Overview of JLab Nuclear Physics Program

- General Introduction: Why Electron Scattering?

- 10+ years of JLab Experiments: Highlights
  - The **Role of Quarks in Nuclear Physics**
    CEBAF's Original Mission Statement

  - **Nucleon and Pion Elastic Form Factors** and
    Transition Form Factors to Nucleon Excited States

  - The **Strange Quark Content** of the Proton

  - The Onset of the **Quark Parton Model**:
    The Quark-Hadron Transition

  - **Deep Exclusive Reactions**:
    Constraints on Angular Momentum
    Proton Tomography

Cool Facts about QCD and Nuclei

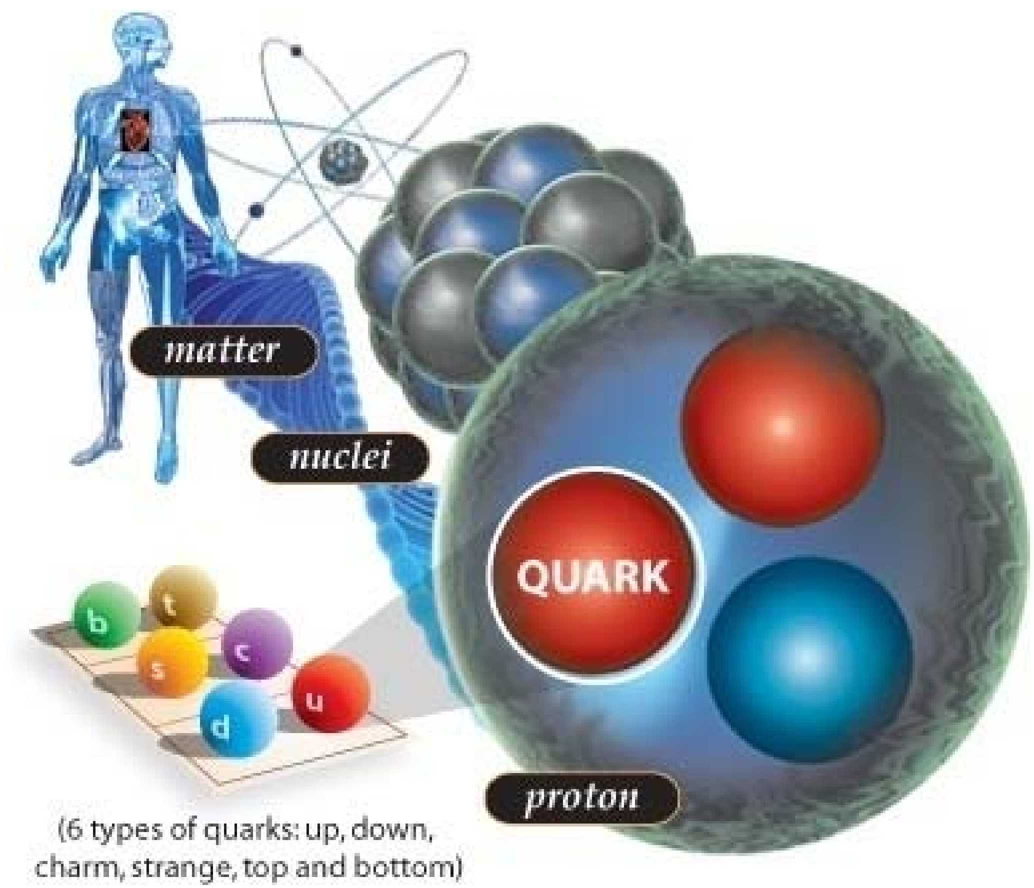
Did you know that … ?

• If an atom was the size of a football field, the (atomic) nucleus would be about the size of a marble.

• Despite its tiny dimensions, the nucleus accounts for 99.9% of an atom's mass.

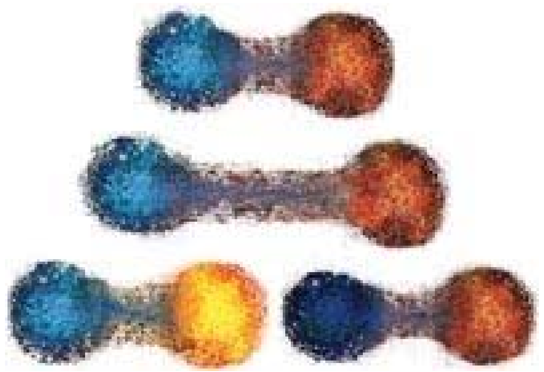
• Protons and neutrons swirl in a heavy atomic nucleus with speeds of up to some $\frac{3}{4}$ of c. More commonly, their speed is some $\frac{1}{4}$ the speed of light. The reason is because they are "strong-forced" to reside in a small space.

• Quarks (and gluons) are "confined" to the even smaller space inside protons and neutrons. Because of this, they swirl around with the speed of light.

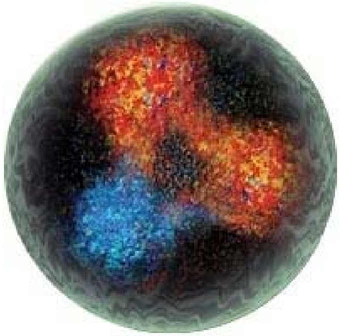


Cool Facts about QCD and Nuclei

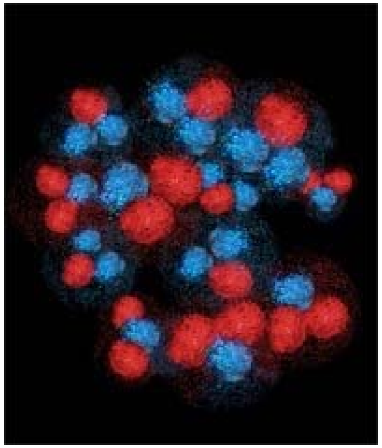
Did you know that … ?



- The strong force is so strong, that you can never find one quark alone (this is called "confinement").
- When pried even a little apart, quarks experience ten tons of force pulling them together again.
- Quarks and gluons jiggle around at nearly light-speed, and extra gluons and quark/anti-quark pairs pop into existence one moment to disappear the next.



- It is this flurry of activity, fueled by the energy of the gluons, that generates nearly all the mass of protons and neutrons, and thus ultimately of all the matter we see.
- 99% of your mass is due to this stored energy.



- A small fraction of the force between quarks and gluons "leaks out" of protons and neutrons, and binds them together to form tiny nuclei. The long-range part of this process can be well described as if **protons and neutrons** exchange **pions**.

Electron Scattering

Electrons as probe of nuclear structure have some distinct advantages over other probes like hadrons or γ-rays:

• The interaction between the electron and the nucleus is known; it is the electromagnetic interaction with the charge ρ and the current **J** of the nucleus: $V_{int} = \rho\phi + \mathbf{J}.\mathbf{A}$, where ϕ and **A** are the scalar and vector potentials generated by the electron.

• The interaction is weak, so that in almost all cases it can be treated in the "one-photon exchange approximation" (OPEA), i.e., two-step processes (two-photon exchange) are small. The exception is charge elastic scattering of the Coulomb field of a heavy-Z nucleus.

• The energy (ω) and linear momentum (**q**) transferred to the nucleus in the scattering process can be varied independently from each other. This is very important, as for a certain $|\mathbf{q}|$ one effectively measures a Fourier component of ρ or **J**. By varying $|\mathbf{q}|$ all Fourier components can be determined and from these the radial dependence of ρ and **J** can be reconstructed.

• Because the photon has no charge, only the $\mathbf{J}.\mathbf{A}$ interaction plays a role, leading to magnetic M_λ and electric E_λ transitions. In electron scattering, one can also have charge C_λ transitions.

Electron Scattering

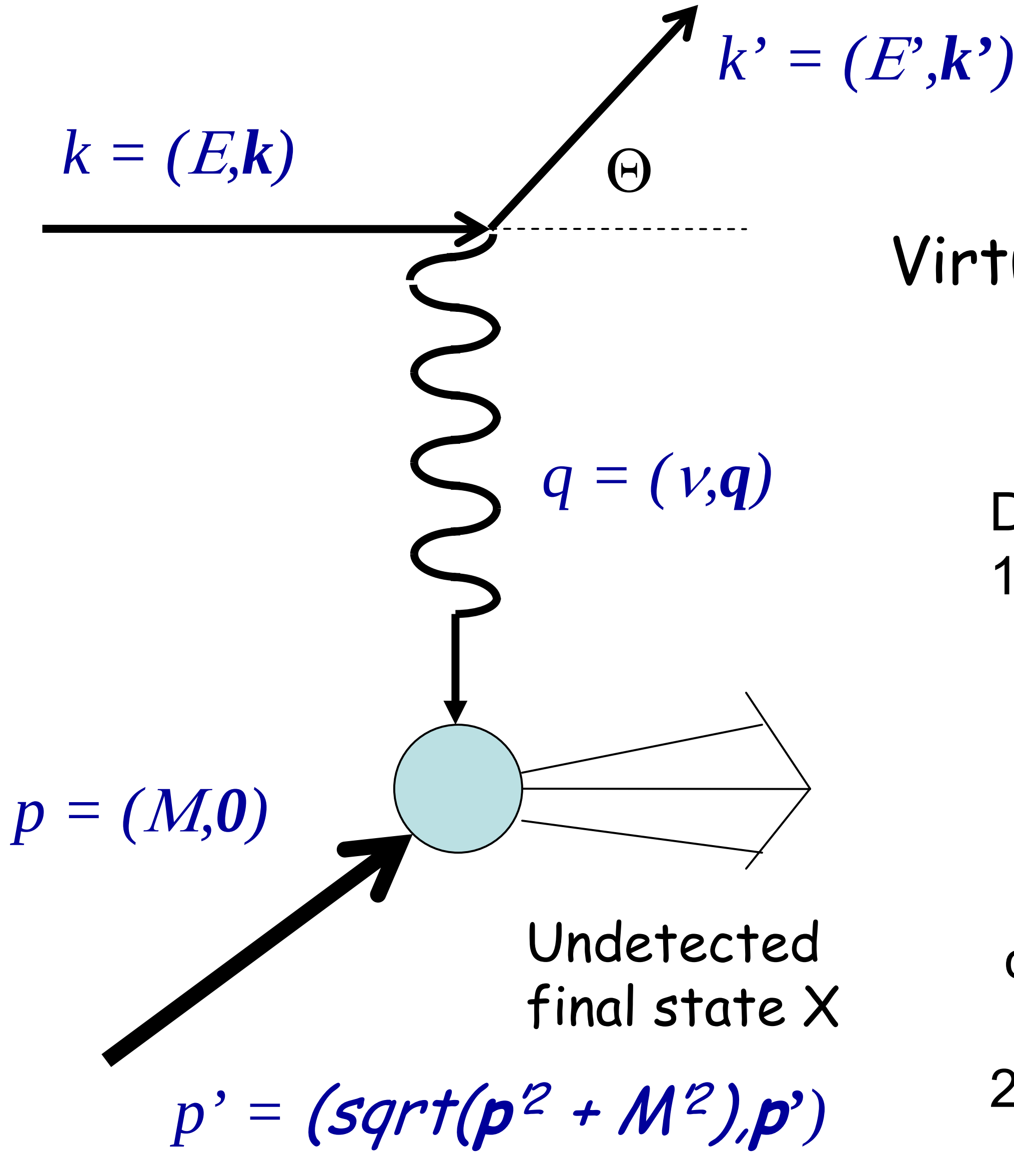
Electron scattering has also some disadvantages:

- The interaction is weak, so cross sections are small, but one can use high electron beam currents and thick targets.

- Neutrons are less accessible than protons, since they do not have a net electric charge.

- Because electrons are very light particles, they easily emit radiation (so-called Bremsstrahlung). This gives rise to radiative tails, with often large corrections for these processes.

Kinematics



$(\rightarrow p'^2 = M'^2 = W^2)$!!

Virtual photon → off-mass shell

$$q_\mu q^\mu = \nu^2 - \mathbf{q}^2 \neq 0$$

Define **two invariants**:

1) $Q^2 = -q_\mu q^\mu \quad = -(k_\mu - k_\mu')(k^\mu - k'^\mu)$

$= -2m_e^2 + 2k_\mu k'^\mu$

(me ~ 0) $\quad = 2k_\mu k'^\mu$

(LAB) $\quad = 2(EE' - \mathbf{k.k'})$

$= 2EE'(1\text{-cos}$

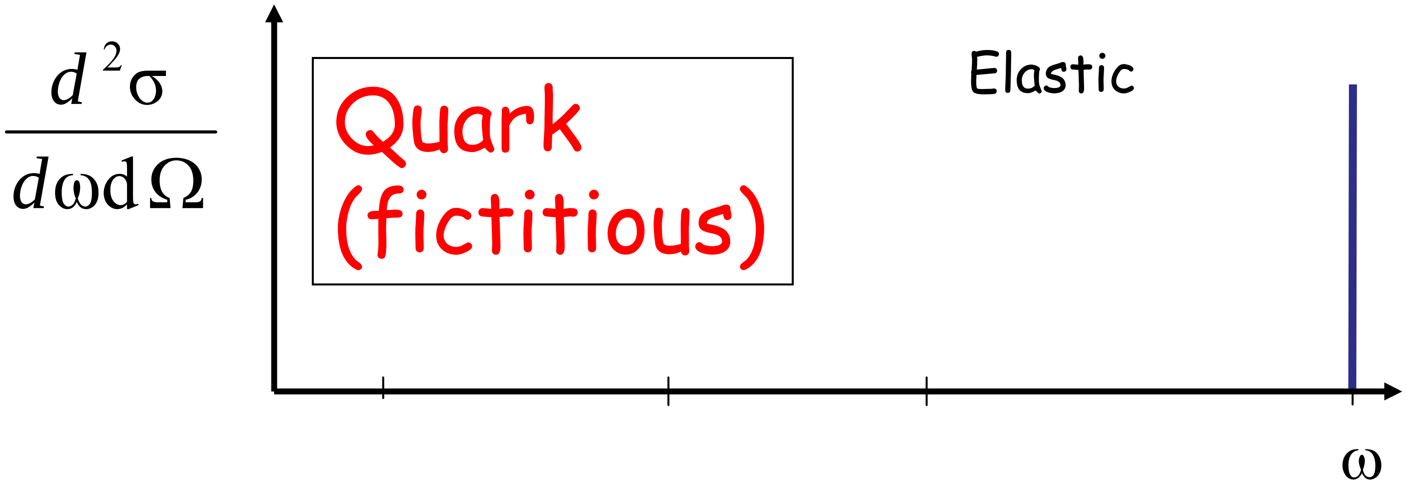
$= 4EE'\sin^2(\Theta$

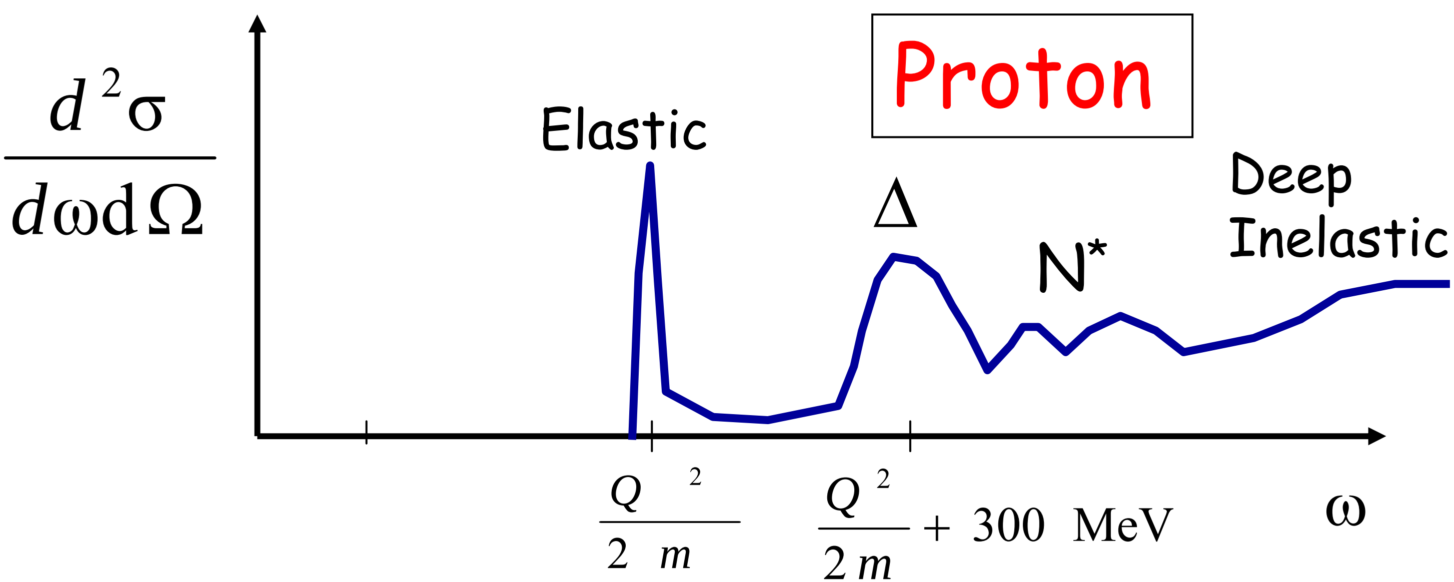
only assumption: neglecting m_e^2!!

2) $2M\nu = 2p_\mu q^\mu = Q^2 + W^2 - M^2$

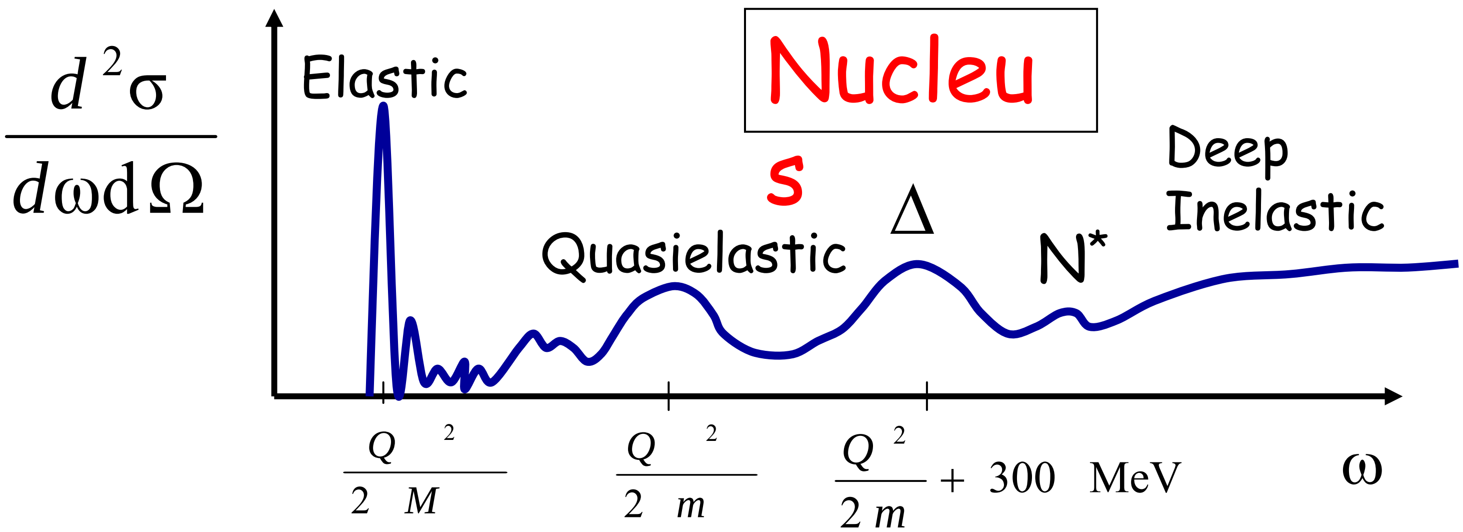
Elastic scattering
$\rightarrow W^2 = M^2 \rightarrow Q^2 = 2M(E-E')$

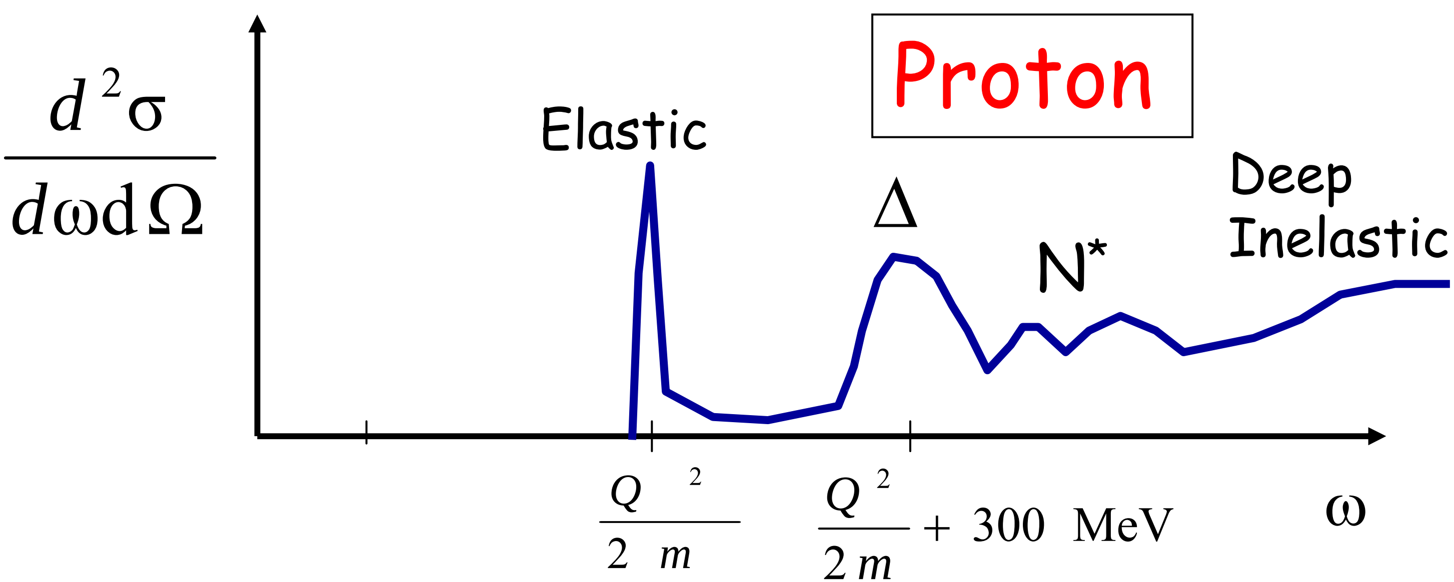
Electron Scattering at Fixed Q^2



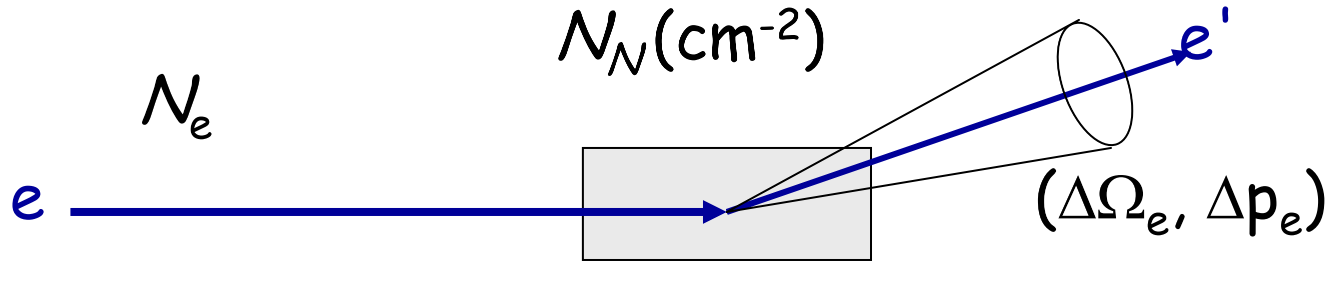


Electron Scattering at Fixed Q^2





Extracting the (e,e') cross section

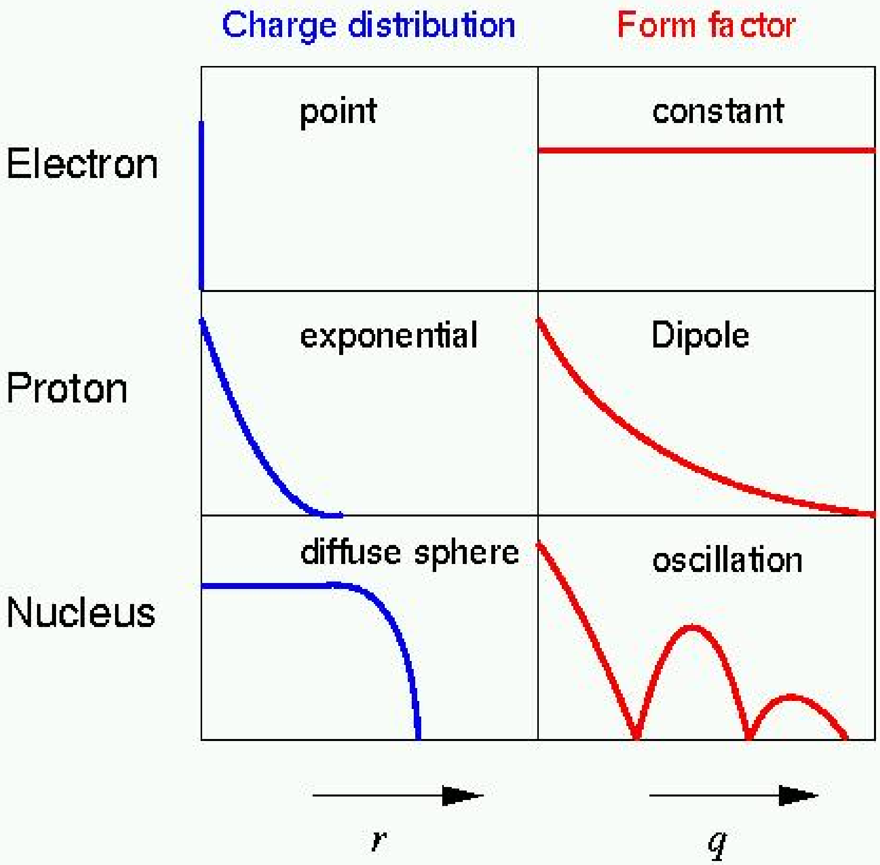


Scattering probability or cross section

$$\boxed{\left\langle \frac{\mathrm{d}^3\sigma}{\mathrm{d}\Omega_\mathrm{e}\mathrm{d}p_e} \right\rangle = \frac{\mathrm{Counts}}{N_e N_N \Delta\Omega_e \Delta p_e}}$$

