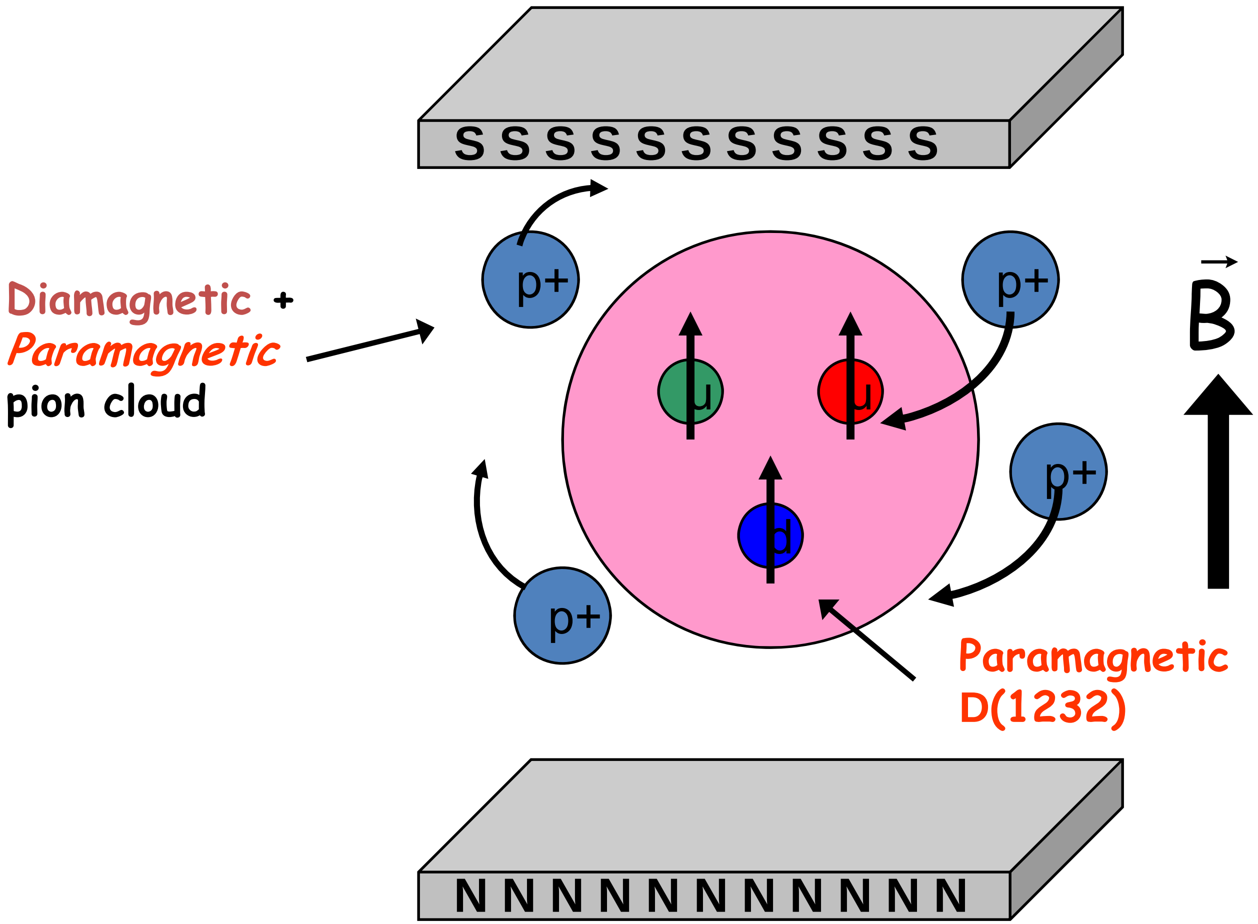
slide from H. Weller, see HUGS 2009



Electric polarizability: proton between charged parallel plates

Proton magnetic polarizability

slide from H. Weller, see HUGS 2009



Magnetic polarizability: proton between poles of a magnet

Electric and magnetic polarizabilities

via Compton Scattering at E_γ > 50 MeV

spin polarizabilities…

$$\left.\frac{d\sigma}{d\Omega}\right|_{\gamma\gamma} = \left(\frac{e^2}{4\pi M}\right)^2 \left(\frac{\omega'}{\omega}\right)^2 \left[\frac{1}{2}\left(1+\cos^2\theta\right) - \frac{4\pi M\omega\omega'}{e^2}\left(\begin{array}{l}\frac{1}{2}\left(\bar{\alpha}+\bar{\beta}\right)\left(1+\cos\theta\right)^2 \\ +\frac{1}{2}\left(\bar{\alpha}-\bar{\beta}\right)\left(1-\cos\theta\right)^2\end{array}\right) + \ldots\right]$$

proton

neutron (best gotten from the deuteron)