Electron – Charge Scattering

Form factors characterize internal structure of particles



- Elastic cross section

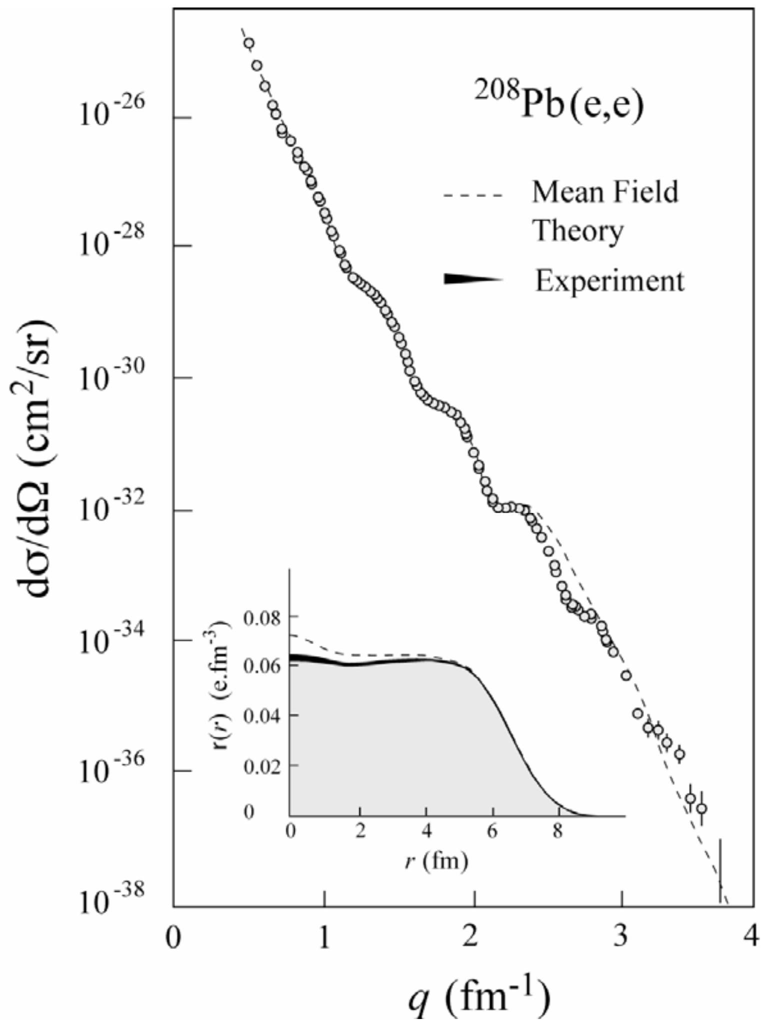
$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{exp}} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \left|F(q^2)\right|^2$$

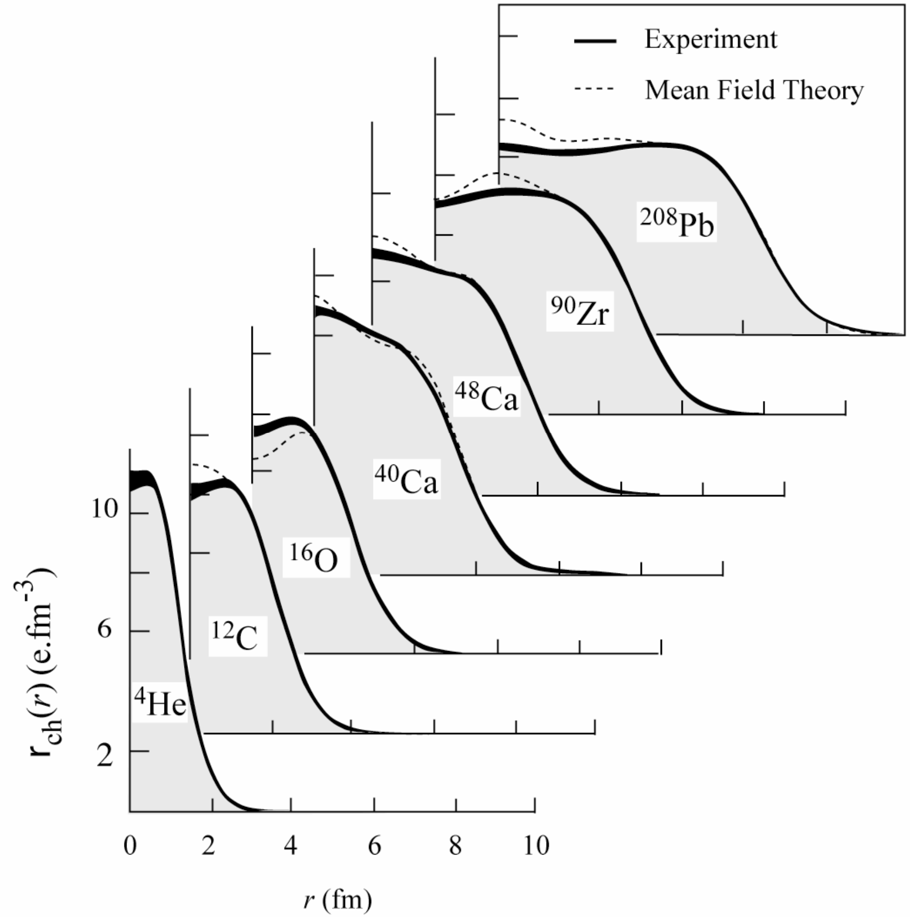
- Form factor

$$F(q^2) = \int e^{iqx/\hbar}\rho(x)d^3x$$

The form factor as a Fourier transformation of the charge distribution is a non-relativistic concept.

History - Charge Distributions



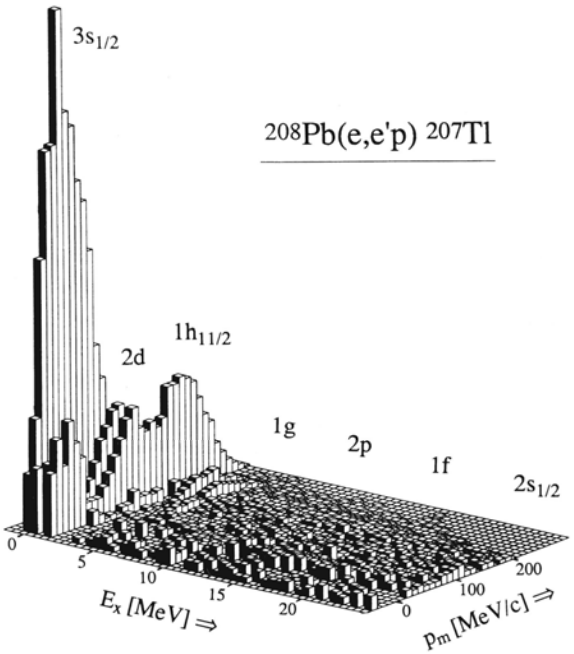


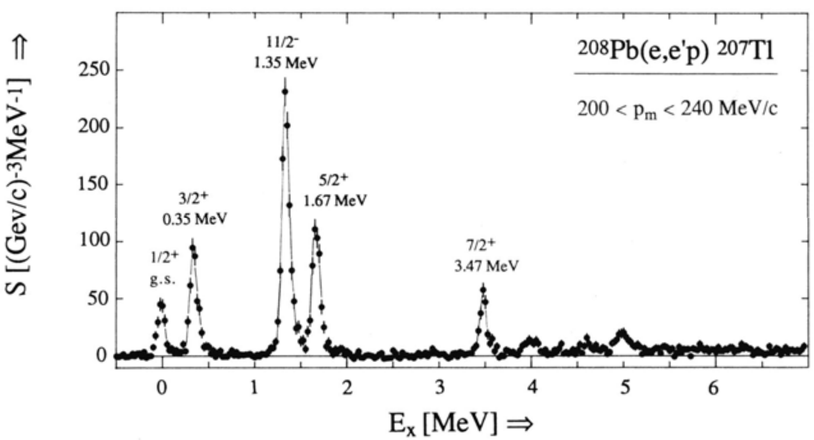
In '70s large data set was acquired on elastic electron scattering (mainly from Saclay) over large Q^2-range and for variety of nuclei

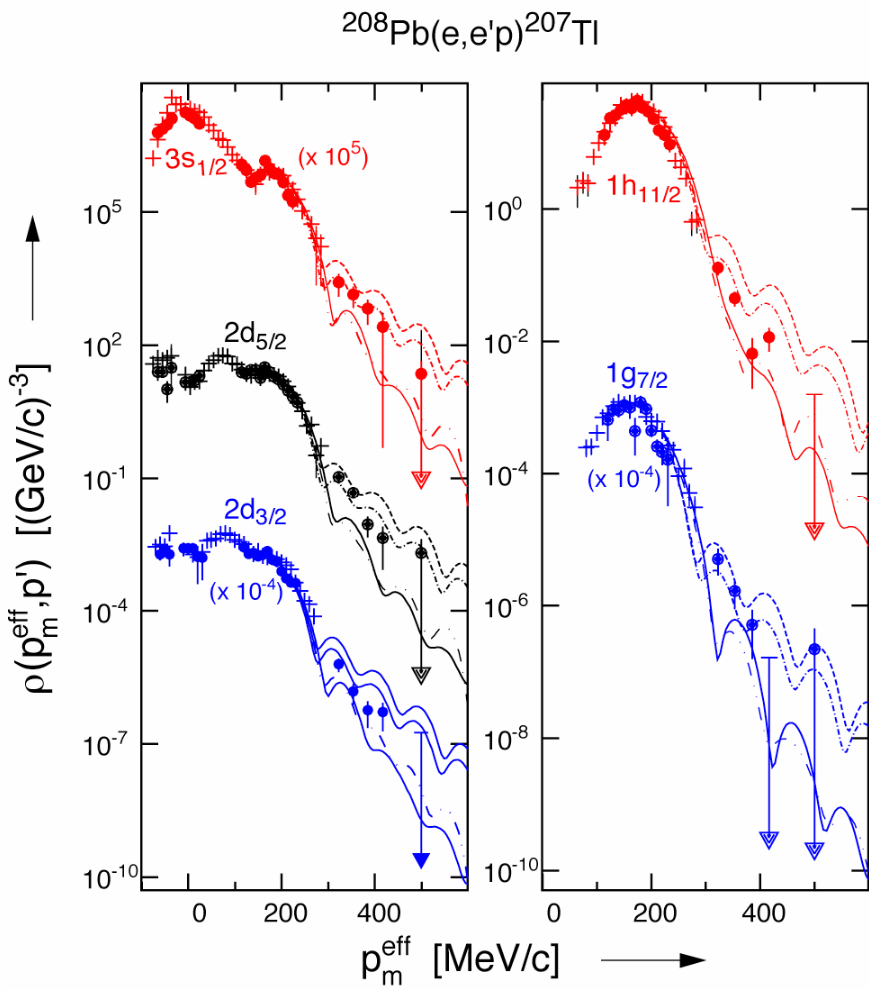
"Model-independent" analysis provided accurate results on charge distribution well described by mean-field Density-Dependent Hartree-Fock calculations

History - Proton Knock-out (NIKHEF)

$$p_m = E_e - E_{e'} - p = q - p$$
$$E_m = \omega - T_p - T_{A-1} = E_{sep} + E_{exc}$$







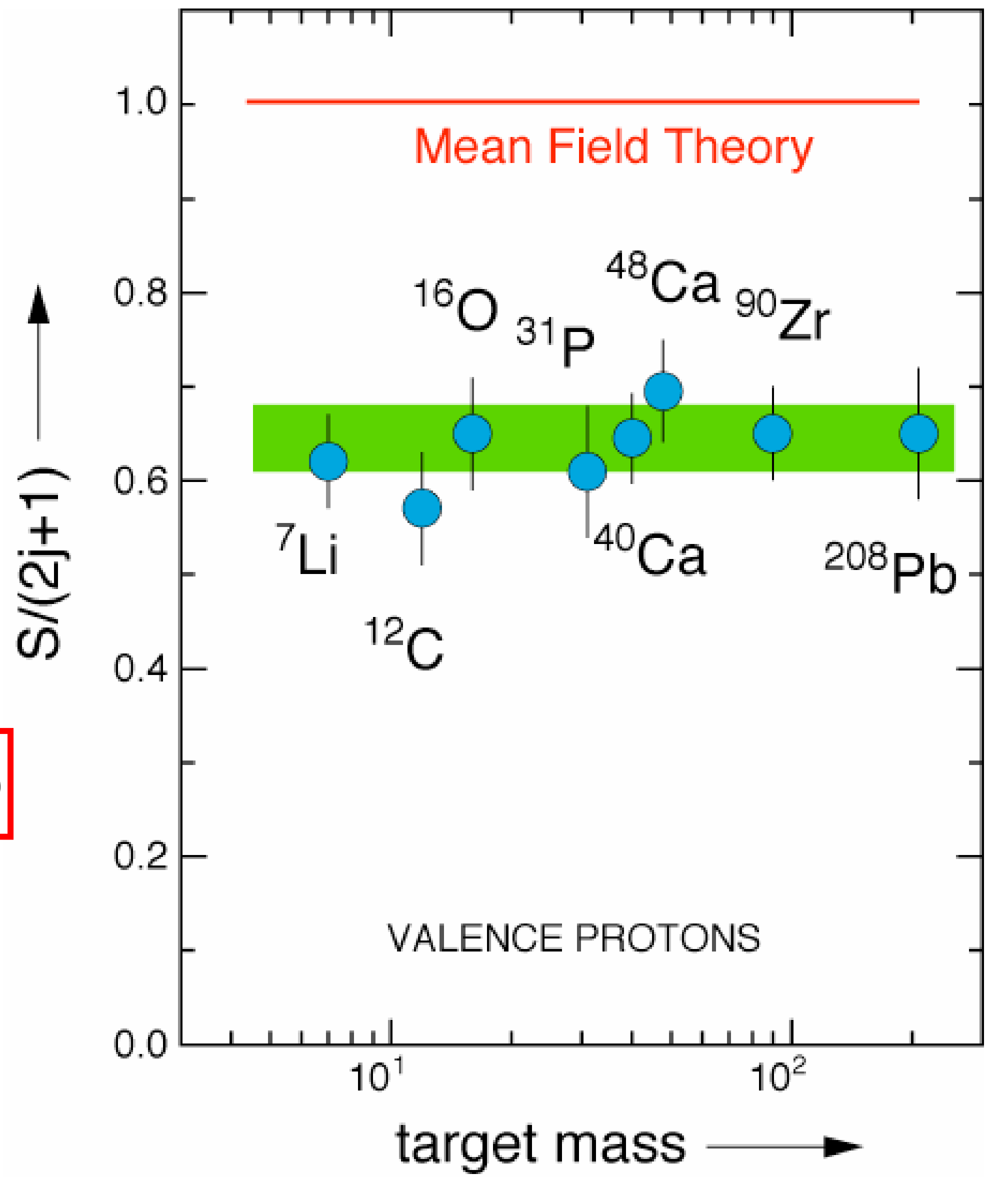
Correlated Strength in Nuclear Spectral Function - History

Electron-induced proton knock-out has been studied systematically since high duty-factor electron beams became available, first at Saclay (70's), then at NIKHEF (80's) with ~100 keV energy resolution.

For complex (A>4) nuclei the spectroscopic strength S for valence protons was found to be 60-65% of the IPSM value

$$S_\alpha = 4\pi \int S(E_m, p_m) p_m^2 dp_m \delta(E_m - E_\alpha)$$

Long-range correlations account for about 10%, but the rest was ascribed to short-range N-N correlations, by which strength was distributed at energies well above the Fermi edge



CEBAF's Original Mission Statement

Key Mission and Principal Focus (1987):

The study of the largely unexplored transition between the nucleon-meson and the quark-gluon descriptions of nuclear matter.

The Role of Quarks in Nuclear Physics

Related Areas of Study:

- **Do individual nucleons change their size, shape, and quark structure in the nuclear medium?**

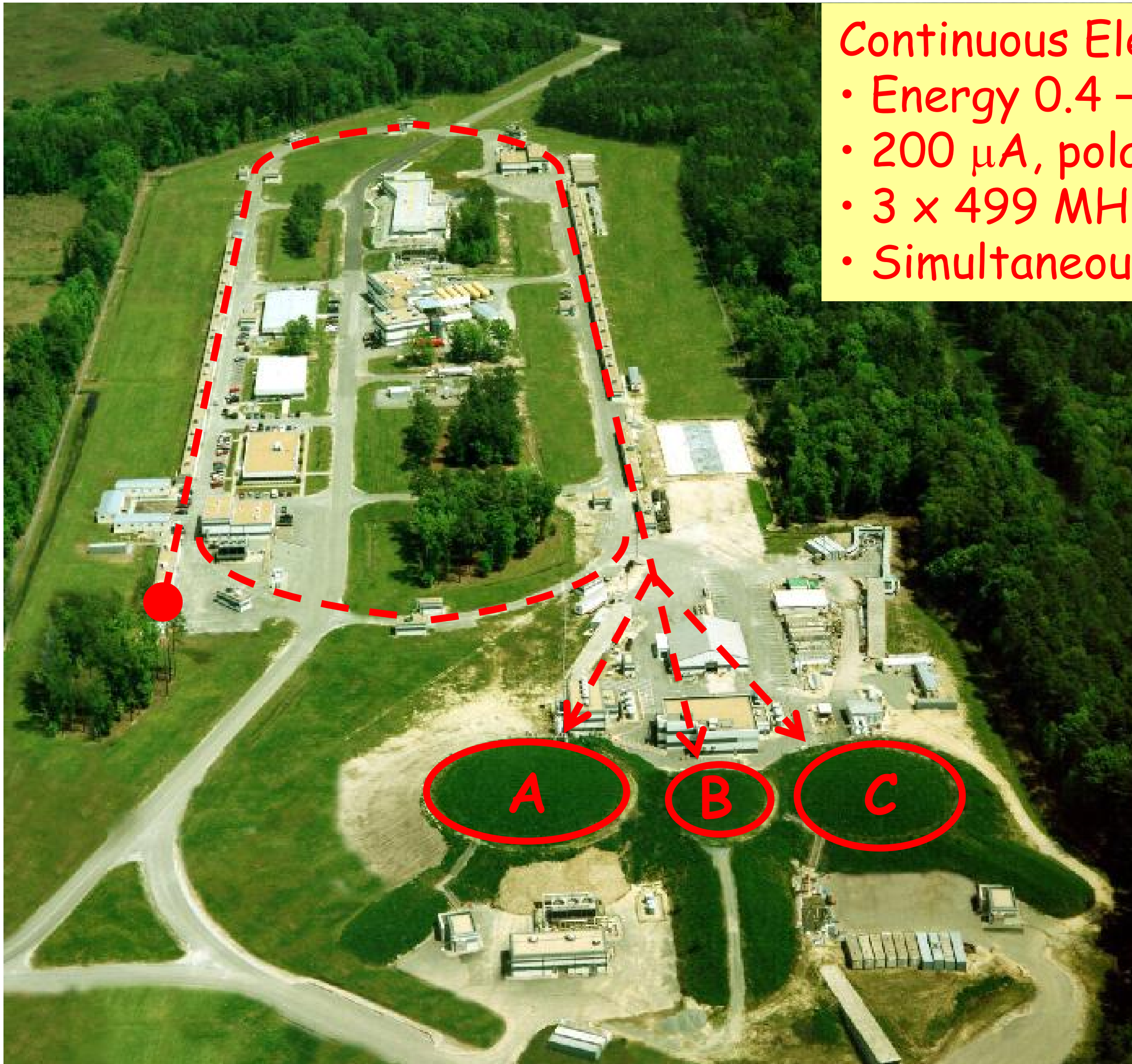
- **How do nucleons cluster in the nuclear medium?**

Pushing the Limits of the Standard Model of Nuclear Physics

- **What are the properties of the force which binds quarks into nucleons and nuclei at distances where this force is strong and the quark confinement mechanism is important?**

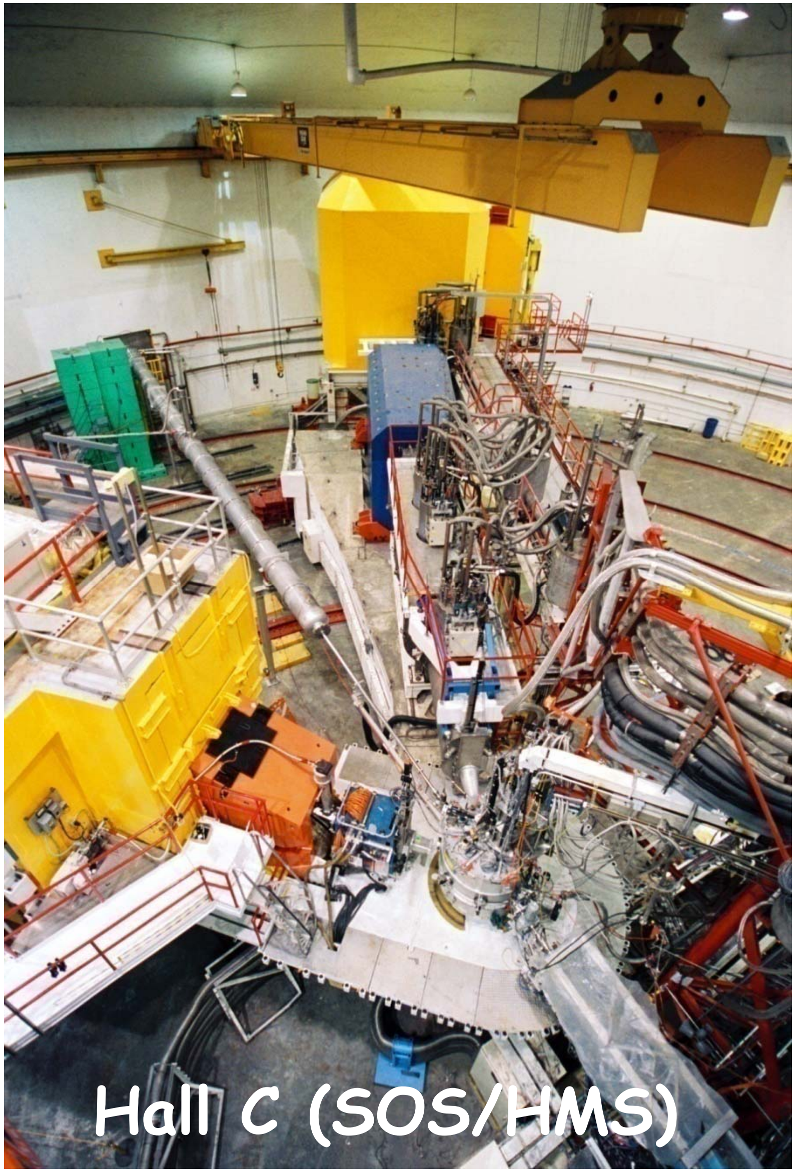
Charge and Magnetization in Nucleons and Pions
The Onset of the Parton Model

JLab accelerator CEBAF

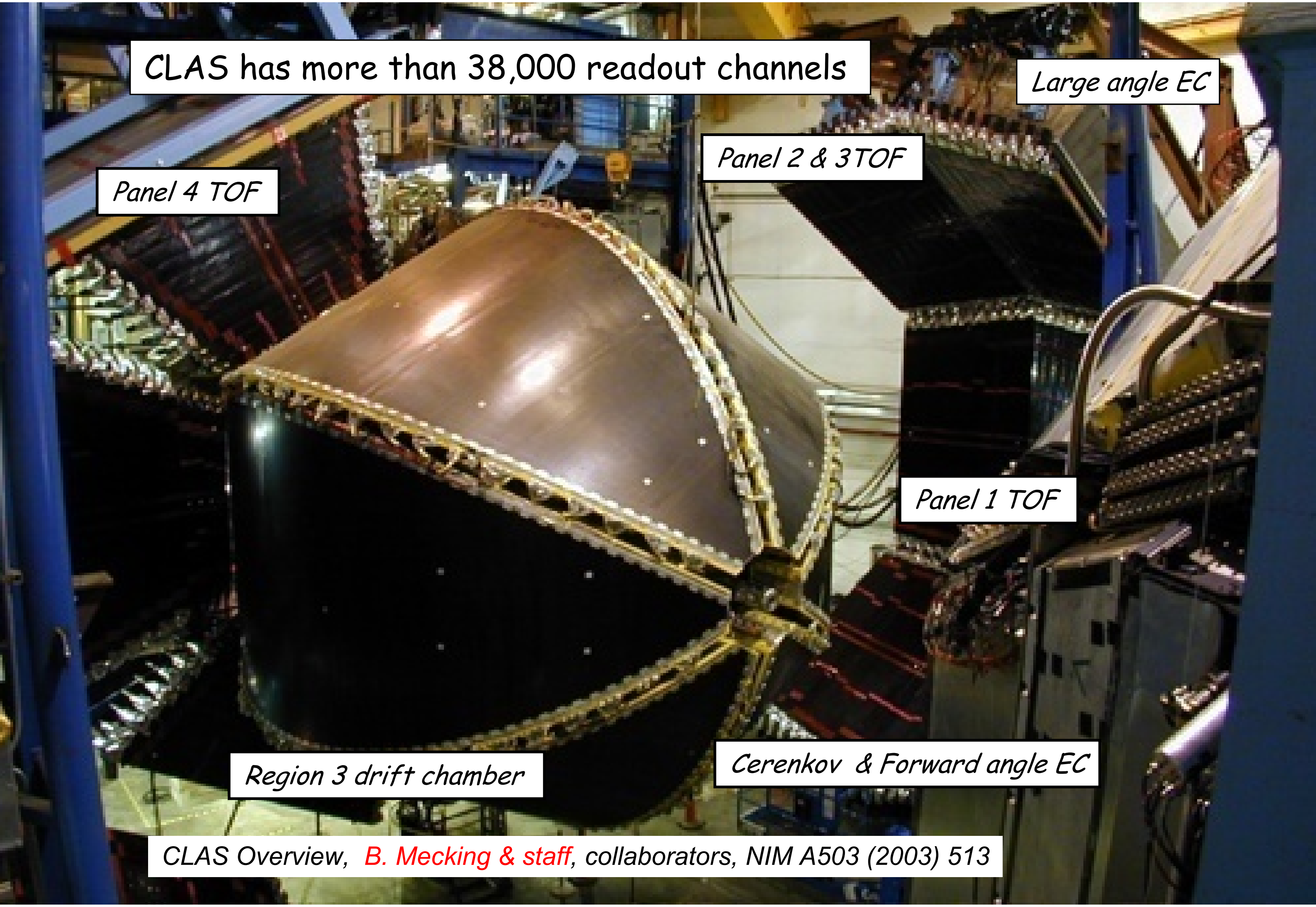


Continuous Electron Beam
- Energy 0.4 – 6.0 GeV
- 200 μA, polarization 85%
- 3 x 499 MHz operation
- Simultaneous delivery 3 halls

Halls A/B/C
Base Equipment

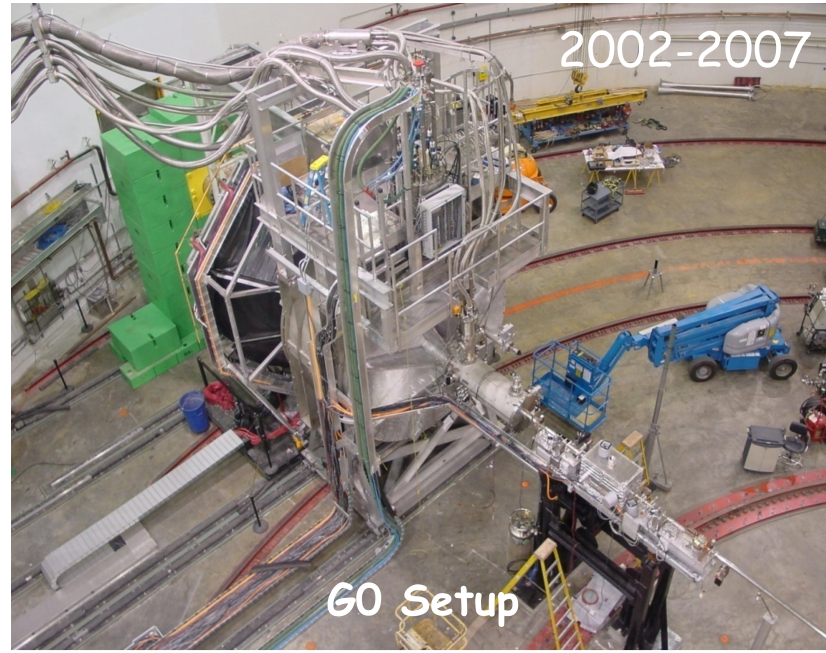


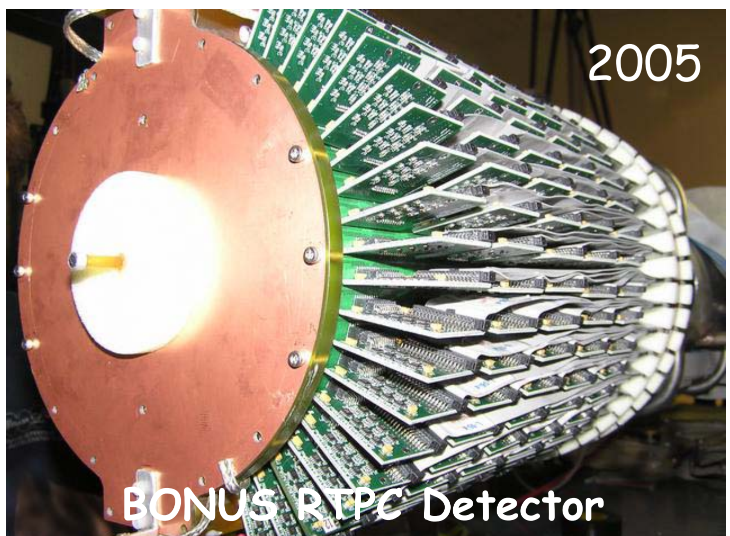
Hall B - CLAS (forward carriage and side clamshells retracted)

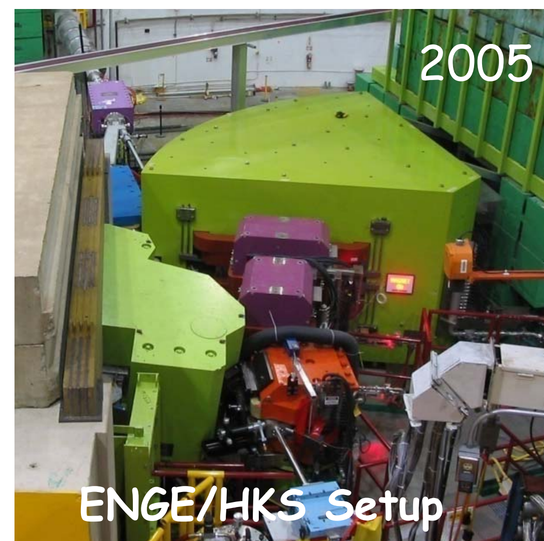


CLAS Overview, B. Mecking & staff, collaborators, NIM A503 (2003) 513

Ancillary Equipment and Experiment-Specific Apparatus







CEBAF's Original Mission Statement

Key Mission and Principal Focus (1987):

The study of the largely unexplored transition between the nucleon-meson and the quark-gluon descriptions of nuclear matter.

The Role of Quarks in Nuclear Physics

Related Areas of Study:

- Do individual nucleons change their size, shape, and quark structure in the nuclear medium?
- How do nucleons cluster in the nuclear medium?

Pushing the Limits of the Standard Model of Nuclear Physics

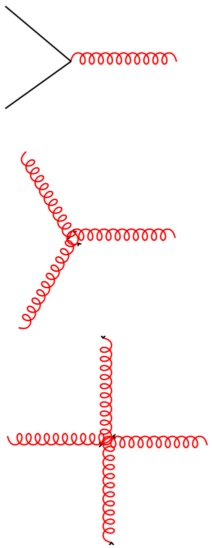
- What are the properties of the force which binds quarks into nucleons and nuclei at distances where this force is strong and the quark confinement mechanism is important?

Charge and Magnetization in Nucleons and Pions

The Onset of the Parton Model

QCD and Nuclei

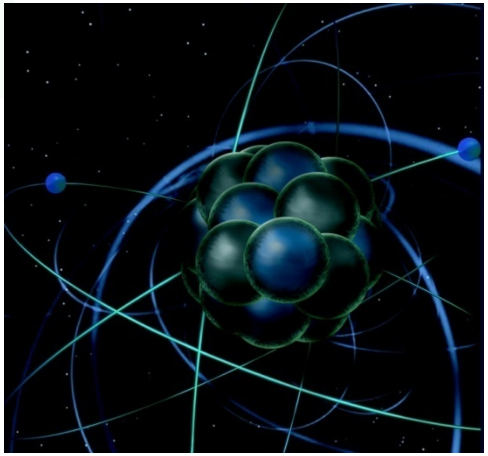
Gluons mediate the strong (color) force, just like photons mediate the electromagnetic force, but … gluons interact with themselves … which gives QCD unique properties



$$L_{QCD} = -\frac{1}{4} F^{a\mu\nu} F^{a}_{\mu\nu} + \sum_{j} \bar{q}_j (i\gamma^{\mu} D_{\mu} - m_j) q_j$$

$$F^{a}_{\mu\nu} \equiv \delta_{\mu} A^{a}_{\nu} - \delta_{\nu} A^{a}_{\mu} - g f^{abc} A^{b}_{\mu} A^{c}_{\nu}$$

$$D_{\mu} \equiv \delta_{\mu} + i g A^{a}_{\mu} \frac{\lambda_a}{2}$$



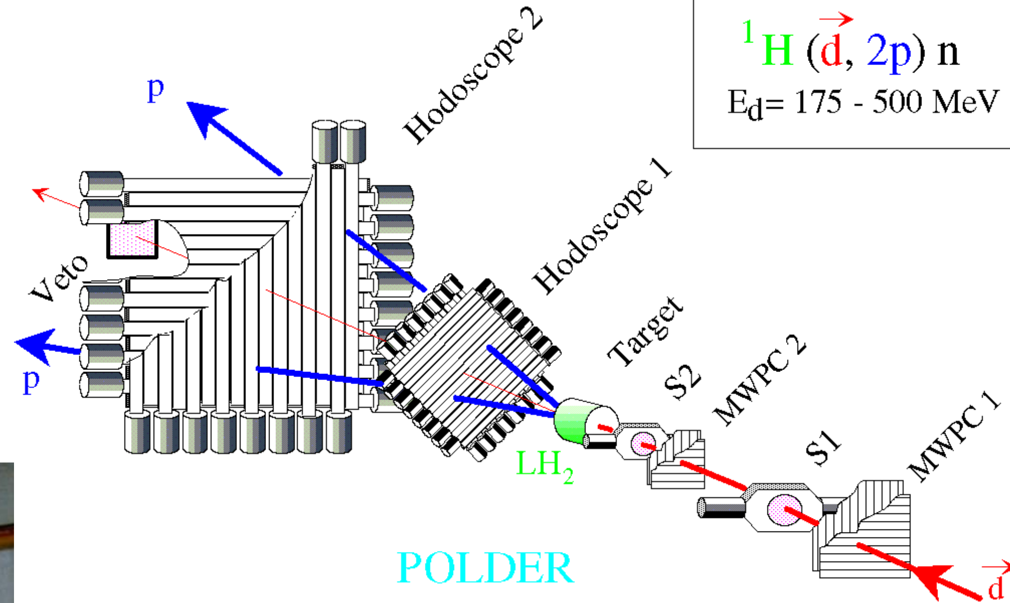
<u>QCD Lagrangian: quarks and gluons</u>

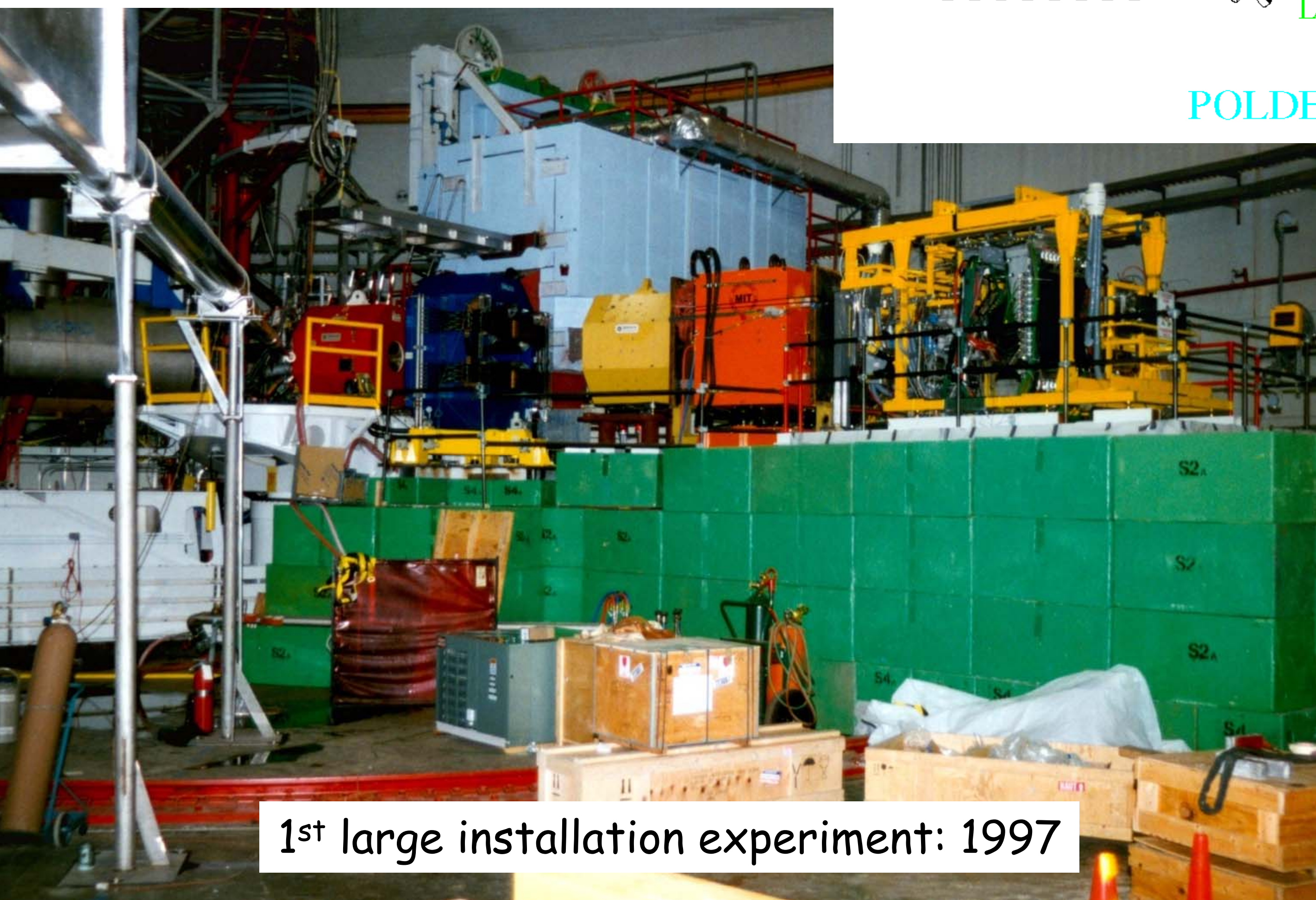
Nuclear Physics Model is an effective (but highly successful!) model using free nucleons and mesons as degrees of freedom.

$^2H(e,e)^2H$ elastic scattering

^2H: spin-1 → 3 form factors to disentangle

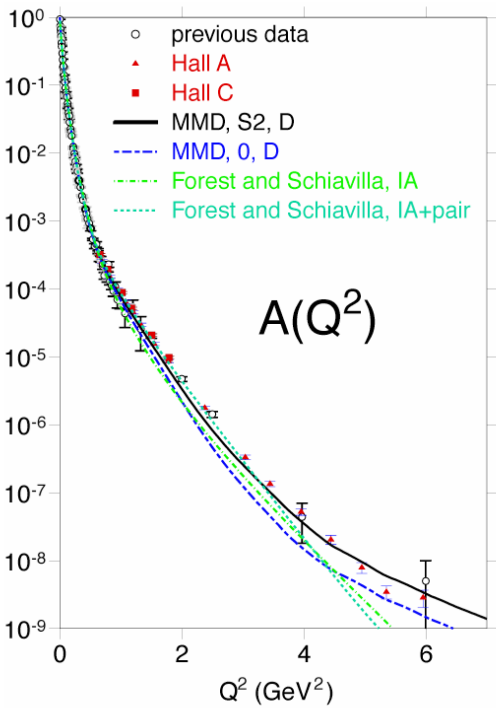
Solution: measure tensor polarization in $^2H(e,e'\overleftrightarrow{d})$

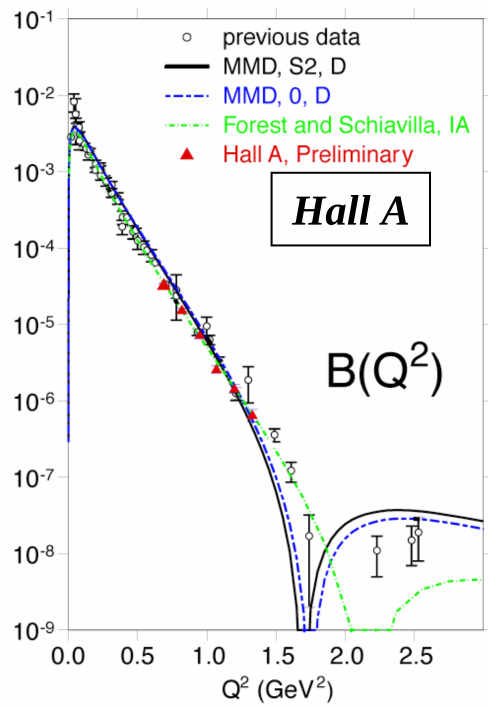



1st large installation experiment: 1997

"T20 experiment" used HMS to detect the scattered electrons and a dedicated magnetic spectrometer on the Hall C floor to detect the recoiling deuteron and measure it's tensor polarization

JLab Data Reveal Deuteron's Size and Shape





For elastic e-d scattering:

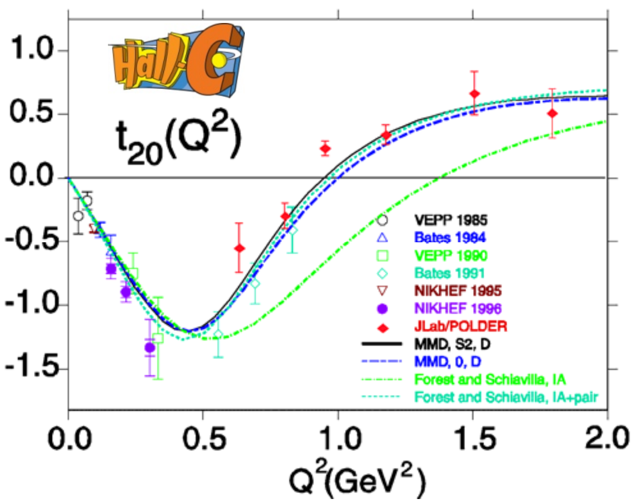
$$\boxed{\frac{d\sigma}{d\Omega} = \sigma_M \left[A + B\tan^2\frac{\theta}{2}\right]}$$

$$A(Q^2) = G_C^2 + \tfrac{8}{9}\tau^2 G_Q^2 + \tfrac{2}{3}\tau G_M^2$$

$$B(Q^2) = \tfrac{4}{3}\tau(1+\tau)G_M^2$$

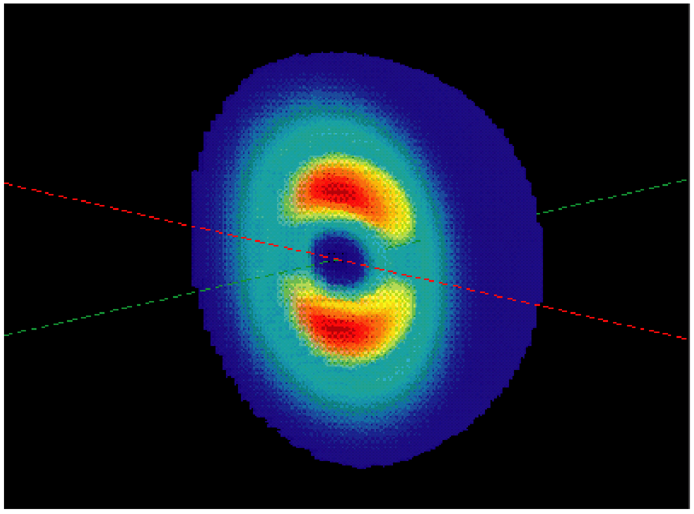
- 3rd observable needed to separate G_C and G_Q

$\rightarrow$ *tensor polarization t_{20}*



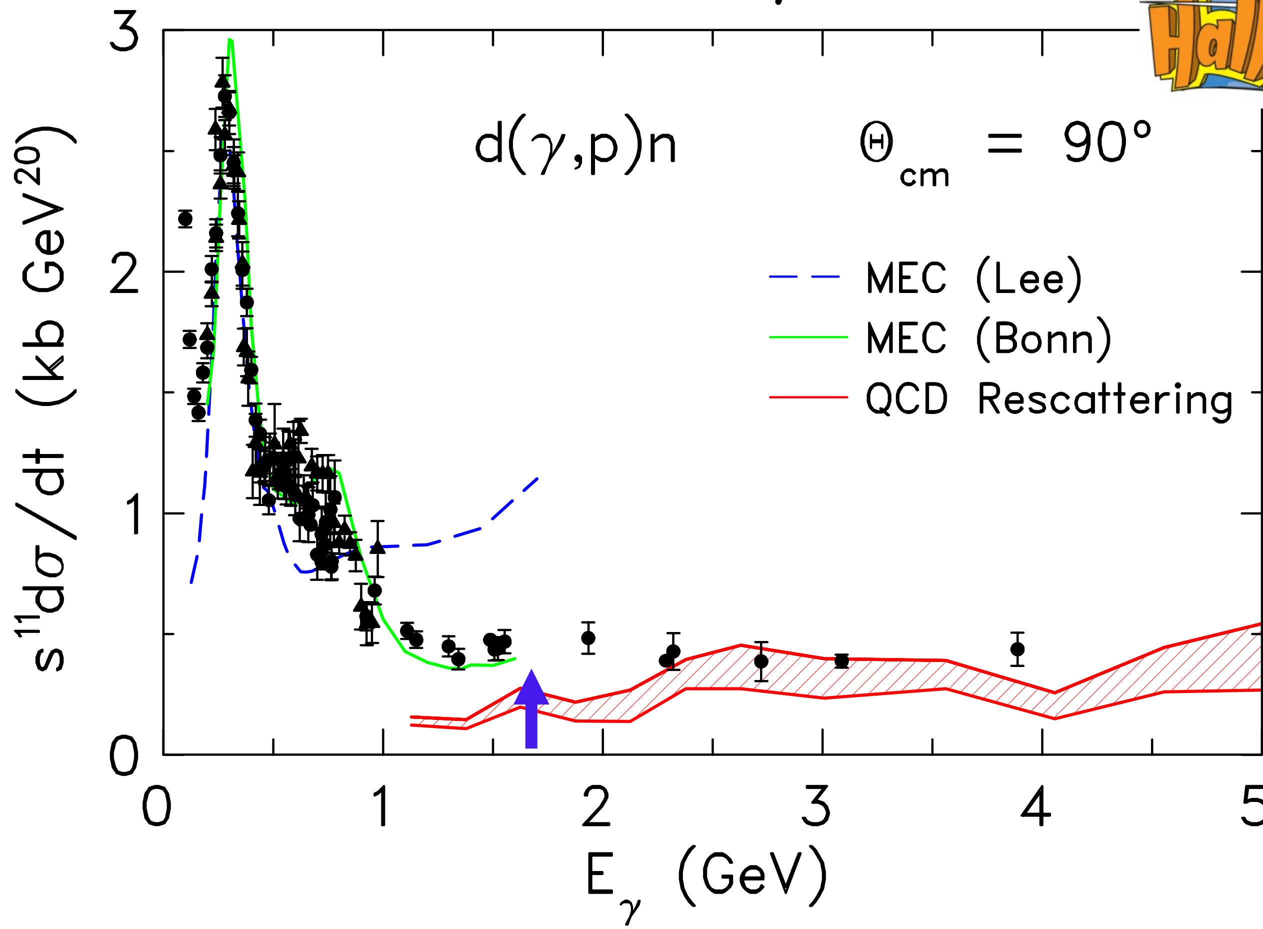
Combined Data -> Deuteron's Intrinsic Shape

The nucleon-based description works down to < 0.5 fm



Is there a Limit for Meson-Baryon Models?

Not really but ...



... there might be a more economical QCD description.

Scaling behavior ($d\sigma/dt \propto s^{-11}$) for $P_T > 1.2$ GeV/c (see ↑)

quark-gluon description sets

CEBAF's Original Mission Statement

Key Mission and Principal Focus (1987):

The study of the largely unexplored transition between the nucleon-meson and the quark-gluon descriptions of nuclear matter.

The Role of Quarks in Nuclear Physics

Related Areas of Study:

- **Do individual nucleons change their size, shape, and quark structure in the nuclear medium?**
- **How do nucleons cluster in the nuclear medium?**

  Pushing the Limits of the Standard Model of Nuclear Physics

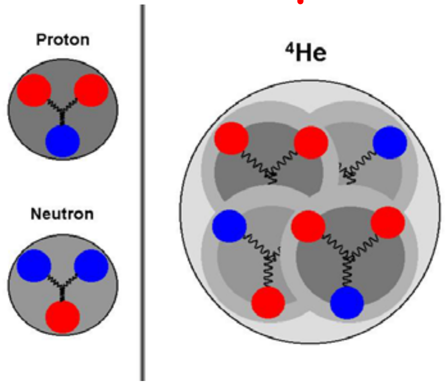
- **What are the properties of the force which binds quarks into nucleons and nuclei at distances where this force is strong and the quark confinement mechanism is important?**

  Charge and Magnetization in Nucleons and Pions

  The Onset of the Parton Model

Hadrons in the Nuclear Medium

- Nucleons and Mesons are not the fundamental entities of the underlying theory.
- At high densities a phase transition must occur to a quark-gluon plasma.
- At nuclear matter densities of 0.17 nucleons/fm^3, nucleon wave functions overlap considerably.



- EMC effect: Change in the inclusive deep-inelastic structure function of a nucleus relative to that of a free nucleon.

Is there a Limit for the Standard Model of Nuclear Physics?

Have found to date: The low-energy proton-neutron effective description of nuclei simply is very, very good!

Use precise polarization transfer technique on nuclei to find cracks…

- Free electron-nucleon scattering

$$\frac{G_E}{G_M} = -\frac{P'_x}{P'_z}\frac{(E_i + E_f)}{2m}\tan\frac{\Theta_e}{2}$$

- Bound nucleons → evaluation within model

- Reaction mechanism effects minimal for $A(\vec{e},e'\vec{p})$ about $P_m = 0$

$$\frac{\tilde{G}_E}{\tilde{G}_M} = -\frac{P'_x}{P'_z}\frac{(E_i + E_f)}{2m}\tan\frac{\Theta_e}{2}$$

→ Form Factors in the Nucleus

Mainz + E93-049:
A (very) small smoking gun for a crack????