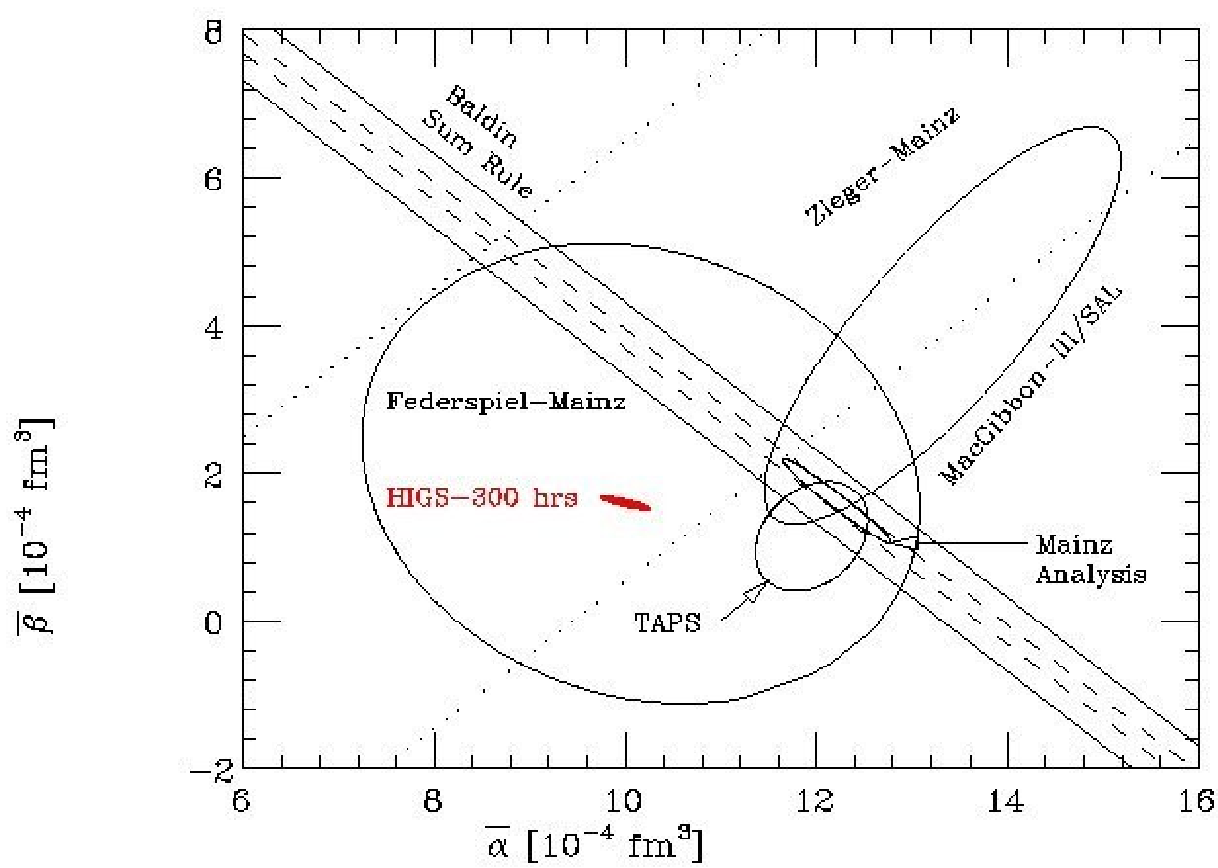
	proton	neutron
e	$\alpha = (12.0 \pm 0.6) x 10^{-4}\ fm^3$	$\alpha = (11.6 \pm 1.5) x 10^{-4}\ fm^3$
m	$\beta = (1.9 \mp 0.6) x 10^{-4}\ fm^3$	$\beta = (3.7 \mp 2.0) x 10^{-4}\ fm^3$

- the numbers are small: the nucleon is very "stiff"

† M. Schumacher, Prog. Part. and Nucl. Phys. **55**, 567 (2005) and PDG.

measurements of the proton polarizabilities

Future measurements will improve these, with the new facility at the Duke University FEL, HiGs



Why study hadron form factors?

They give us the ground state properties of (visible) matter:

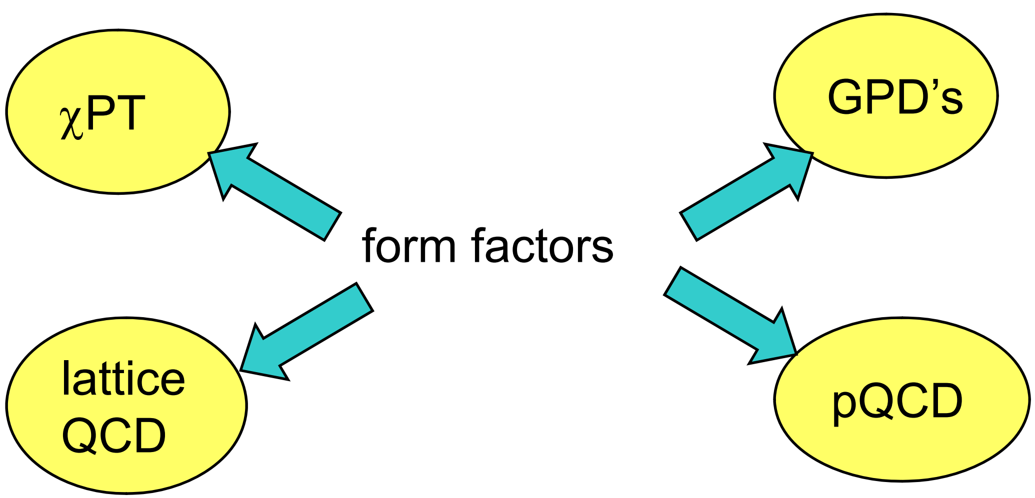
size and shape, charge and magnetism distributions
spin and angular momentum

They are required elsewhere

baseline for structure of nuclei at short distances
Proton charge radius → Lamb shift
precision symmetry tests at low Q^2
needed input for ν-N interactions: impact on ν oscillation data

Benchmarks for connecting QCD across energy/distance scales

low energy
long distance
nonperturbative



high energy
short distance
perturbative