1) Measure $^4He(\vec{e},e'\vec{p})^3H$
- Extract "Double Superratio": $[(P'_x/P'_z)$ in ^4He / (P'_x/P'_z) in $^1H]$ / [PWIA ratio]
- After corrections for reaction mechanism effects: deviation from 1 a measure of the medium dependence of G_E/G_M

2) Measure $^4He(e,e'\vec{p})^3H$
- Zero in PWIA
- Deviation from 0 a measure of the reaction mechanism effects

Polarization transfer in $^4He(\vec{e},e'\vec{p})^3H$

- E93-049 (Hall A): Measured $^4He(\vec{e},e'\vec{p})^3H$ in quasi-elastic kinematics for Q^2 = 0.5, 1.0, 1.6 and 2.6 $(GeV/c)^2$ using Focal Plane Polarimeter
- Extracted "Superratio": (P'_x/P'_z) in $^4He/(P'_x/P'_z)$ in ^1H

- Free electron-nucleon scattering

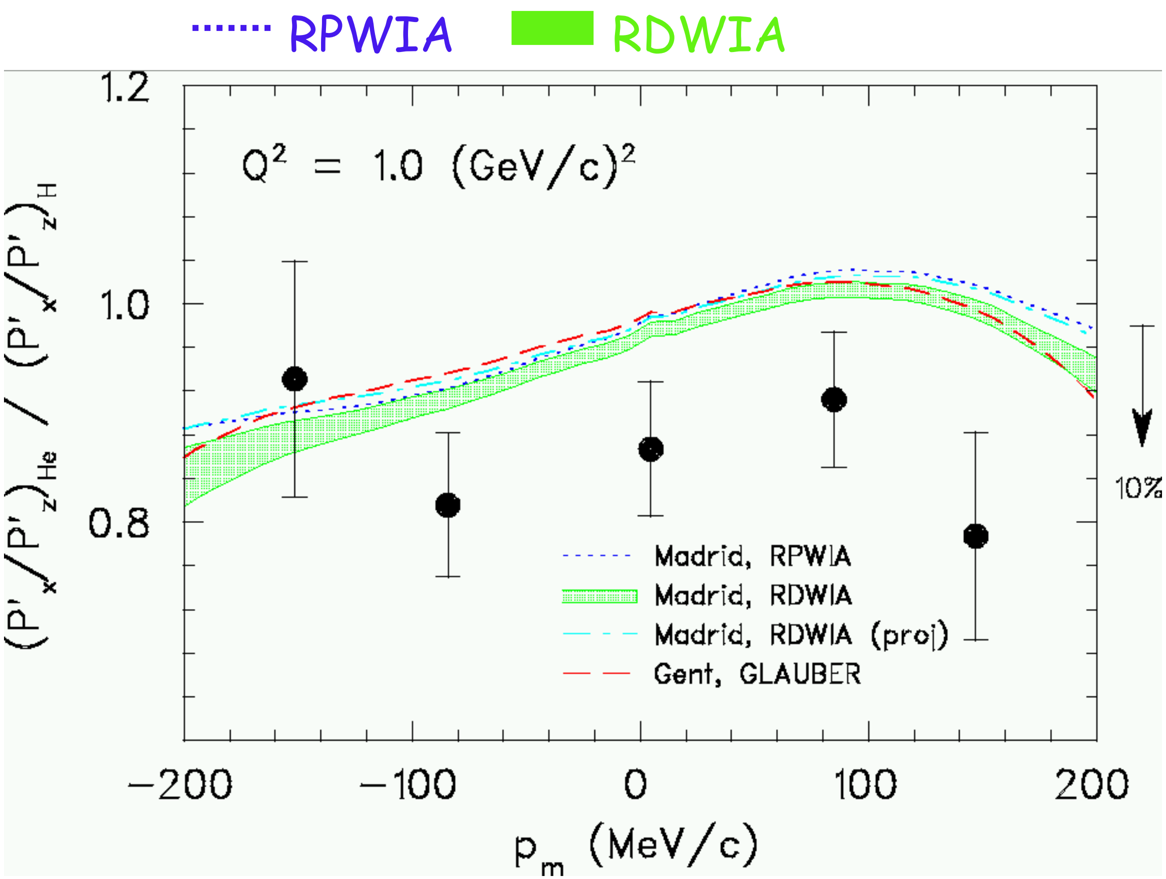
$$\frac{G_E}{G_M} = -\frac{P'_x}{P'_z}\frac{(E_i+E_f)}{2m}\tan\frac{\Theta_e}{2}$$

- Bound nucleons → evaluation within model

- Reaction mechanism effects minimal for $A(\vec{e},e'\vec{p})$ about $P_m = 0$

$$\frac{\tilde{G}_E}{\tilde{G}_M} = -\frac{P'_x}{P'_z}\frac{(E_i+E_f)}{2m}\tan\frac{\Theta_e}{2}$$

→ Form Factors in the Nucleus

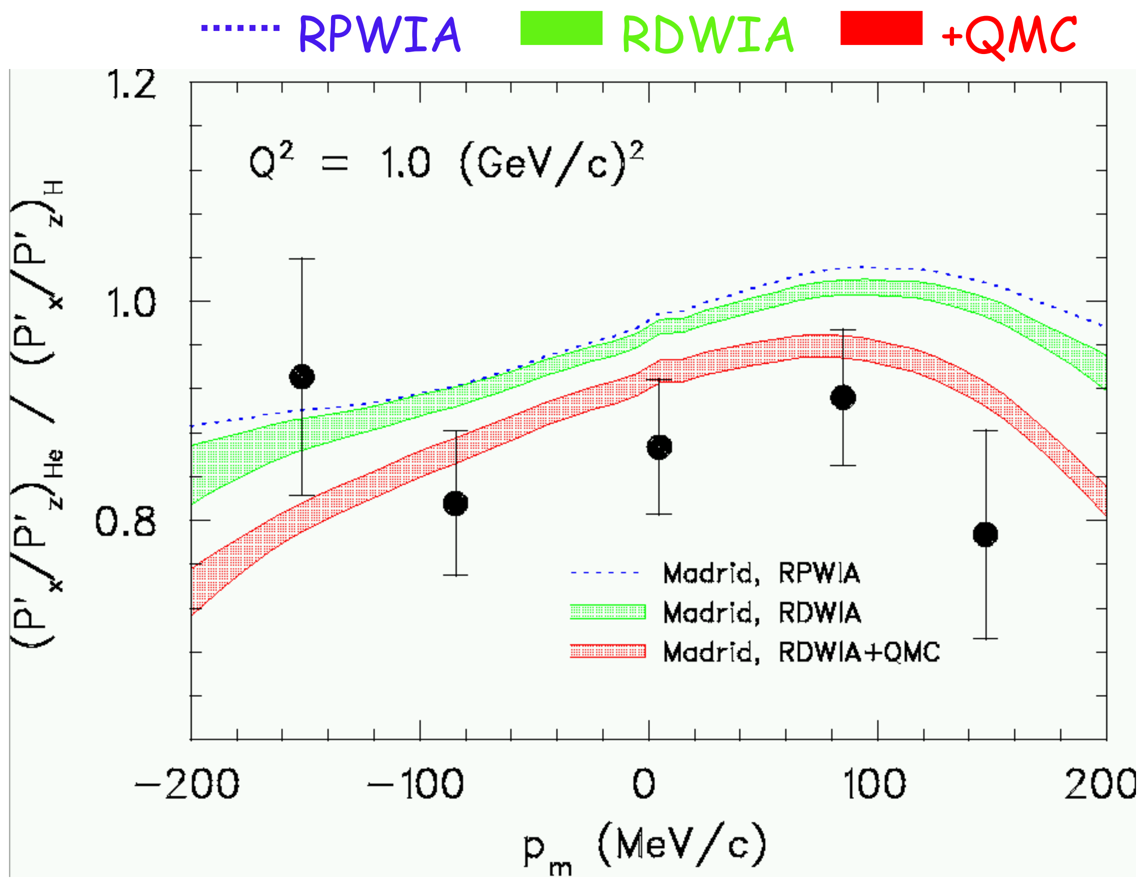


Polarization transfer in $^4He(\vec{e},e'\vec{p})^3H$

- E93-049 (Hall A): Measured $^4He(\vec{e},e'\vec{p})^3H$ in quasi-elastic kinematics for Q^2 = 0.5, 1.0, 1.6 and 2.6 $(GeV/c)^2$ using Focal Plane Polarimeter
- Extracted "Superratio": (P'_x/P'_z) in $^4He/(P'_x/P'_z)$ in ^1H

Medium Modifications of Nucleon Form Factor

- Compared to calculations by Udias without and with inclusion of medium effects predicted by Thomas *et al.* (Quark Meson Coupling model).



CEBAF's Original Mission Statement

Key Mission and Principal Focus (1987):

The study of the largely unexplored transition between the nucleon-meson and the quark-gluon descriptions of nuclear matter.

The Role of Quarks in Nuclear Physics

Related Areas of Study:

- **Do individual nucleons change their size, shape, and quark structure in the nuclear medium?**

- **How do nucleons cluster in the nuclear medium?**

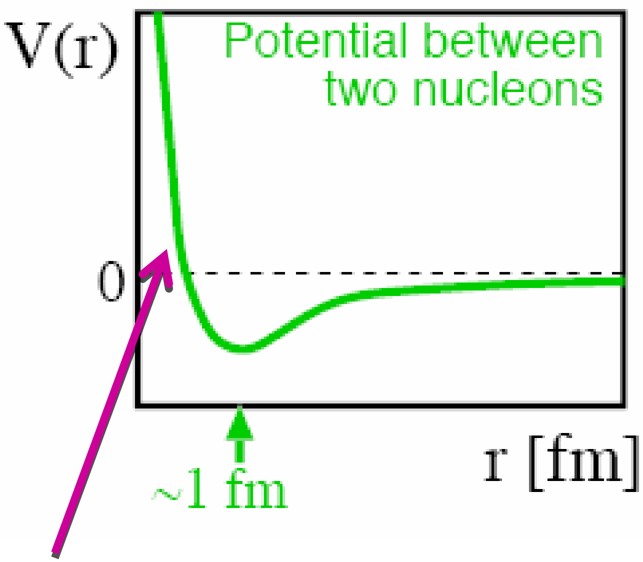
Pushing the Limits of the Standard Model of Nuclear Physics

- **What are the properties of the force which binds quarks into nucleons and nuclei at distances where this force is strong and the quark confinement mechanism is important?**

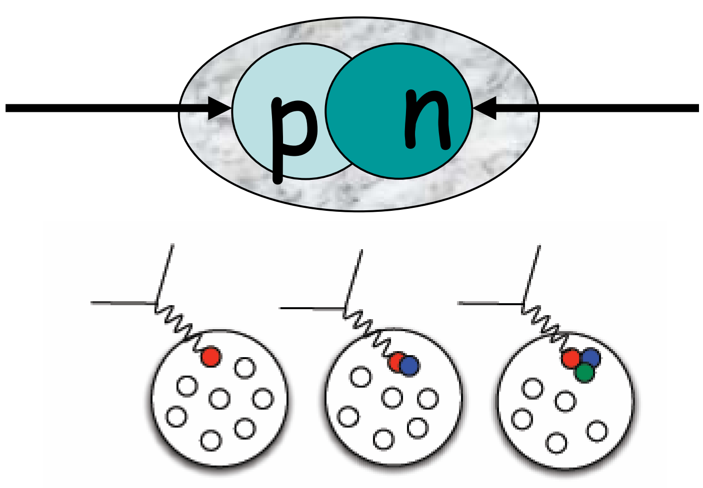
The Onset of the Parton Model

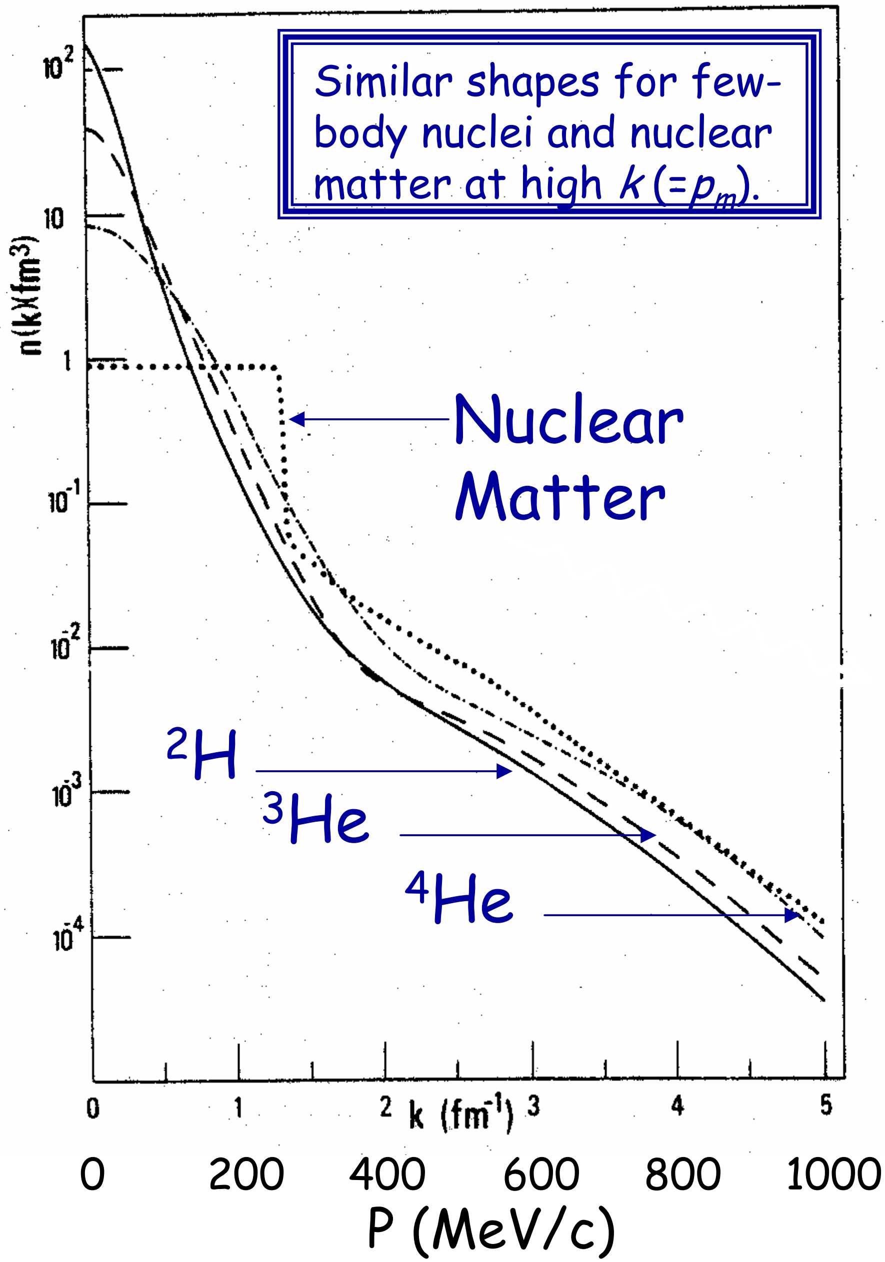
Use the Nuclear Arena to Study QCD

Proton Momenta in the nucleus



Short-range repulsive core gives rise to high proton momenta

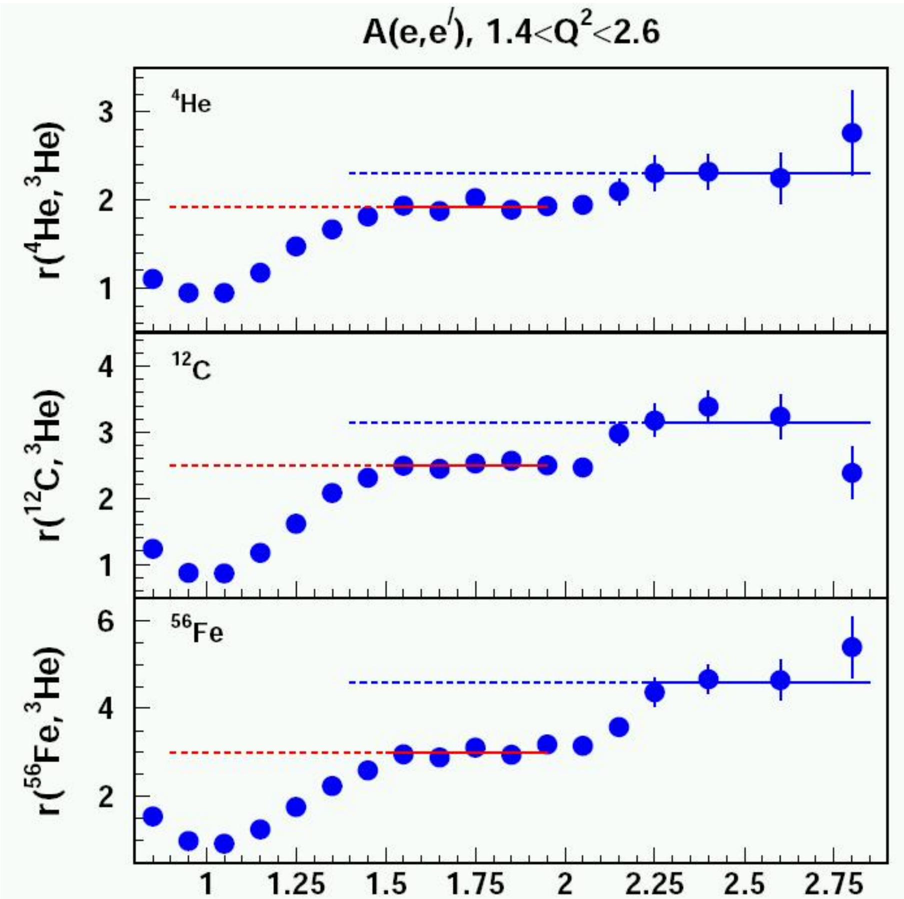




Hall B **Short Range Correlations in Nuclei** CLAS

A(e,e')X, A = ^{3}He, ^{4}He, ^{12}C, ^{56}Fe

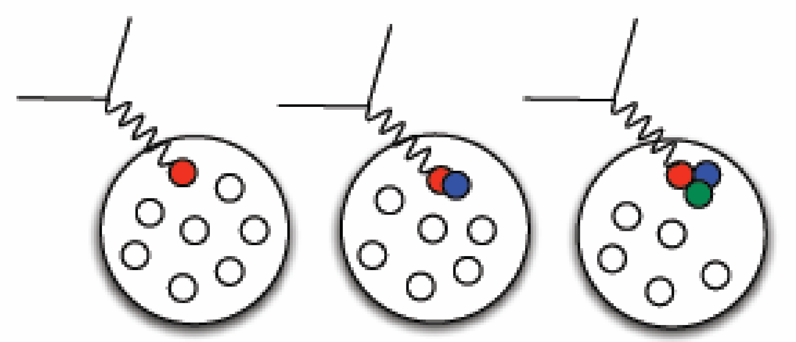
K. Egiyan, et al, (CLAS), PRC 68:014313,2003; PRL 96, 082501,2006.



$Q^2/2M\nu$ →

Measured Composition (%)

	1N state	2N SRC	3N SRC
^{2}H	96 ± 0.7	4.0 ± 0.7	---
^{3}He	92 ± 1.6	8.0 ± 1.6	0.18 ± 0.06
^{4}He	86 ± 3.3	15.4 ± 3.3	0.42 ± 0.14
^{12}C	80 ± 4.1	19.3 ± 4.1	0.55 ± 0.18
^{56}Fe	76 ± 4.7	23.0 ± 4.7	0.79 ± 0.25



CEBAF's Original Mission Statement

Key Mission and Principal Focus (1987):

The study of the largely unexplored transition between the nucleon-meson and the quark-gluon descriptions of nuclear matter.

The Role of Quarks in Nuclear Physics

Related Areas of Study:

- **Do individual nucleons change their size, shape, and quark structure in the nuclear medium?**

- **How do nucleons cluster in the nuclear medium?**

Pushing the Limits of the Standard Model of Nuclear Physics

- **What are the properties of the force which binds quarks into nucleons and nuclei at distances where this force is strong and the quark confinement mechanism is important?**

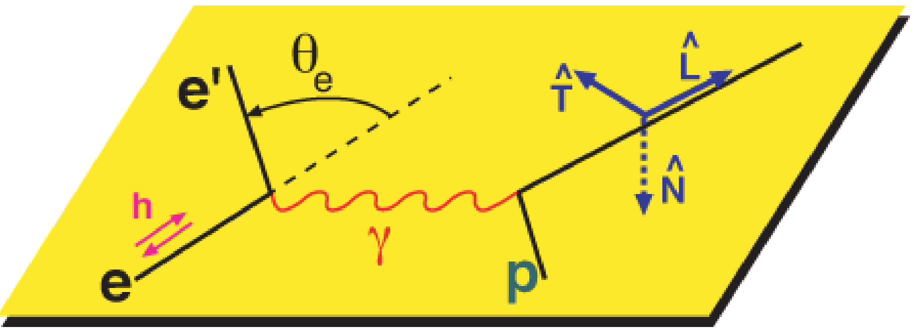
Charge and Magnetization in Nucleons and Pions

The Onset of the Parton Model

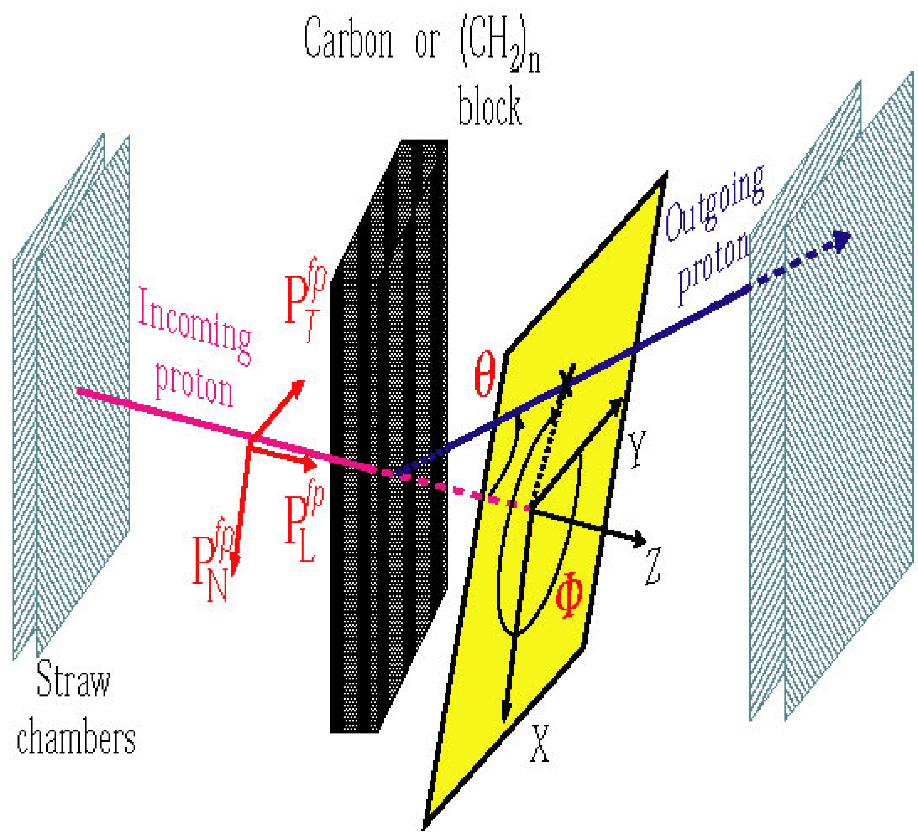
Revolutionized Polarized Beam Experiments!

Precise access to (small) charge form factor of proton utilizing polarization transfer technique: $\vec{e} + p \rightarrow e' + \vec{p}$

Focal Plane Polarimeter



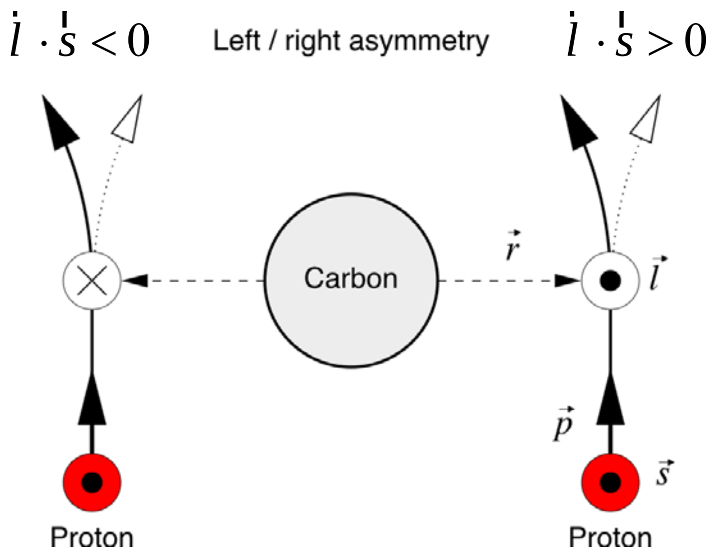
$$\frac{G_E}{G_M} = -\frac{P'_x}{P'_z}\frac{(E_i + E_f)}{2m}\tan\frac{\Theta_e}{2}$$



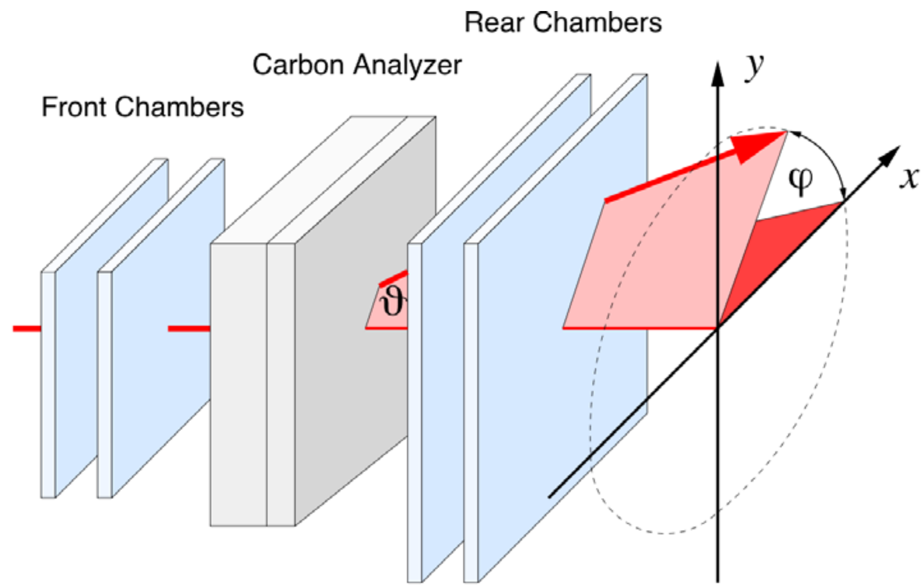
No error contributions from
- analyzing power
- beam polarimetry

Polarization Measurement

Spin-dependent scattering



Focal-Plane Polarimeter

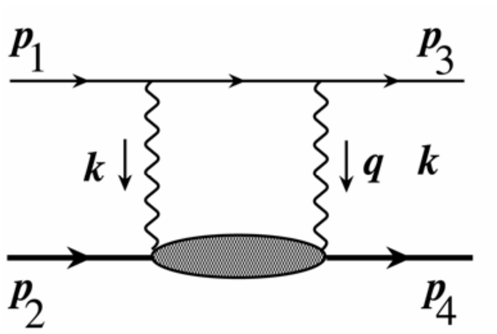


Observed angular distribution

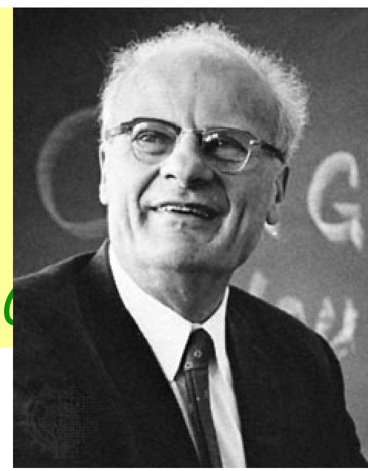
$$
\begin{aligned}
I(\vartheta,\varphi) &= I_0(\vartheta)\,(1+\epsilon_y\cos\varphi+\epsilon_x\sin\varphi) \\
&= I_0(\vartheta)\,[1+A_C(P_y\cos\varphi-P_x\sin\varphi)]
\end{aligned}
$$

Proton charge and magnetism in 2006

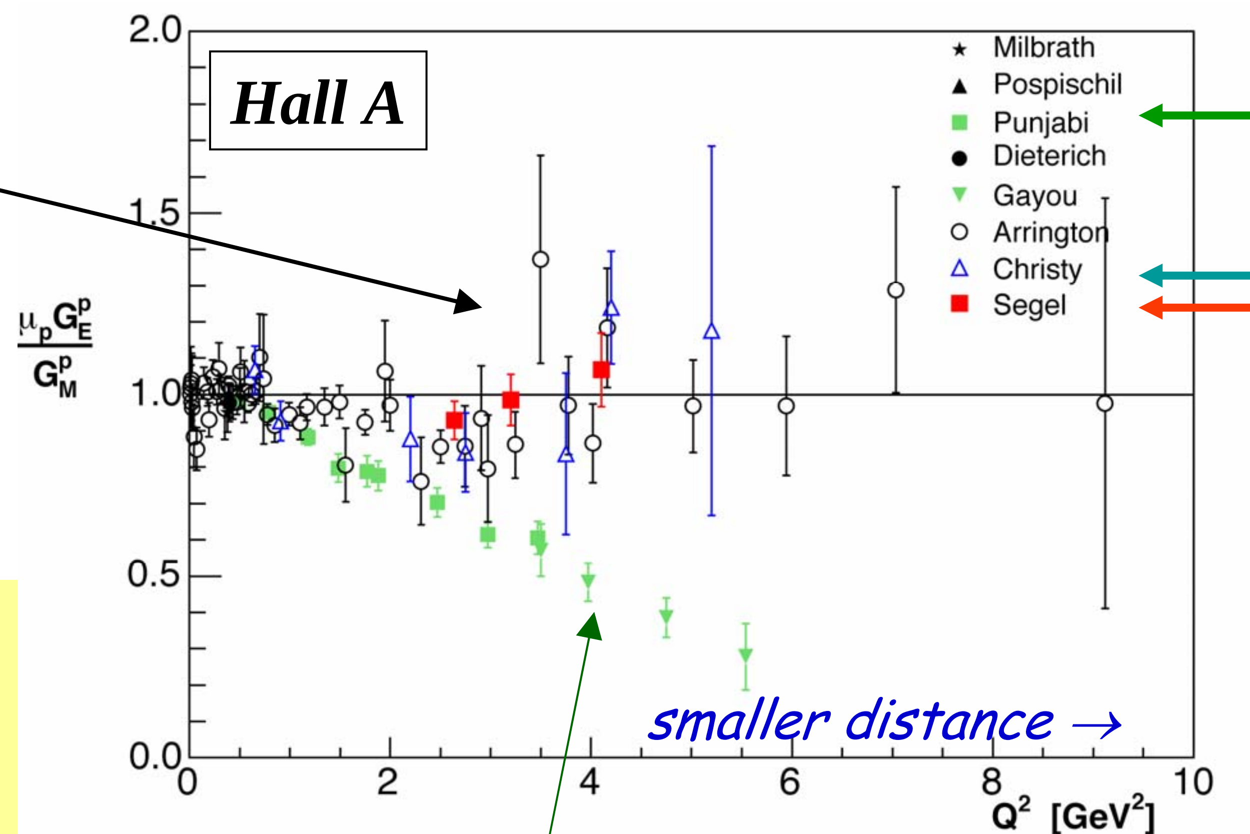
2-γ exchange important



’ + p
stant
’ + $\vec{p}$
(
with Q^2



H. Bethe
PR 72 (1947) 339
Lamb shift in hydrogen



charge depletion in interior of proton

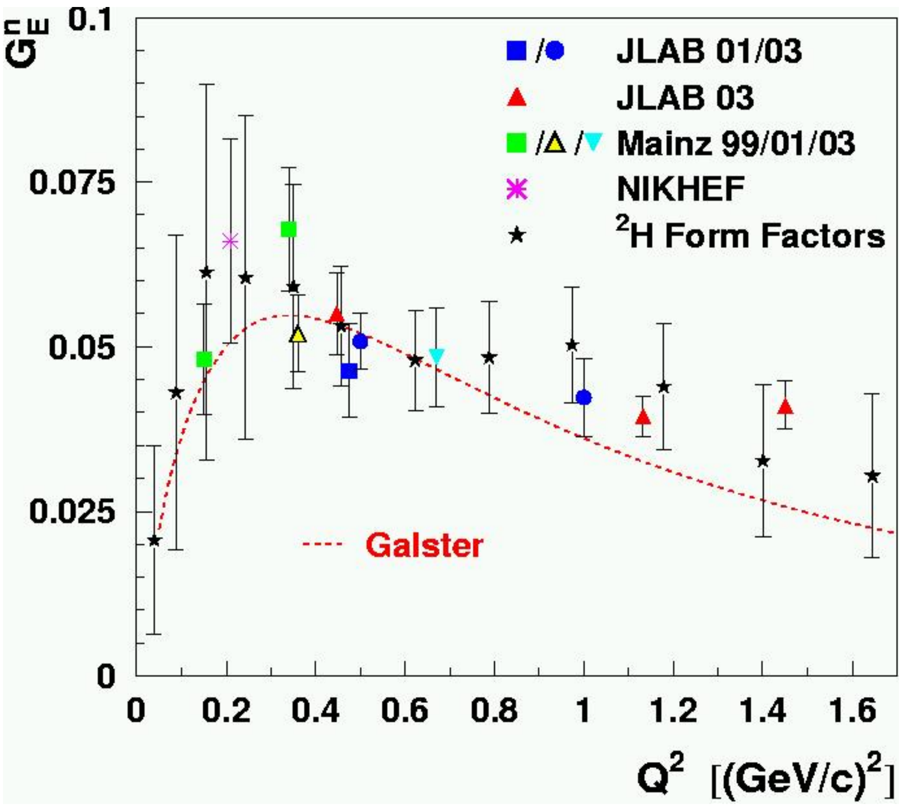
Orbital motion of quarks play a key role
(Belitsky, Ji + Yuan PRL 91 (2003) 092003)

Hall A

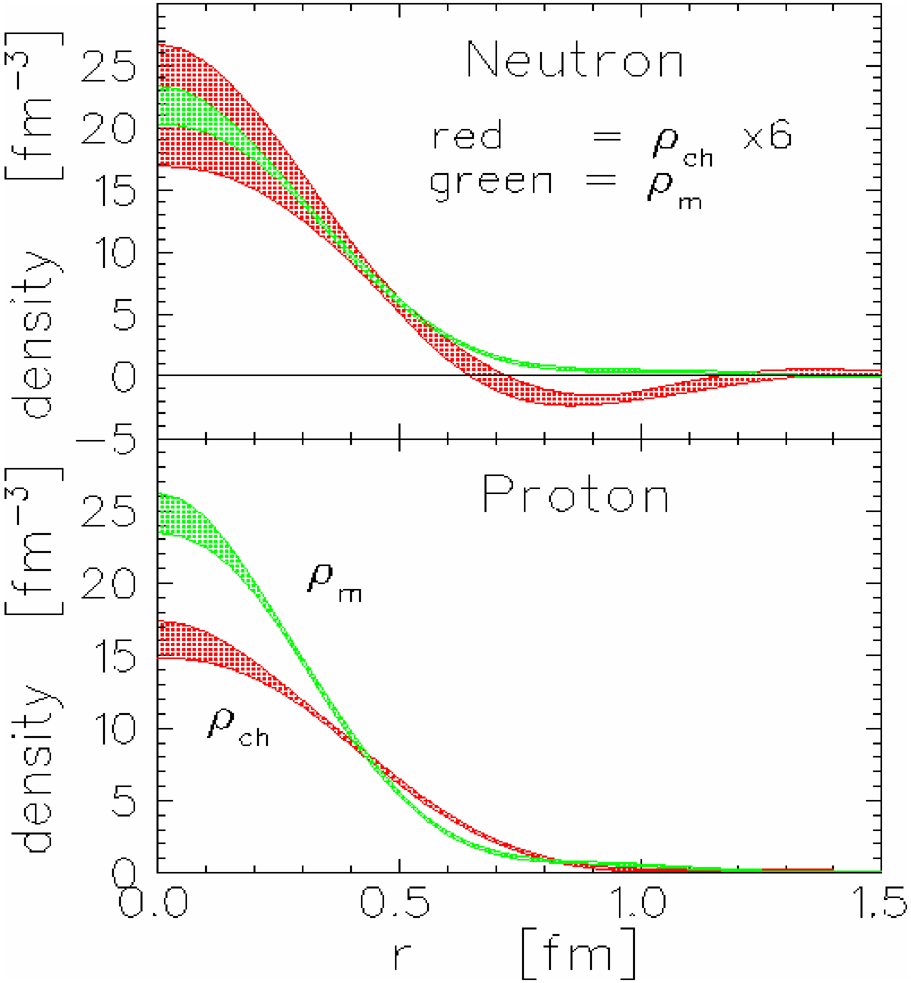
What about the neutron?

Neutron has no charge, but does have a charge distributions: n = p + π^-, n = ddu.
Use polarization and ^{2}H(e,e'n) to access.
"Guarantee" that electron hits a neutron AND electron transfers its polarization to this neutron.

(Polarization Experiments only)



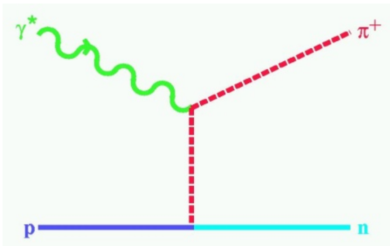
charge and magnetization density



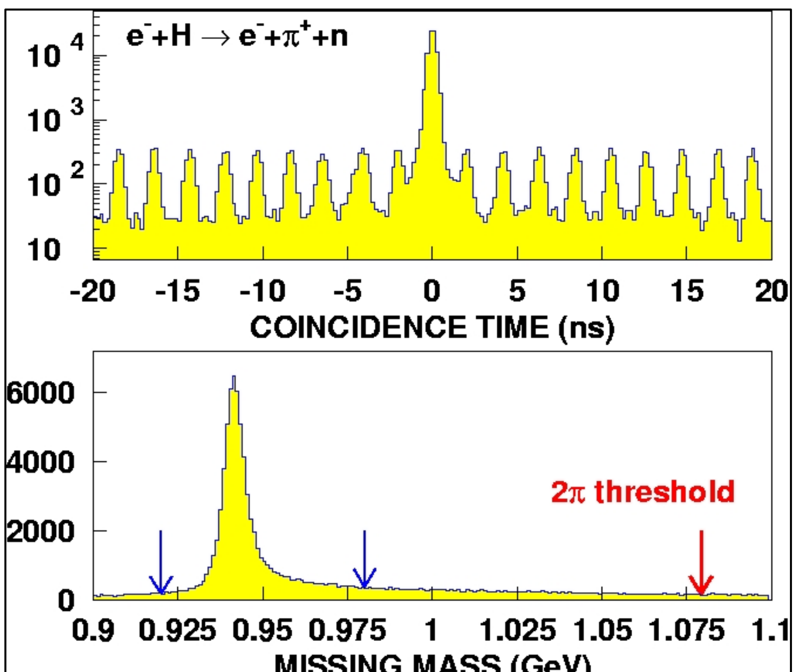
J. J. Kelly, PRC 66 (2002) 065203

Pion's charge distribution

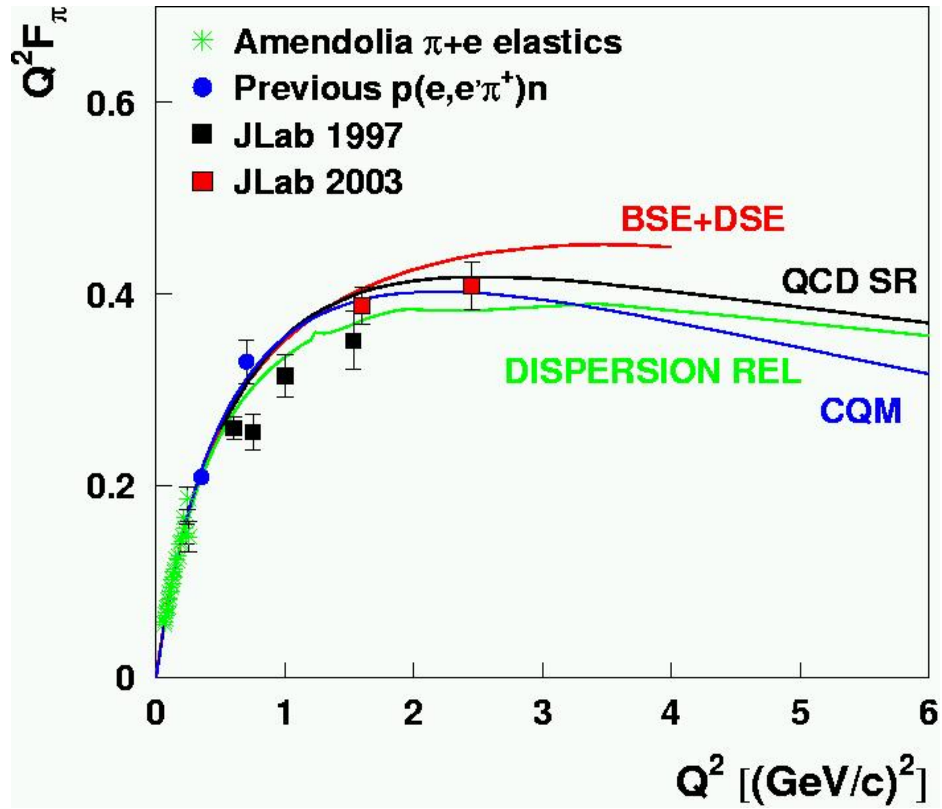
- At low Q^2 (< 0.3 $(GeV/c)^2$): use π + e scattering → R_{rms} = 0.66 fm
- At higher Q^2: use $^1H(e,e'\pi^+)n$



- Use a realistic pion electroproduction (Regge-type) model to extract F_π



- In asymptotic region, $F_\pi \to 8\pi\alpha_s f_\pi^2 Q^{-2}$



T. Horn et al., nucl-ex/0607005
V. Tadevosyan, et al., nucl-ex/0607007

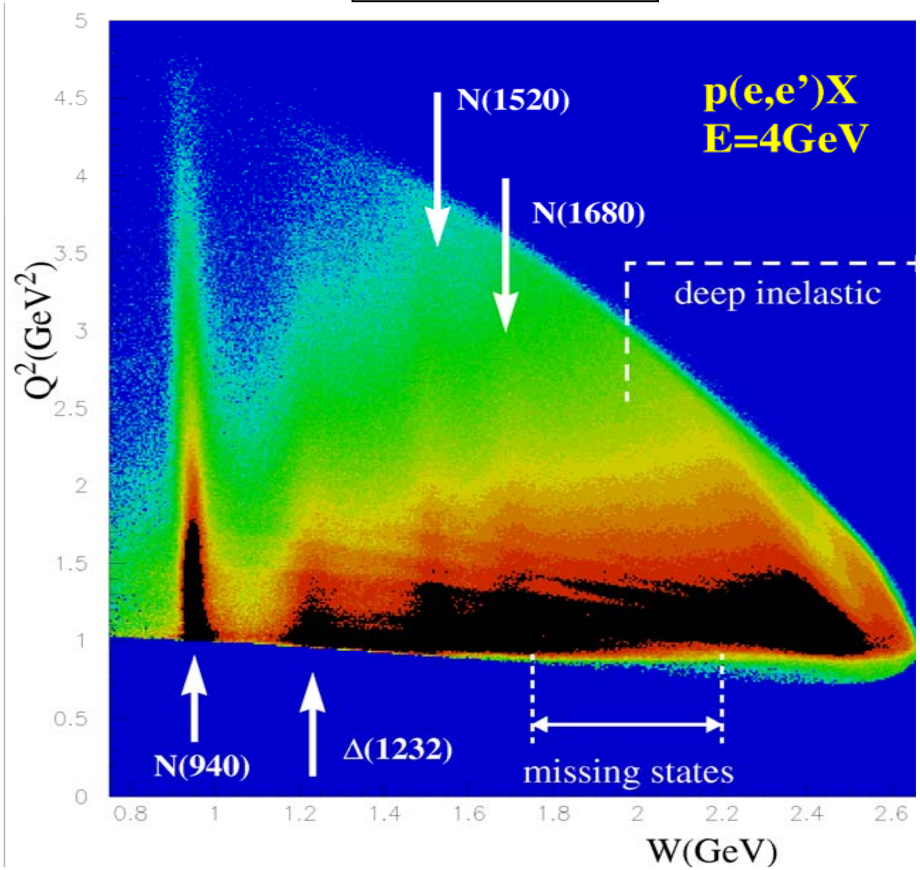
First measurements away from region where F_π is simply given by the π radius

Hall B

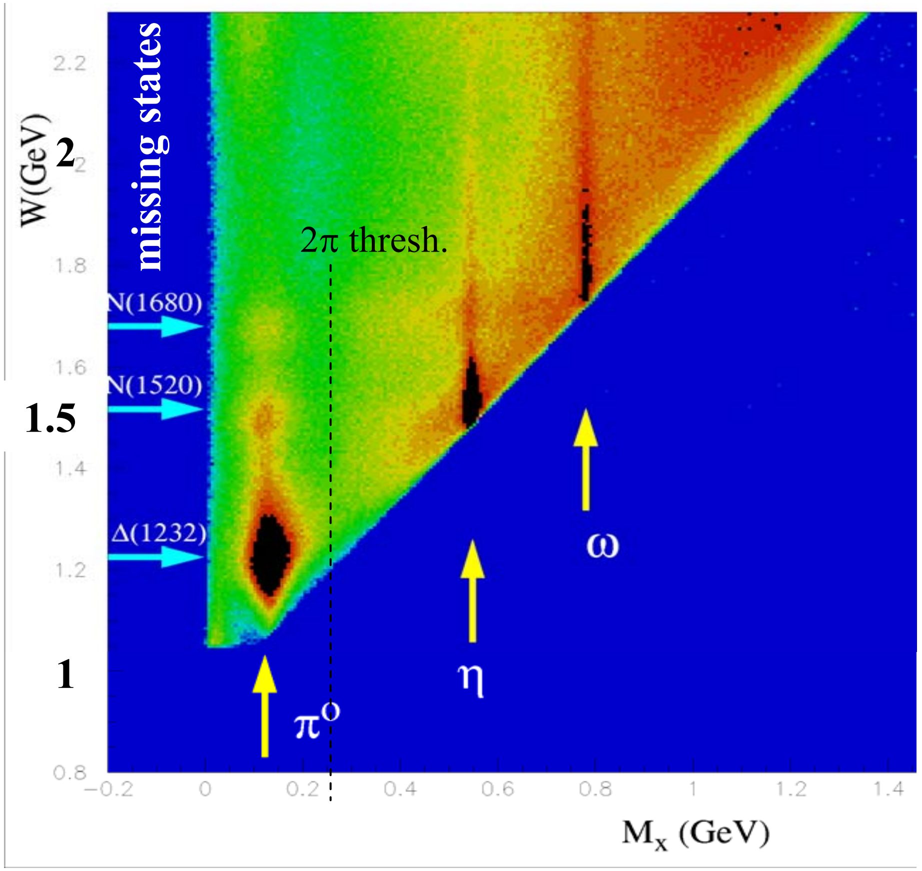
Electron Scattering

CLAS

p(e,e')X

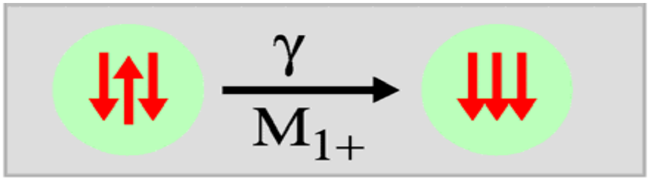


p(e,e'p)X

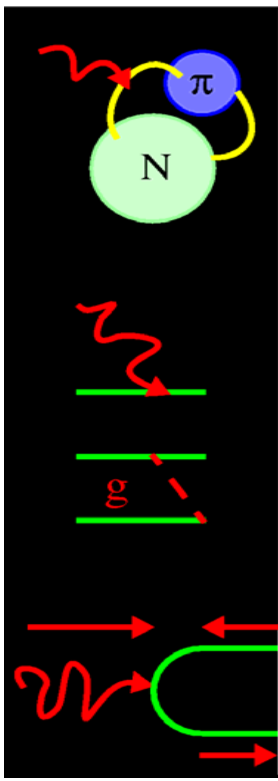


➢ Resonances cannot be uniquely separated in inclusive scattering → measure exclusive processes.

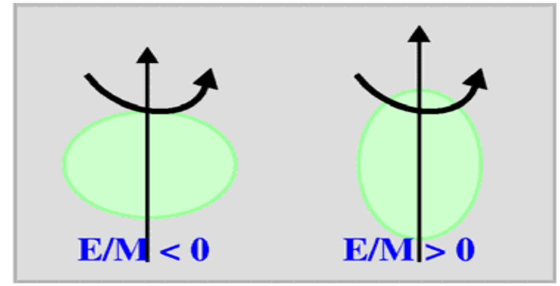
The $\gamma N\Delta(1232)$ Quadrupole Transition



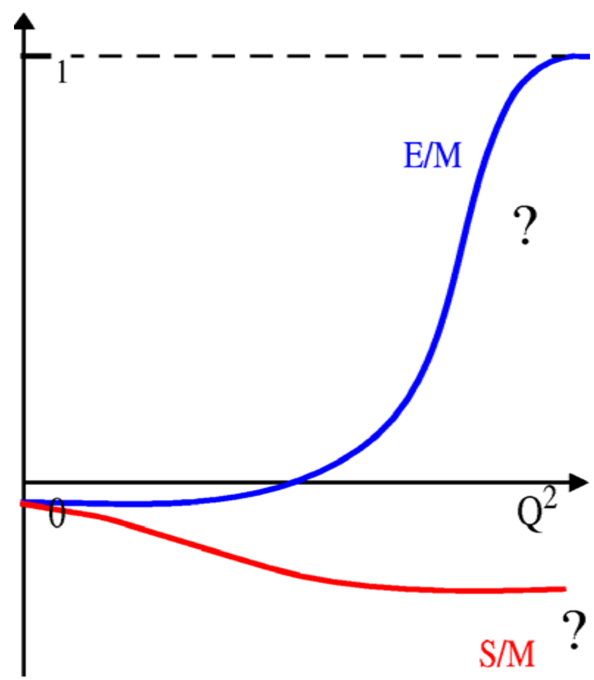
SU(6): $E_{1+} = S_{1+} = 0$



	E/M	S/M
pion cloud	~0.03	~0.1
one-gluon exch.	~ 0.01	
pQCD	+1	const.



(A. Buchmann, E. Henley, 2000)

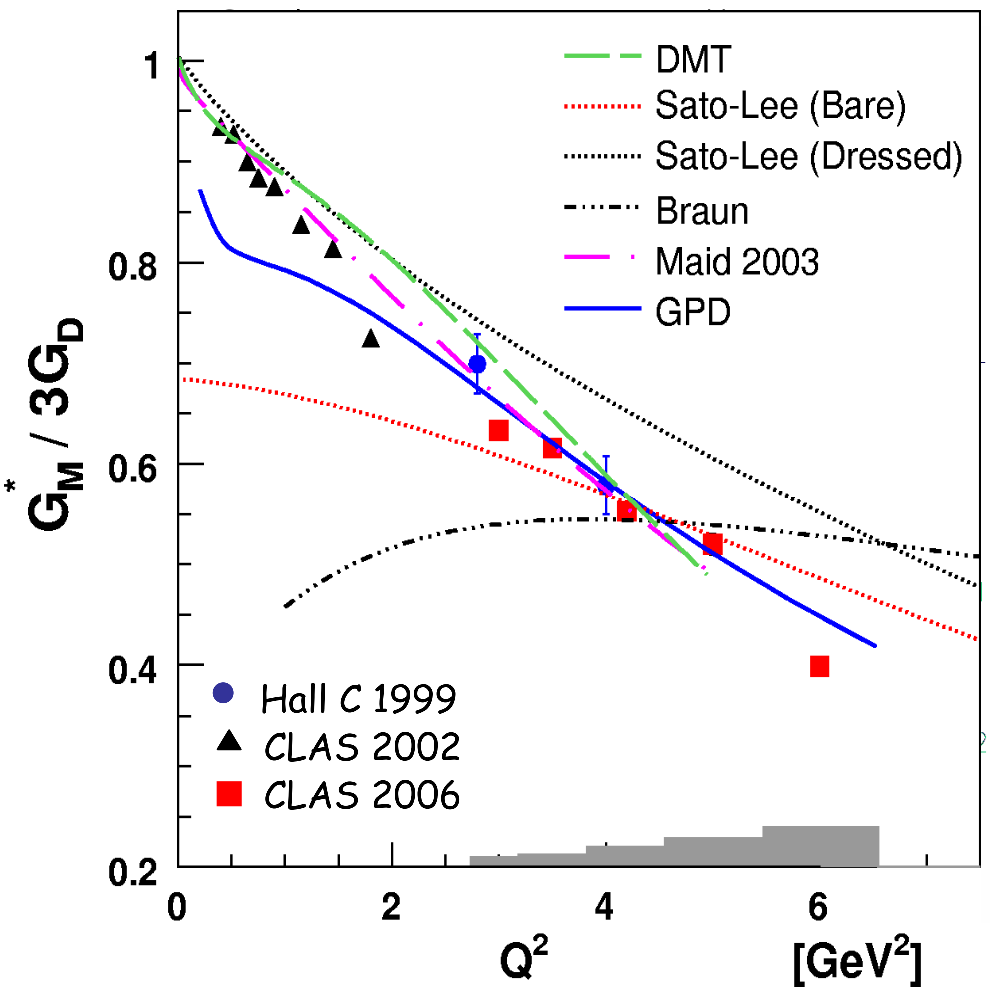


Hall B

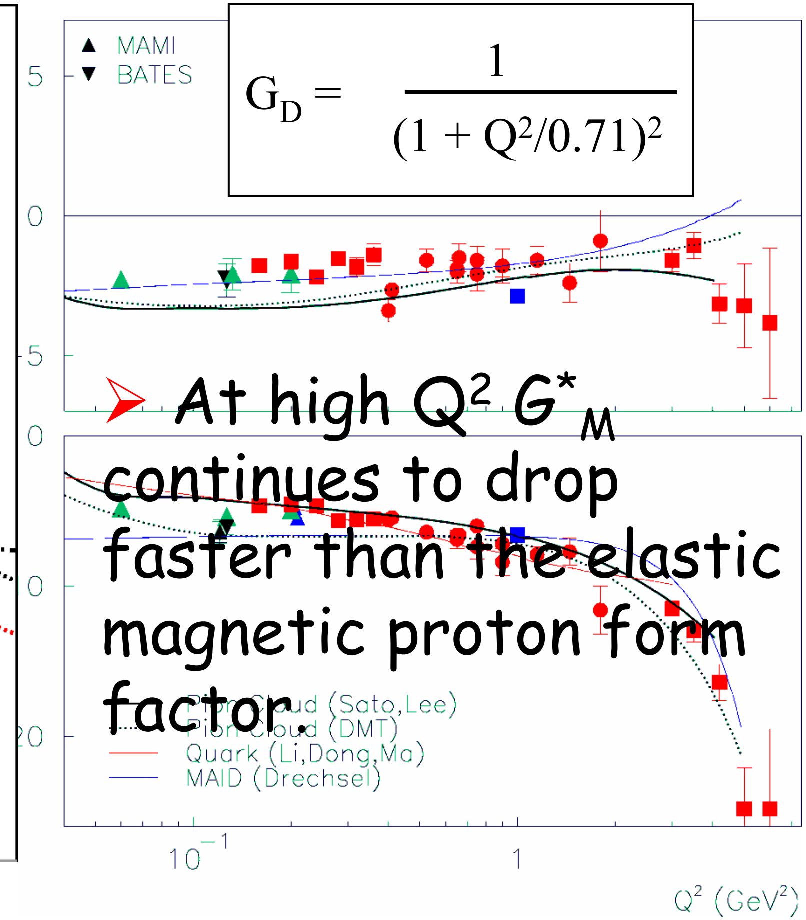
Transition amplitudes $\gamma_V p \rightarrow N_{3/2^+}(1232)$

(The N-Δ Transition)

CLAS



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



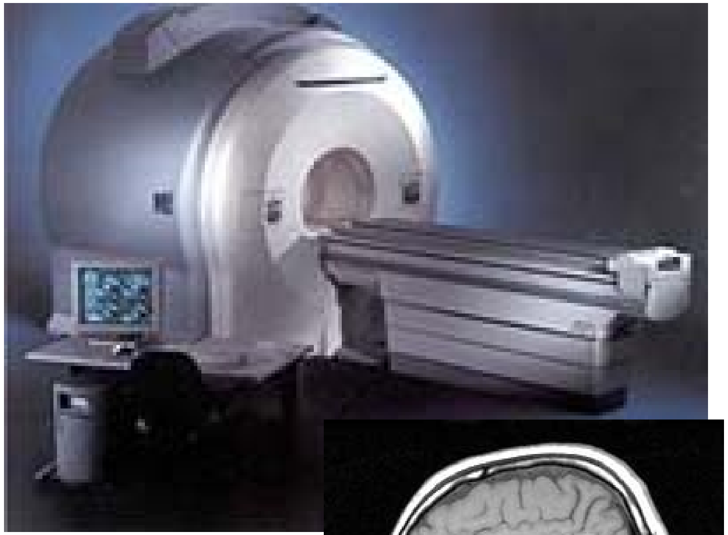
- At high Q^2 G^*_M continues to drop faster than the elastic magnetic proton form factor.

The proton's magnetic moment

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)

Otto Stern



2002 experiment:

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

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

2006 theory:

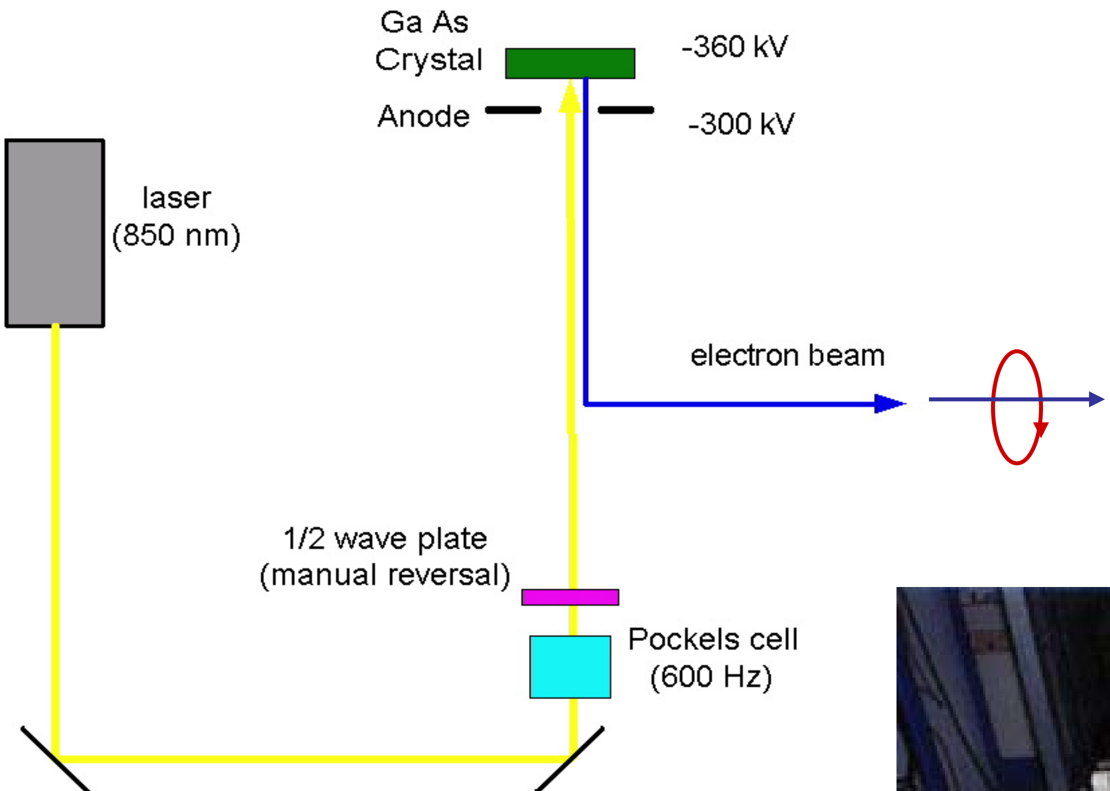
$\mu_p \sim 2.8\ \mu_N$

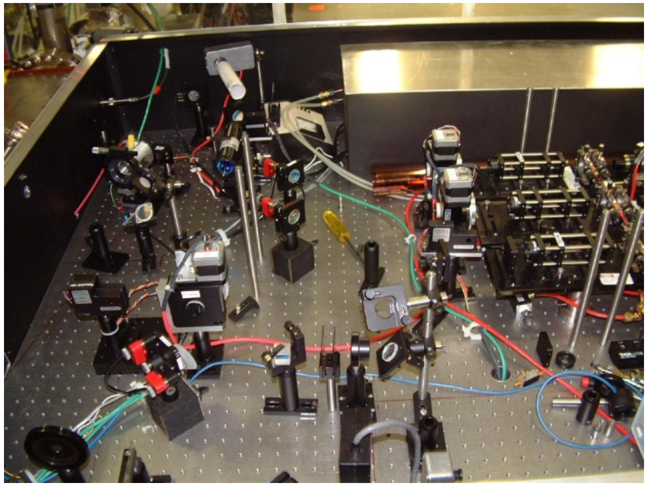
$\mu_n \sim -1.8\ \mu_N$

How do the quark contributions add up?

How are charge and magnetism distributed?

JLab: Polarized Electrons!!!

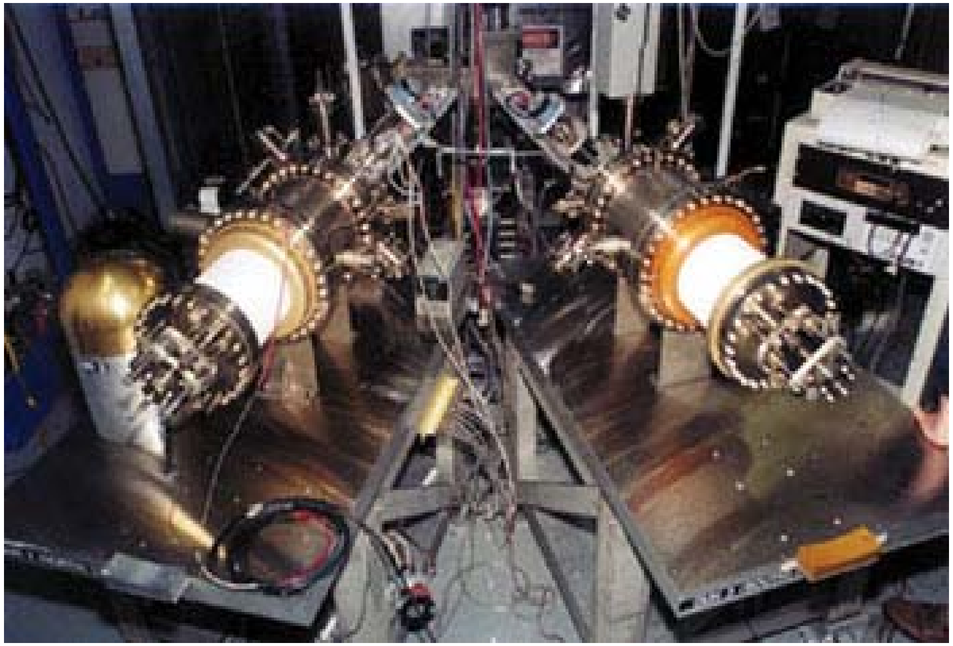




Electron retains circular polarization of laser beam

Reverse polarization of beam at rate of 30 Hz

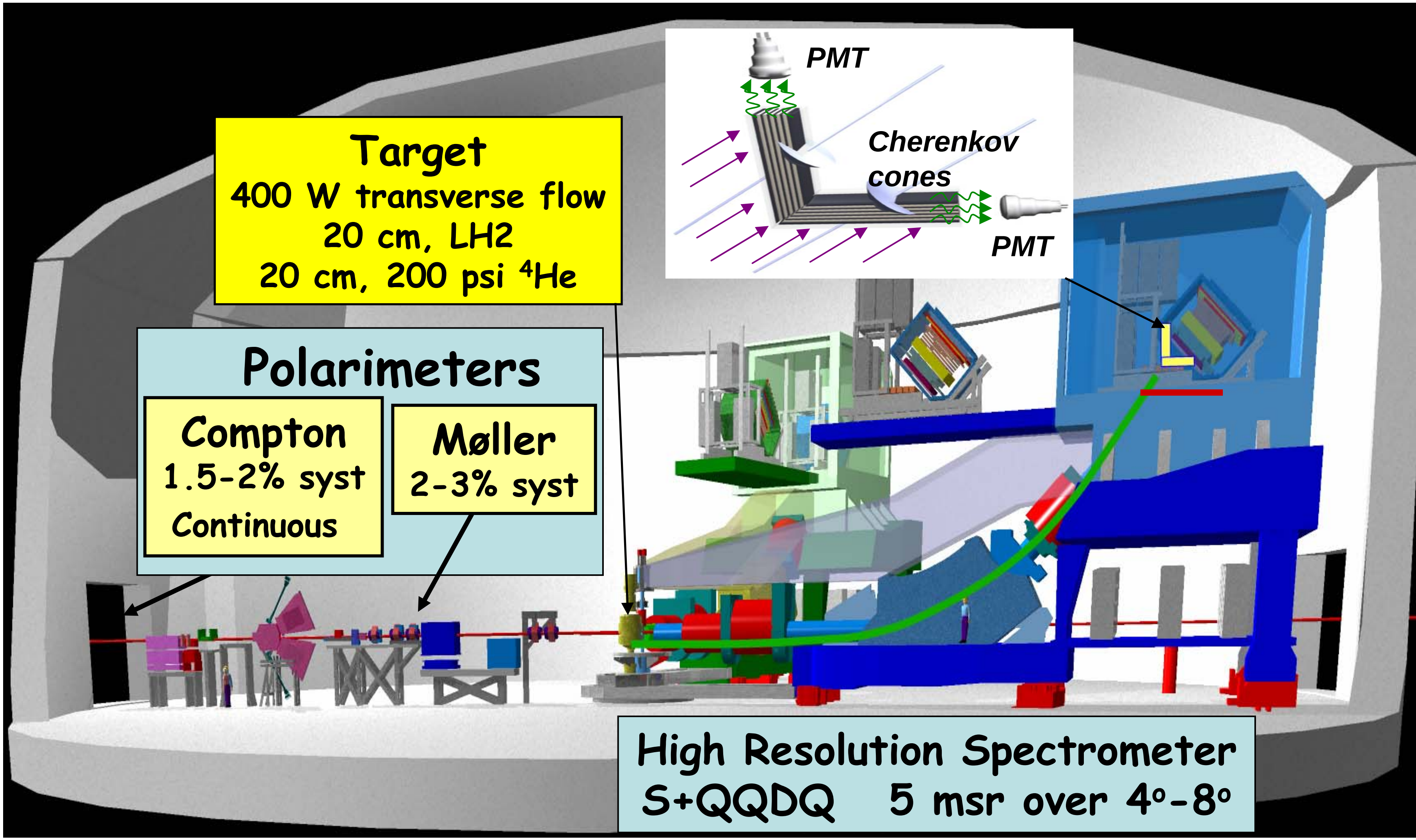
Feedback on laser intensity and position at high rate



Hall A

Parity Violating Studies on ^{1}H and ^{4}He

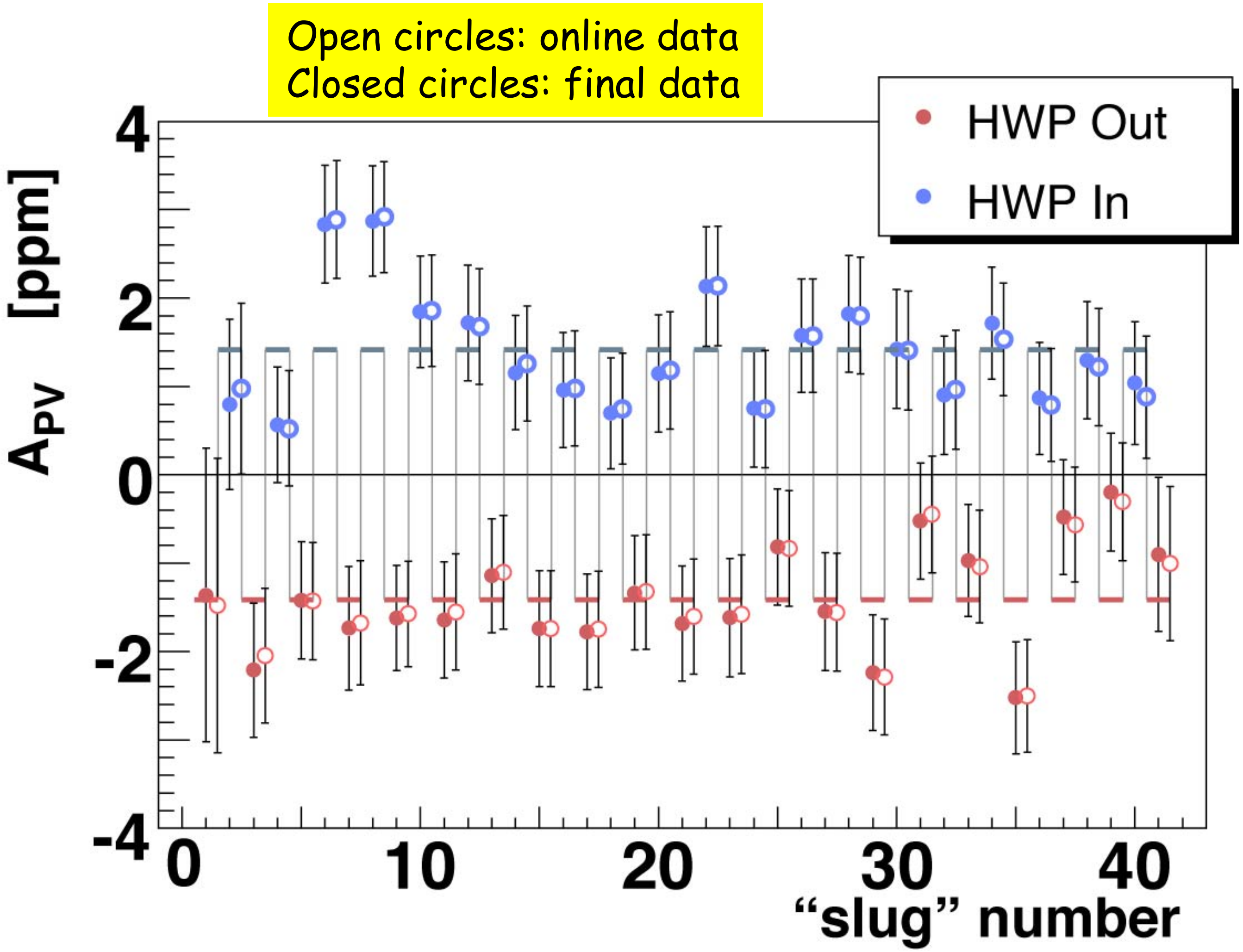
The HAPPEx Program: Strange Quark Contributions to the Proton

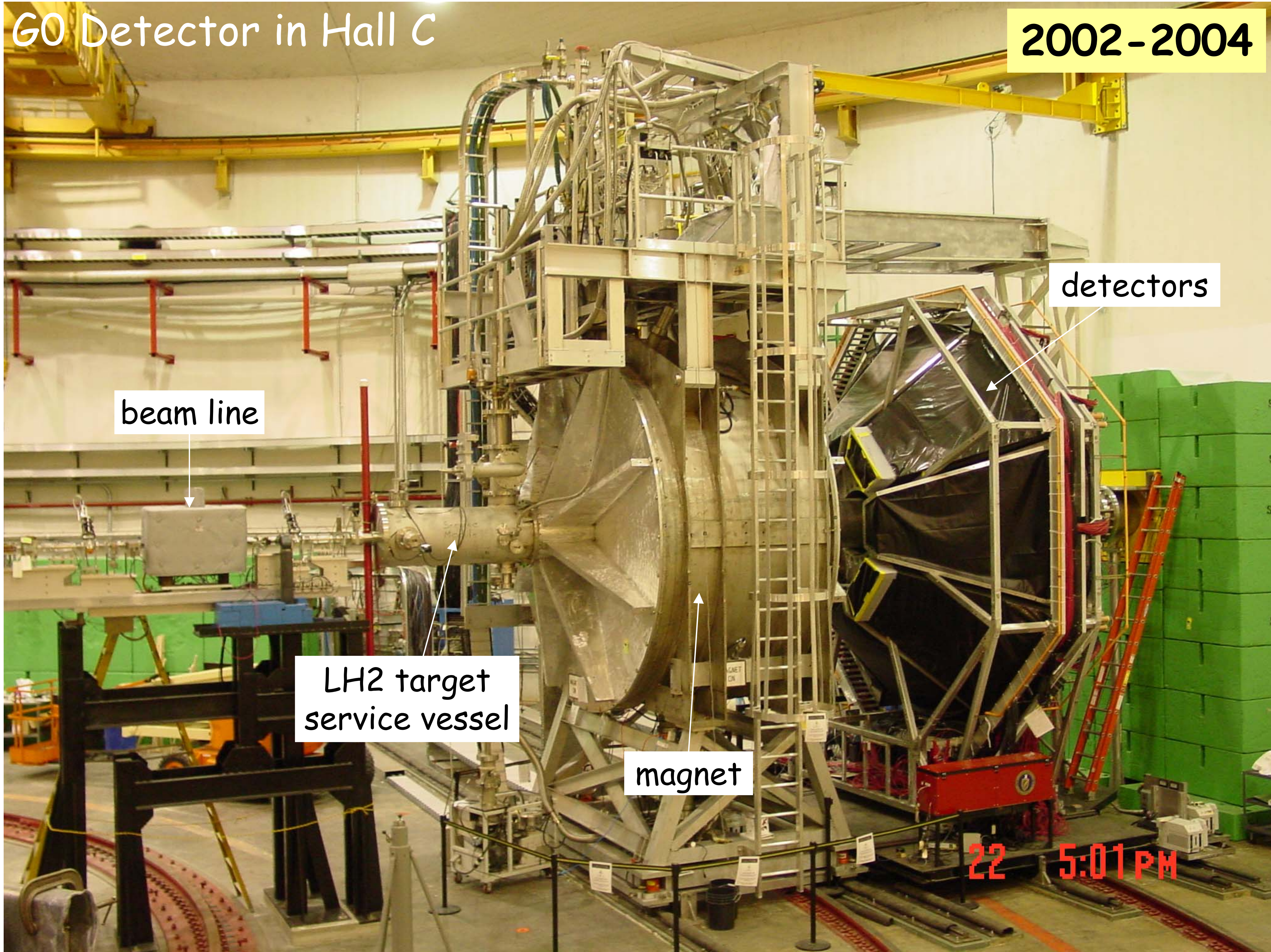


Hall A

Parity Violating Studies on ^1H and ^4He

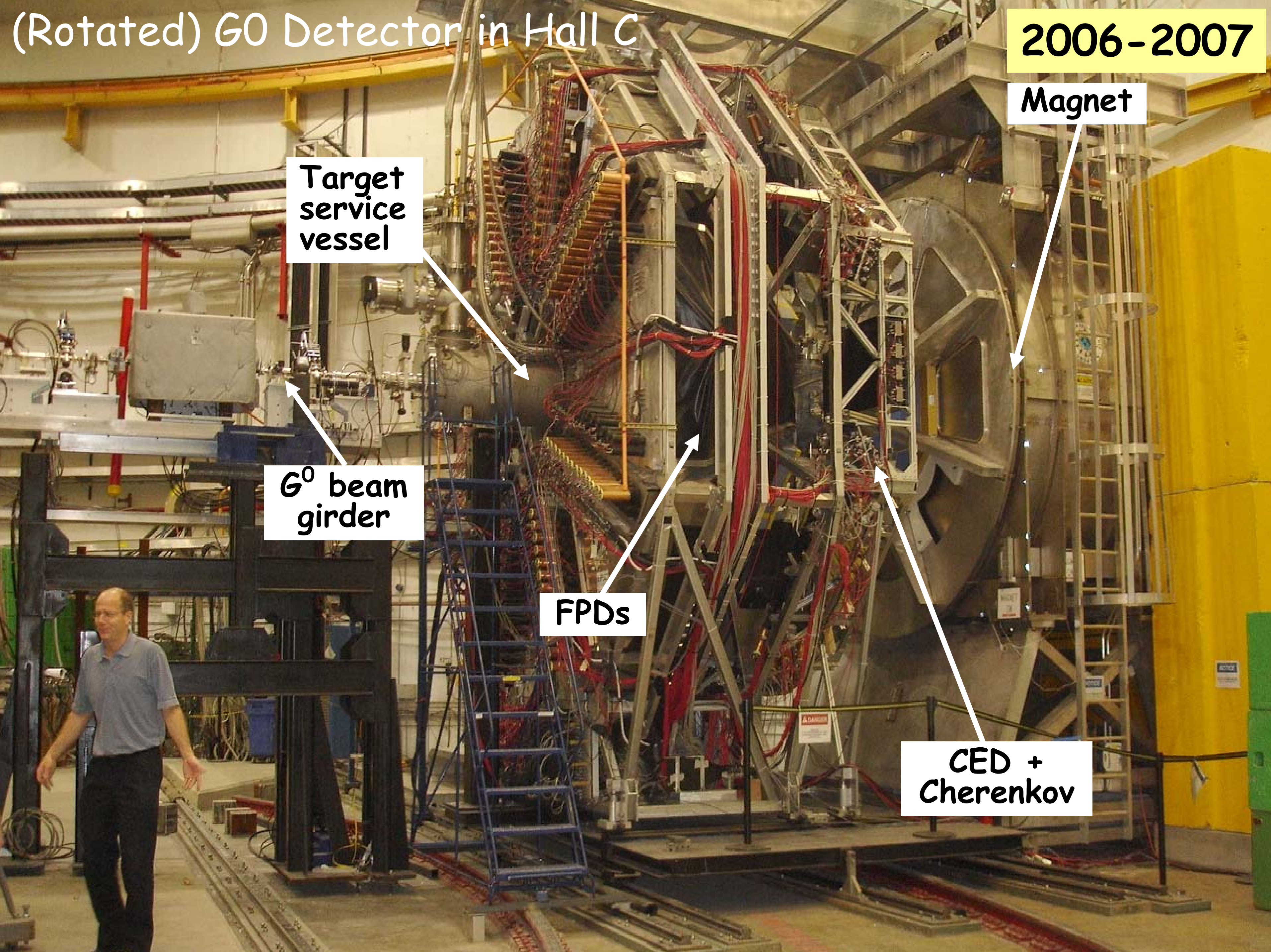
The HAPPEx Program: Strange Quark Contributions to the Proton




G0 Detector in Hall C
2002-2004
detectors
beam line
LH2 target
service vessel
magnet
22 5:01PM

(Rotated) G0 Detector in Hall C

2006-2007



JLab polarized beam

G0 forward running beam:

- strained GaAs ($P_B \sim 73\%$)
- 32 ns pulse spacing
- 40 μA beam current

HAPPEX-II beam (2005):

- superlattice ($P_B > 85\%$)
- 2 ns pulse spacing
- 35 μA beam current

Beam Parameter	G0 beam (Hall C)	HAPPEx beam (Hall A)
Charge asymmetry	-0.14 ± 0.32 ppm	-2.6 ± 0.15 ppm
Position difference	**4 ± 4 nm**	**-8 ± 3 nm**
angle difference	1.5 ± 1 nrad	4 ± 2 nrad
Energy difference	29 ± 4 eV	66 ± 3 eV
Total correction to Asymmetry	-0.02 ± 0.01 ppm	0.08 ± 0.03 ppm

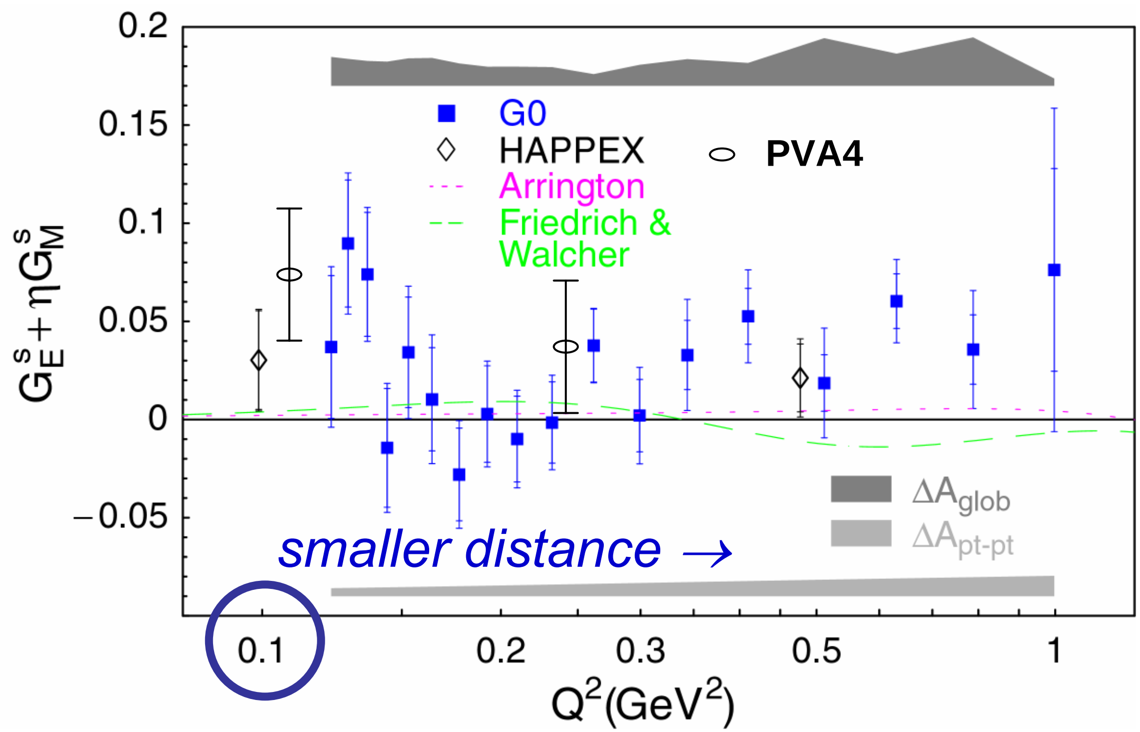
The spatial distribution of quarks and the proton's magnetism

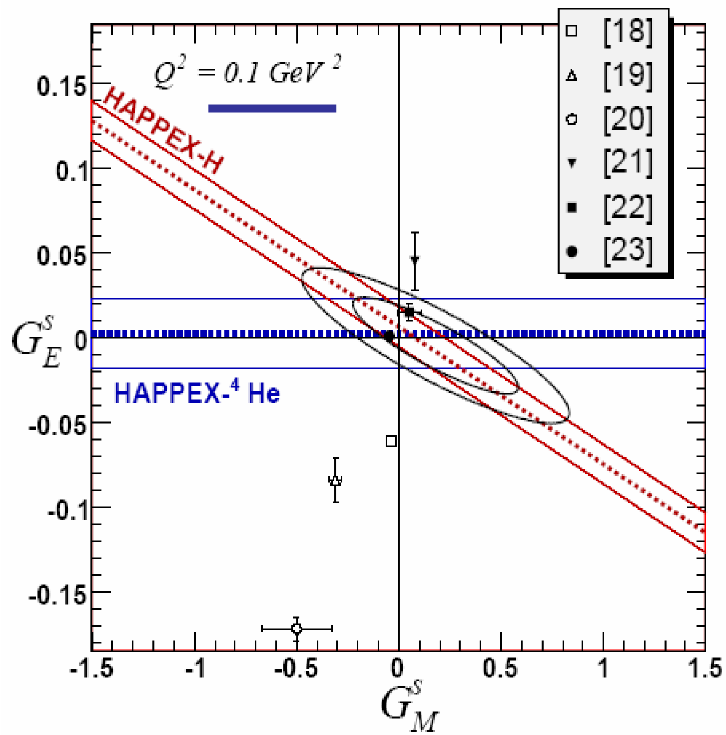
Hall A

$$G_M^p(Q^2) = \tfrac{2}{3}G_M^u(Q^2) - \tfrac{1}{3}G_M^d(Q^2) - \tfrac{1}{3}G_M^s(Q^2)$$

proton charge/magnetism
neutron charge/magnetism
proton response to Weak force

up
down
strange ← ~ 5%





Extracting Nucleon Strange Form Factors from World Data

Ross Young (JLab-Theory), Julie Roche, Roger Carlini (JLab), Tony Thomas (JLab-Theory)

Approach: Use the complete (SAMPLE, PVA4, HAPPEx, G0) world set of parity-violating electron scattering asymmetries up to $Q^2 = 0.3$ GeV^2.

$$G_E^s = \rho_s Q^2 + \rho'_s Q^4$$
$$G_M^s = \mu_s + \mu'_s Q^2$$

<u>Contours</u>

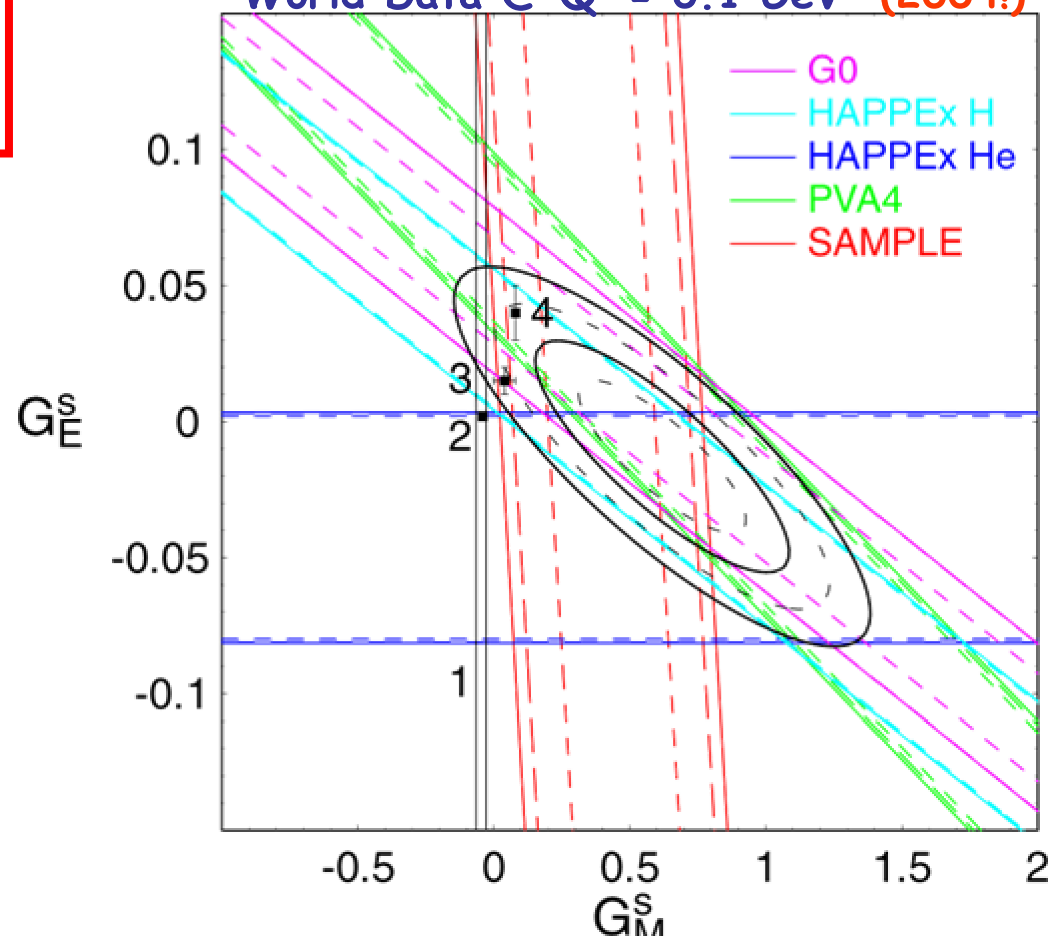
1σ, 2σ

68.3, 95.5% CL

<u>Theories</u>

1. Leinweber, et al. PRL **94** (05) 212001
2. Lyubovitskij, et al. PRC **66** (02) 055204
3. Lewis, et al. PRD **67** (03) 013003
4. Silva, et al. PRD **65** (01) 014016

World Data @ Q^2 = 0.1 GeV^2 (2004!)



Extracting Nucleon Strange Form Factors from World Data

Ross Young (JLab-Theory), Julie Roche, Roger Carlini (JLab), Tony Thomas (JLab-Theory)

Approach: Use the complete (SAMPLE, PVA4, HAPPEx, G0) world set of parity-violating electron scattering asymmetries up to $Q^2 = 0.3\ GeV^2$.

$$G_E^s = \rho_s Q^2 + \rho'_s Q^4$$
$$G_M^s = \mu_s + \mu'_s Q^2$$

<u>Contours</u>

1σ, 2σ

68.3, 95.5% CL

<u>Theory</u>

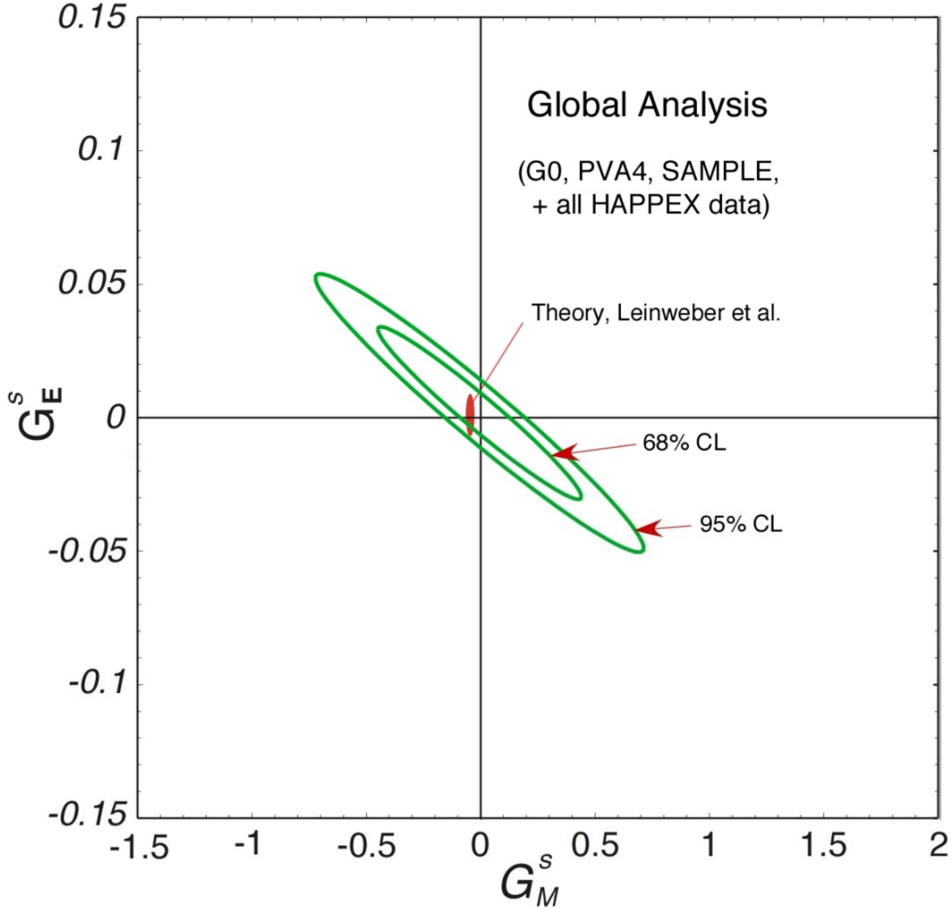
Leinweber, et al.

PRL **94** (05) 212001;

hep-lat/0601025

... or include recent HAPPEx-H and -He data

World Data @ $Q^2 = 0.1\ GeV^2$



CEBAF's Original Mission Statement

Key Mission and Principal Focus (1987):

The study of the largely unexplored transition between the nucleon-meson and the quark-gluon descriptions of nuclear matter.

The Role of Quarks in Nuclear Physics

Related Areas of Study:

- **Do individual nucleons change their size, shape, and quark structure in the nuclear medium?**

- **How do nucleons cluster in the nuclear medium?**

Pushing the Limits of the Standard Model of Nuclear Physics

- **What are the properties of the force which binds quarks into nucleons and nuclei at distances where this force is strong and the quark confinement mechanism is important?**

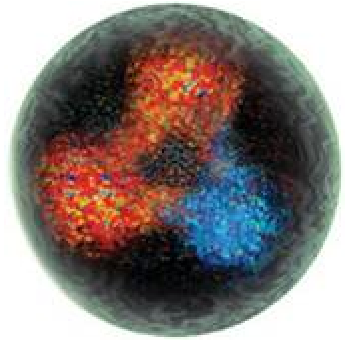
Charge and Magnetization in Nucleons and Pions

The Onset of the Parton Model

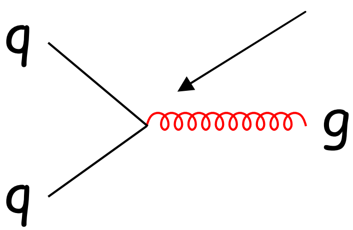
The Double-Faced Strong Force

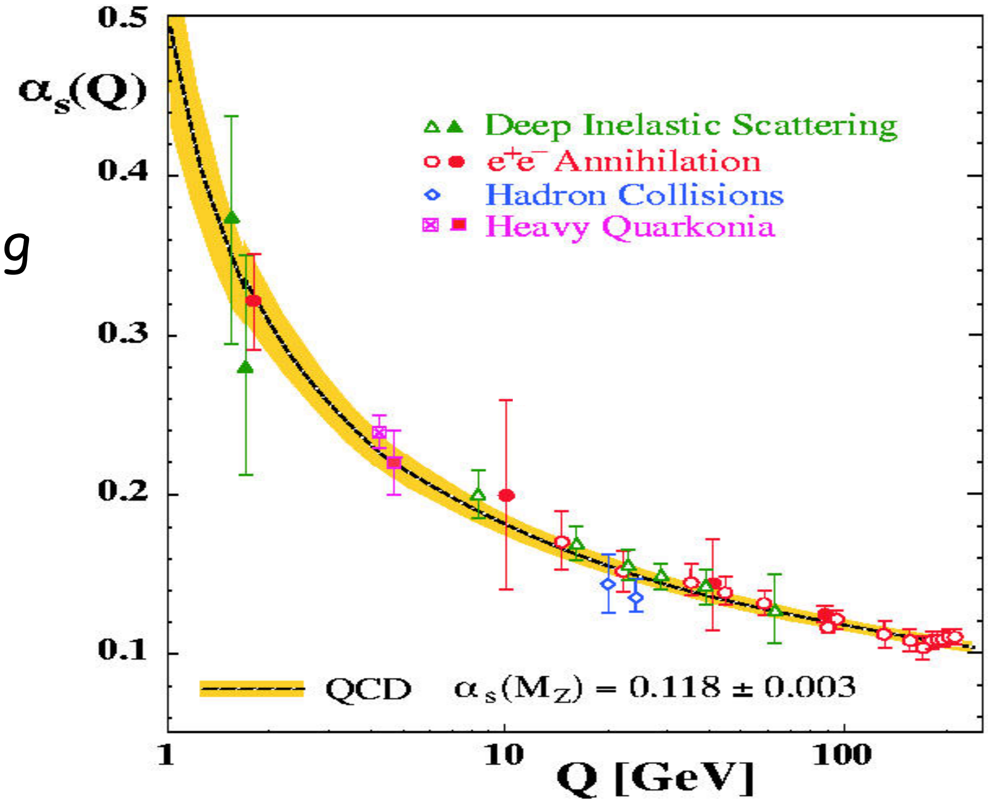
<u>Confinement</u>
Nucleons
$Q < \Lambda$
$\alpha_s(Q) > 1$

Constituent
Quarks
$Q > \Lambda$
$\alpha_s(Q)$ large



Asymptotically
Free Quarks
$Q \gg \Lambda$
$\alpha_s(Q)$ small





One parameter, Λ_{QCD},
~ Mass Scale or
Inverse Distance Scale
where $\alpha_s(Q) = \infty$

"Separates" Confinement
and Perturbative Regions

Mass and Radius of the
Proton are (almost)
completely governed by

$\Lambda_{QCD} \approx 0.213$ GeV

Quark Model

Quark Parton Model

Nuclear Physics in terms of protons, neutrons and pion exchange is a very good effective model.

Momentum transfer Q is negligible

Protons and Neutrons in terms of constituent (valence) quarks is a very decent effective model:

the Constituent Quark Model works surprisingly well.

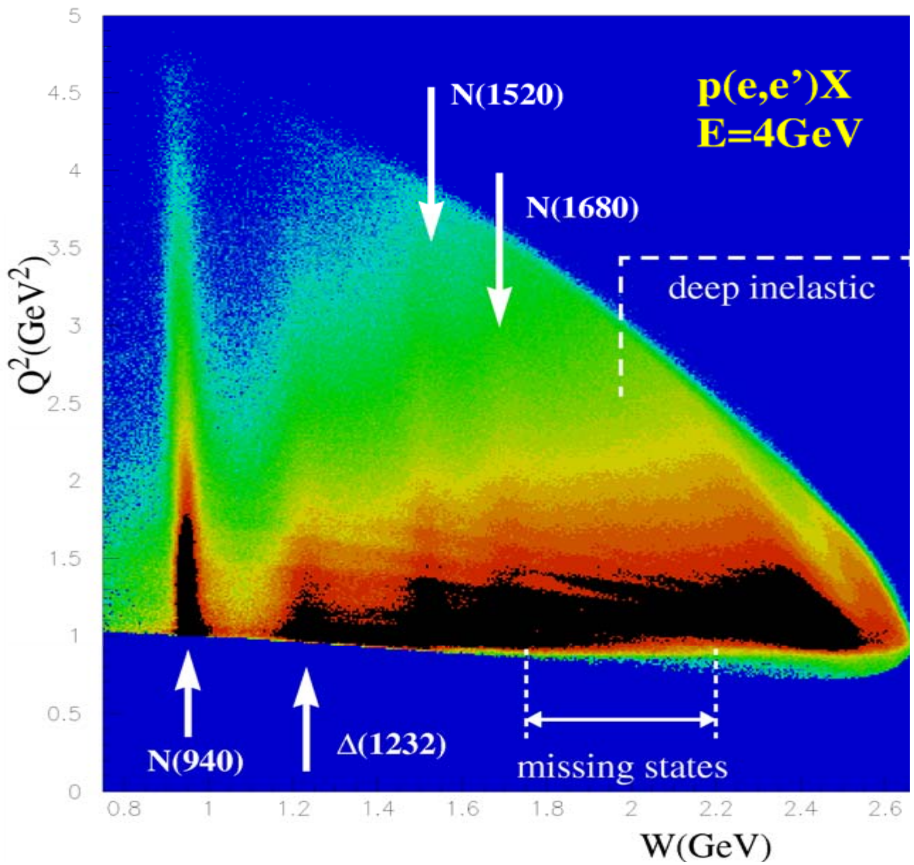
Momentum transfer Q is small

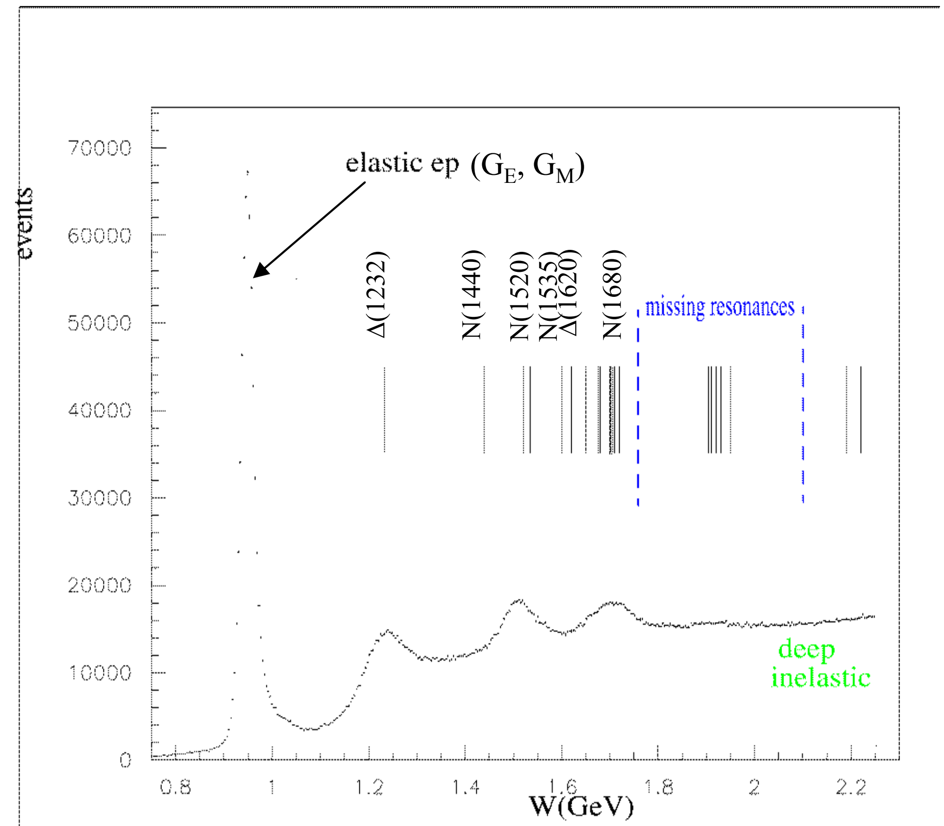
Looking deep inside protons and neutrons, they are really balls of energy, with lots of gluons and quark-antiquark pairs popping in and out of existence.

Momentum transfer Q is "large"

Hall B Electron Scattering CLAS

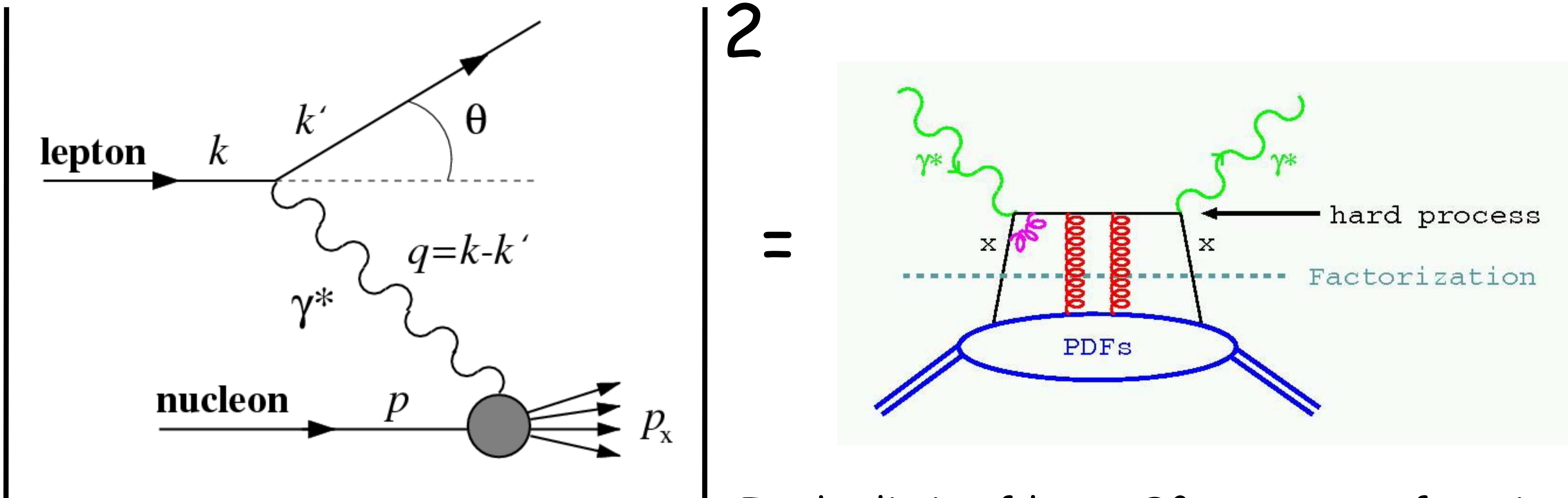
p(e,e')X





Map "Quark-Hadron Transition"
in electron-proton scattering
(From Resonance to Deep Inelastic Region / From Quark Model to Parton Model)

Deep Inelastic Scattering



Bjorken Limit: $Q^2 \to \infty, \nu \to \infty$

(Infinite Momentum Frame)

In the limit of large Q^2, structure functions scale (with logarithmic corrections)

$$MW_1(\nu, Q^2) \to F_1(x)$$

$$\nu W_1(\nu, Q^2) \to F_2(x)$$

$$x = \frac{Q^2}{2M\nu}$$

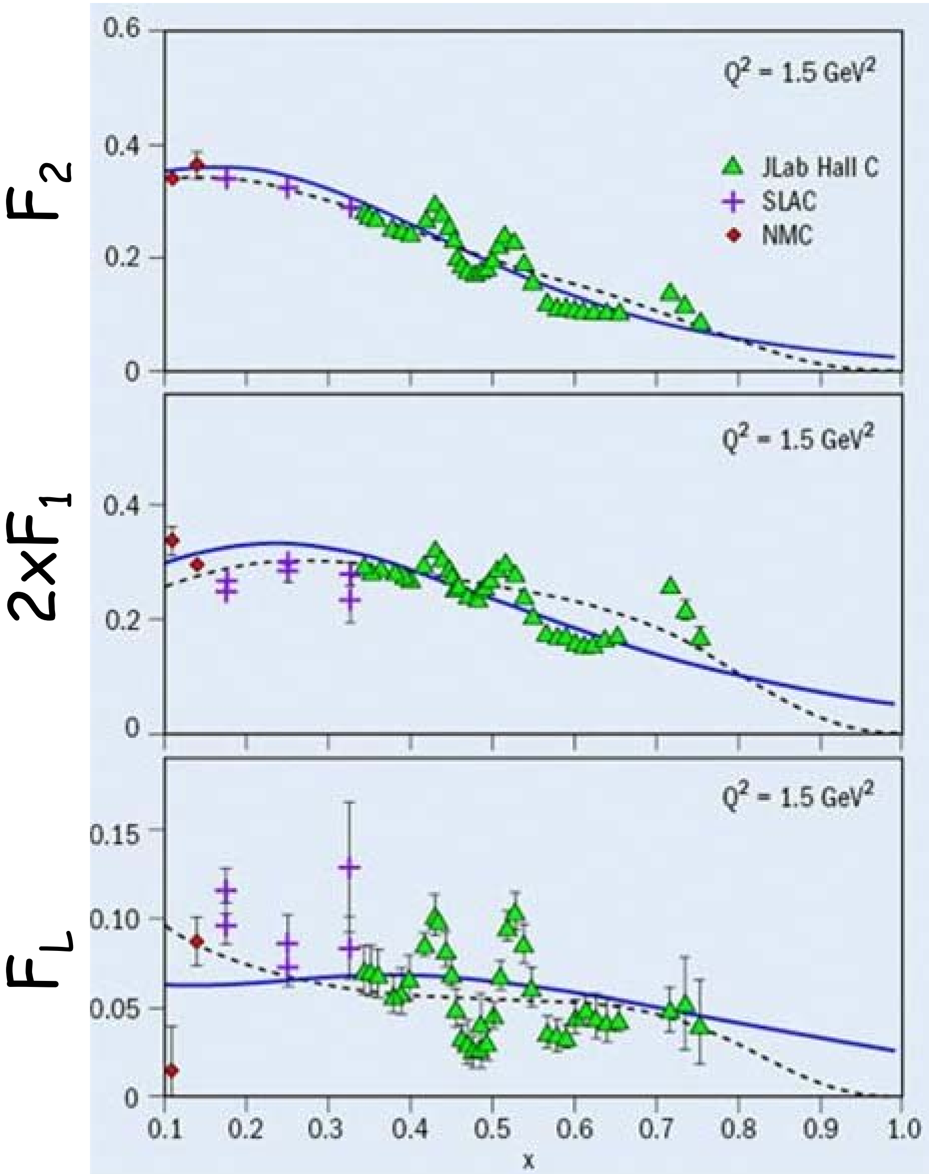
F_2 interpreted in the **quark-parton model** as the charge-weighted sum over quark distributions:

$$F_2(x) = \sum_i e_i^2 x q_i(x)$$

Empirically, DIS region is where logarithmic scaling is observed

$Q^2 > 1\ \mathrm{GeV}^2$, $W^2 > 4\ \mathrm{GeV}^2$

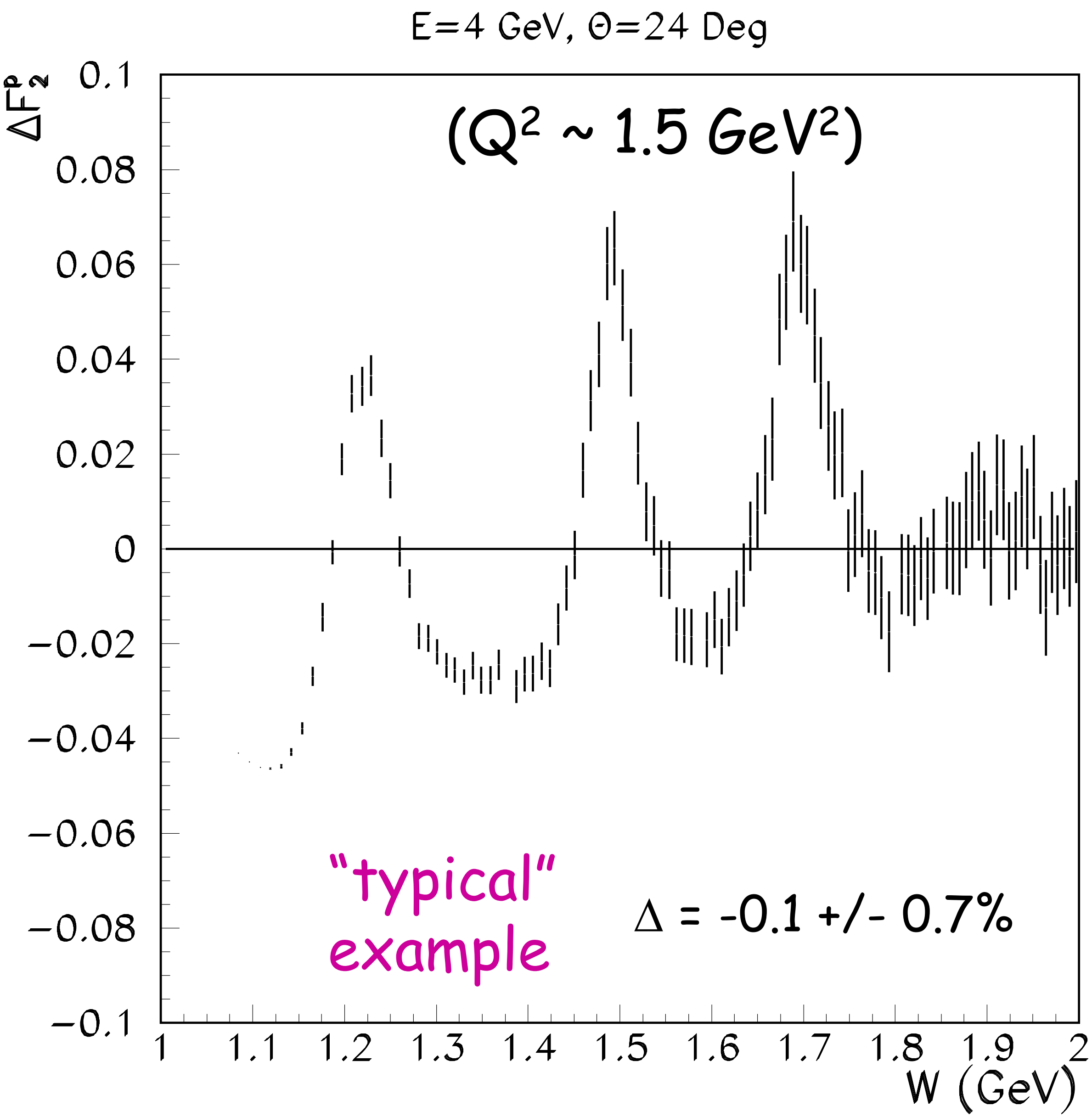
E94-110 : Separated Structure Functions
Duality works well for F_2, $2xF_1$ (F_T), and F_L



- The resonance region is, on average, well described by NNLO QCD fits.
- This implies that Higher-Twist (FSI) contributions cancel, and are on average small. "Quark-Hadron Duality"
- The result is a smooth transition from Quark Model Excitations to a Parton Model description, or a smooth quark-hadron transition.
- This explains the success of the parton model at relatively low W^2 (=4 GeV^2) and Q^2 (=1 GeV^2).

"The successful application of duality to extract known quantities suggests that it should also be possible to use it to extract quantities that are otherwise kinematically inaccessible."
(CERN Courier, December 2004)

Quantification: Resonance Region F_2 w.r.t. Alekhin NNLO Scaling Curve

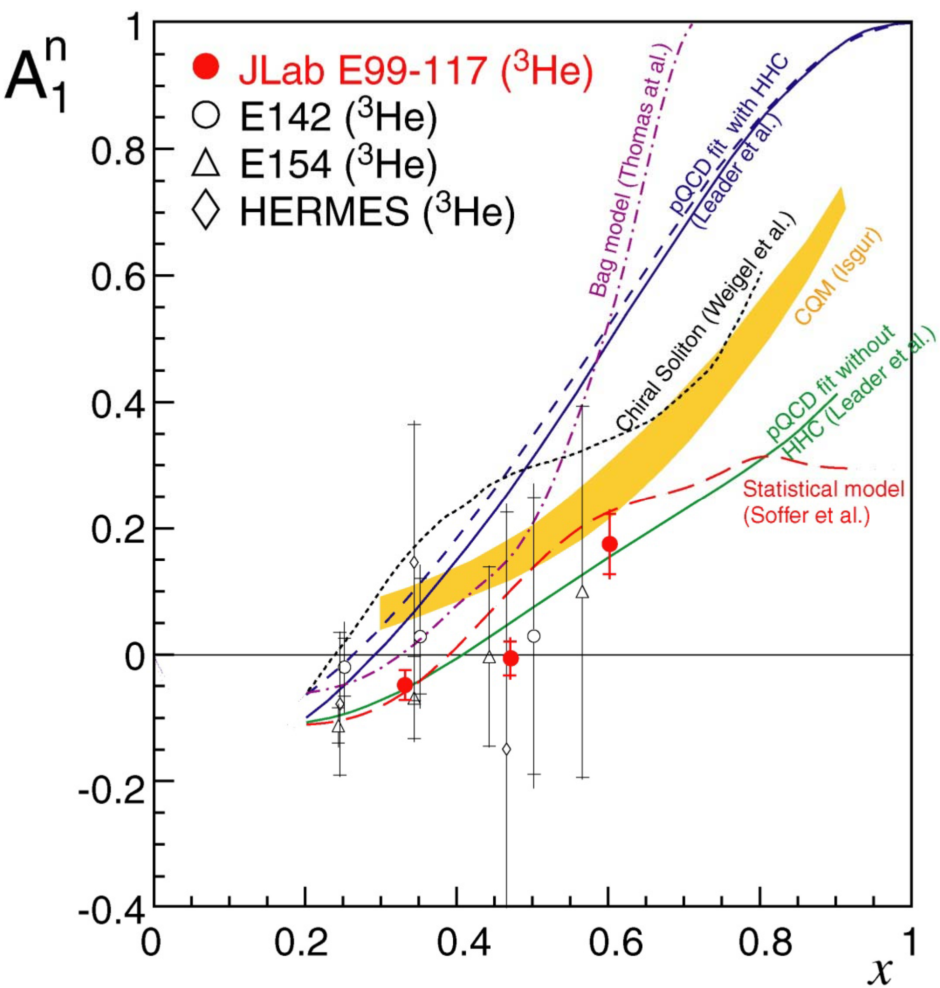


- Evidence of resonance transitions is "bumps and valleys" around the expected parton model behavior.
- Similar as standard textbook example of $e^+e^- \rightarrow$ hadrons
- **"Resonances build the parton subprocess cross section because of a separation of scales between hard and soft processes."**
- **Confinement is Local**

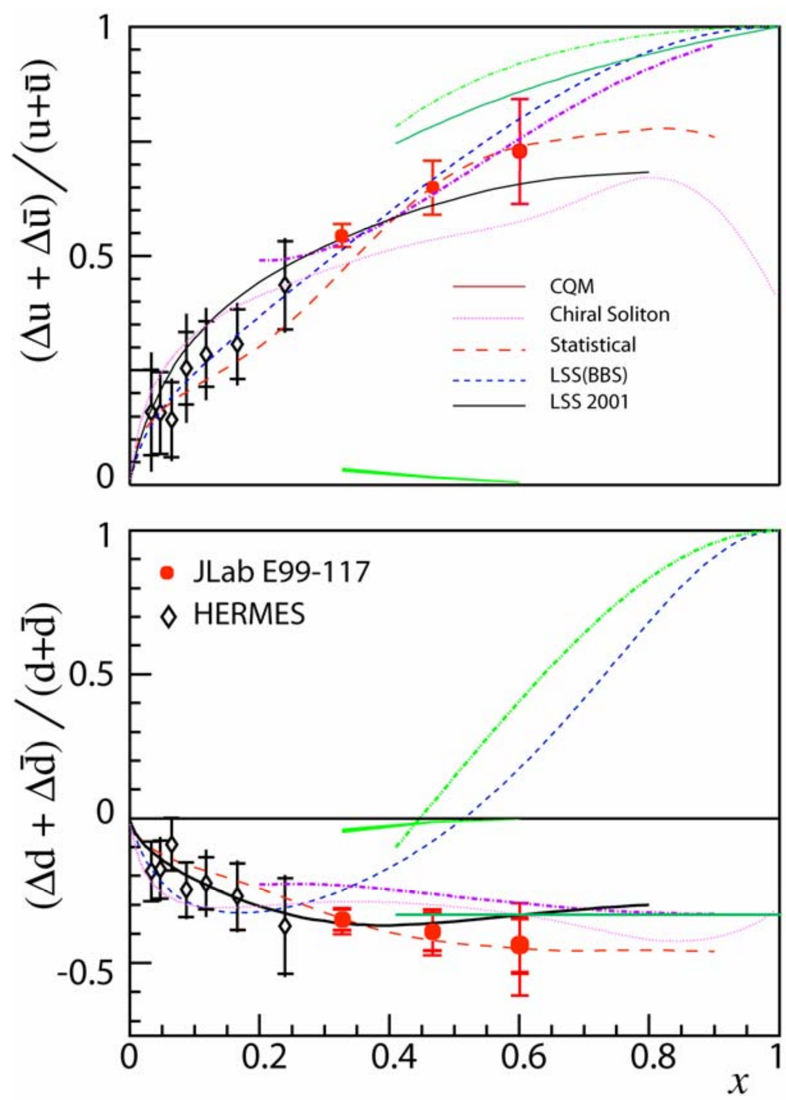
Parton Model Ideas Valid @ 6 GeV

Hall A

First measurement in large-x region unambiguously showing that $A_1^n > 0$ ($A_1^n = 0$ in the SU(6) Quark Model)



Allows for Flavor Decomposition:



Structure function g_1 and its $\Gamma_1(Q^2)$ Moment

$$\Gamma_1(Q^2) = \int_0^1 g_1(x, Q^2)\,dx$$

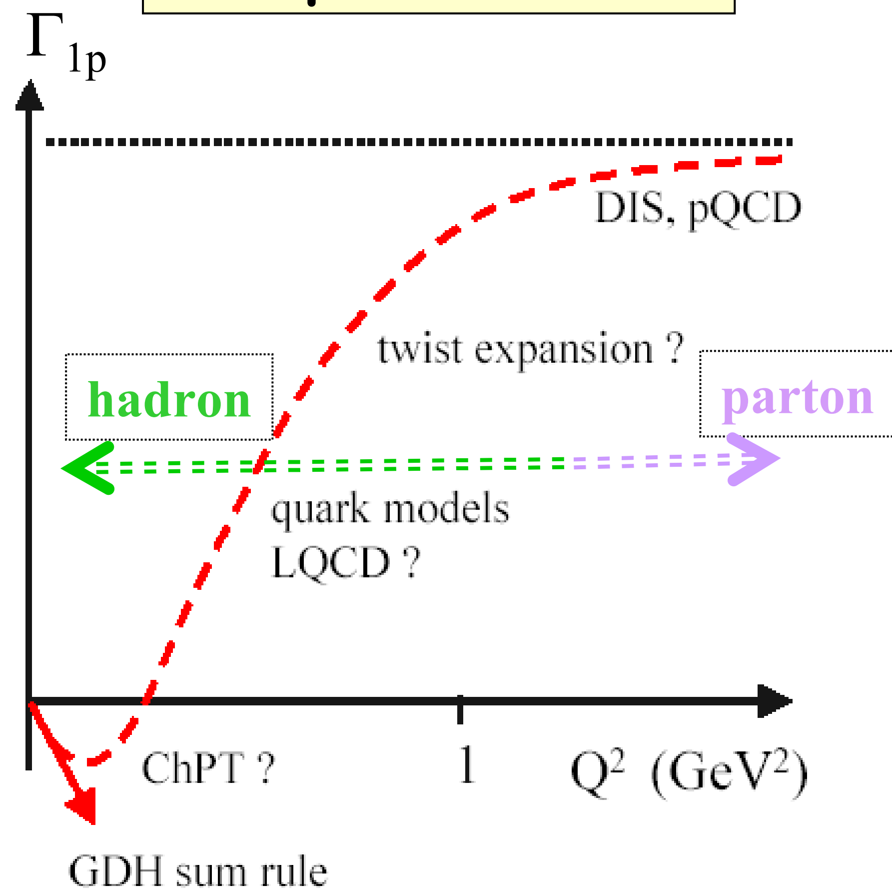
$$\vec{e} + \vec{p} \rightarrow e + X$$

As $Q^2 \rightarrow \infty$, isospin symmetry and current algebra lead to the Bjorken sum rule, relating the n-p difference to the neutron β-decay coupling constant g_A

$$\Gamma_1^p - \Gamma_1^n = g_A/6$$

As $Q^2 \rightarrow 0$, Lorentz invariance, unitarity, and dispersion relations lead to the GDH sum rule, relating it to the anomalous magnetic moment of the nucleon

$$\Gamma_1 \xrightarrow[Q^2 \rightarrow \infty]{} \frac{Q^2}{2M^2} I_{GDH}$$

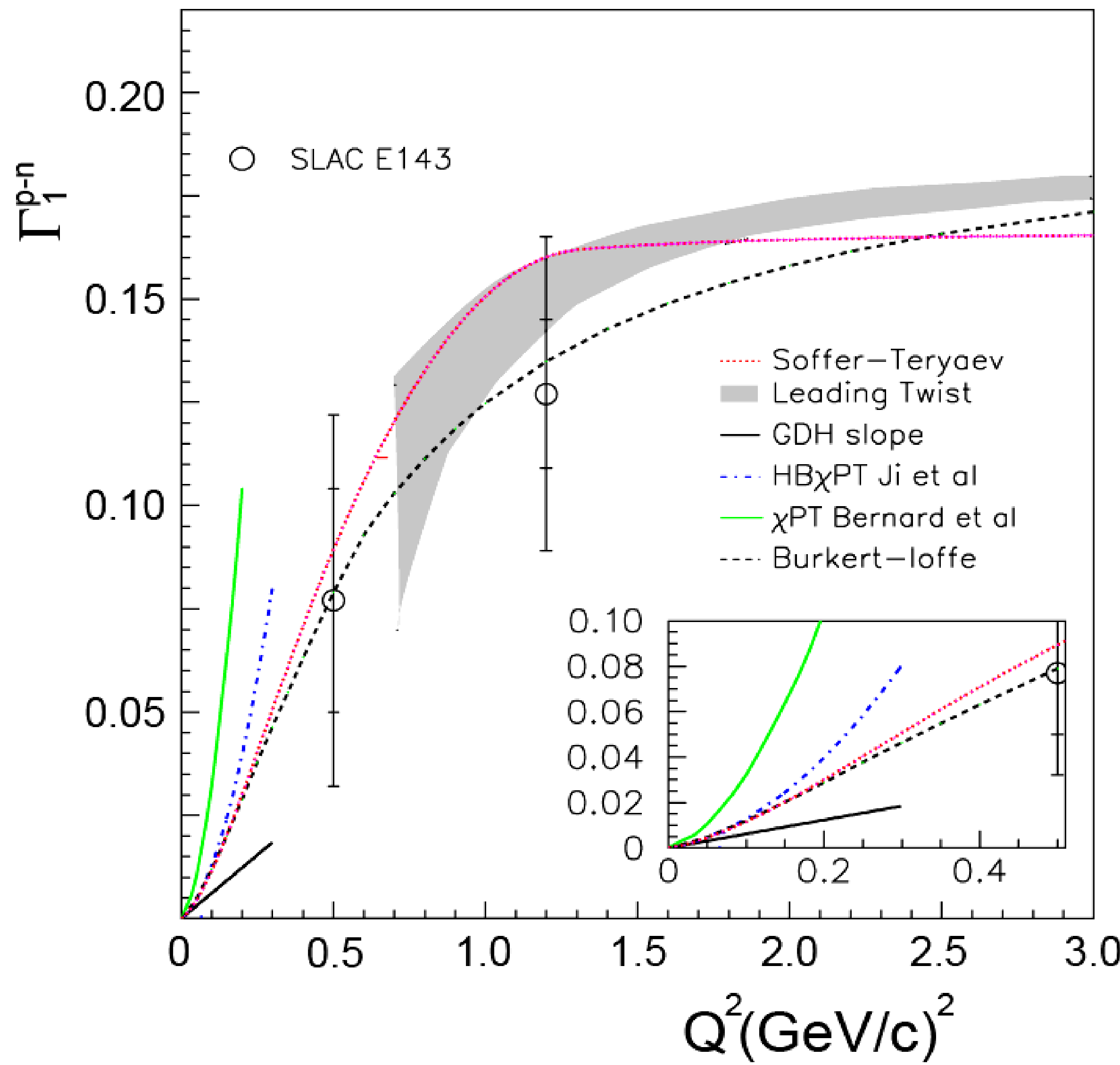


Expect rapid change of Γ_1 in transition from the hadronic to the partonic regimes.

"Zoom in" from tiny lenght scales (DIS) to large length scales

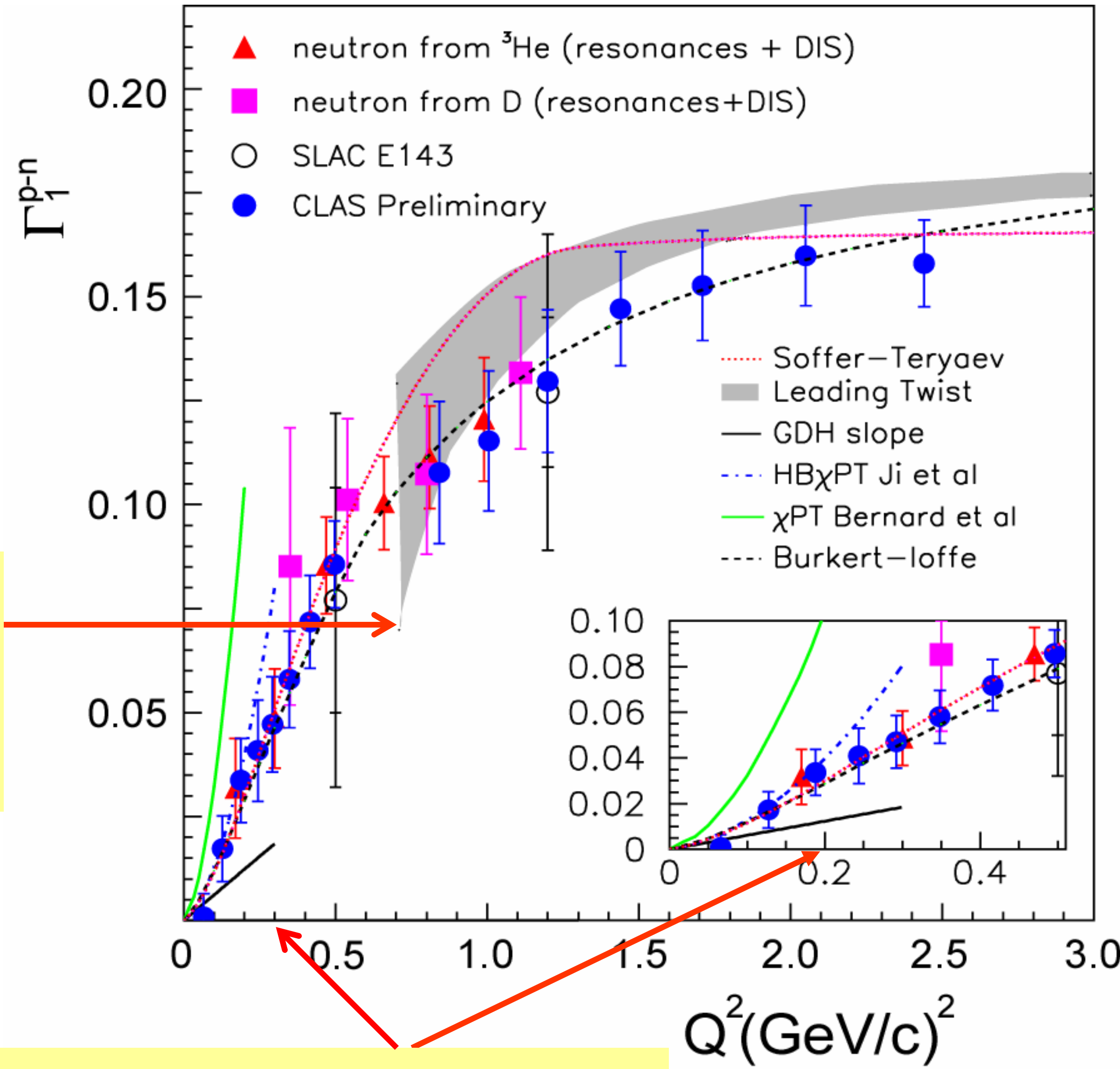
Bjorken Integral Γ_1^{p-n} (pre-JLab)

Impressive set of data at larger Q^2 (not shown) validates Bjorken Sum Rule to ~10-15%.



Bjorken Integral Γ_1^{p-n} (today)

Hall B ***Hall A***



- Operator Product Expansion description works surprisingly well for $Q^2 > 0.7\ GeV^2$.

- HBχPT compatible for $Q^2 < 0.2\ GeV^2$

The Spin Structure of the Proton

Proton helicity sum rule:

$$\boxed{\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g}$$

~ 0.3

Small?

? Large ?

The Impact of Quark and Gluon Motion on the Nucleon Spin

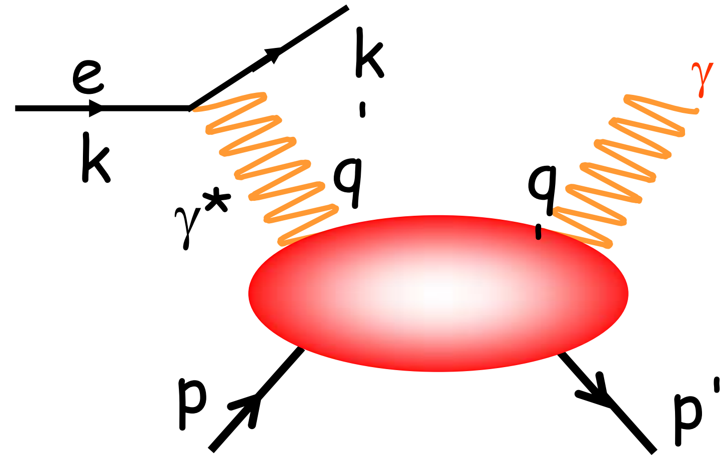
"TMDs and GPDs"

Generalized Parton Distributions and Nucleon Tomography

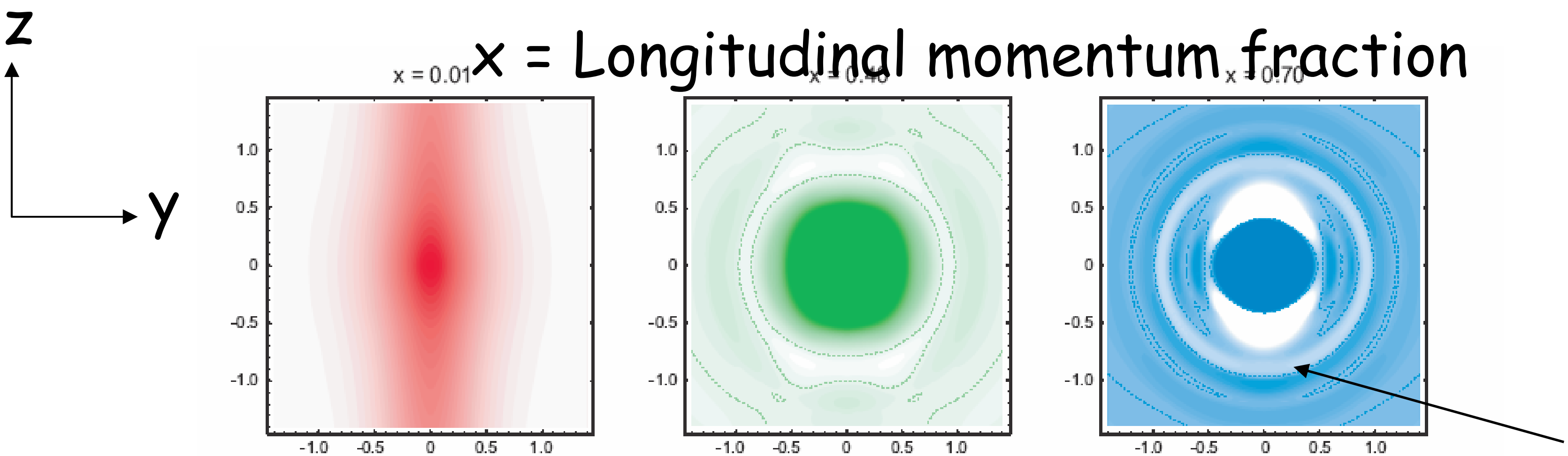
Accessible through (Deep) Exclusive Reactions

A Major new direction in Hadron Physics aimed at the 3-D mapping of the quark structure of the nucleon.

Simplest process:
Deep-Virtual Compton Scattering



x = Longitudinal momentum fraction



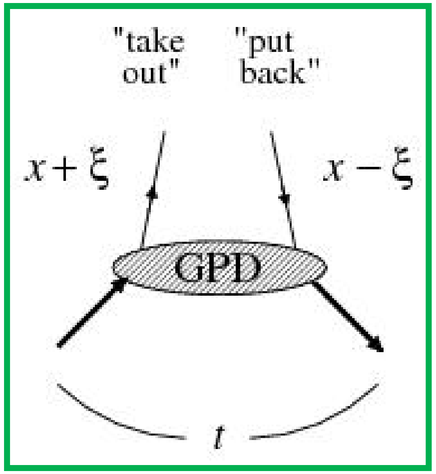
interference pattern

Charge density distributions for u-quarks

3D image is obtained by rotation around the z-axis

What's the use of GPDs?

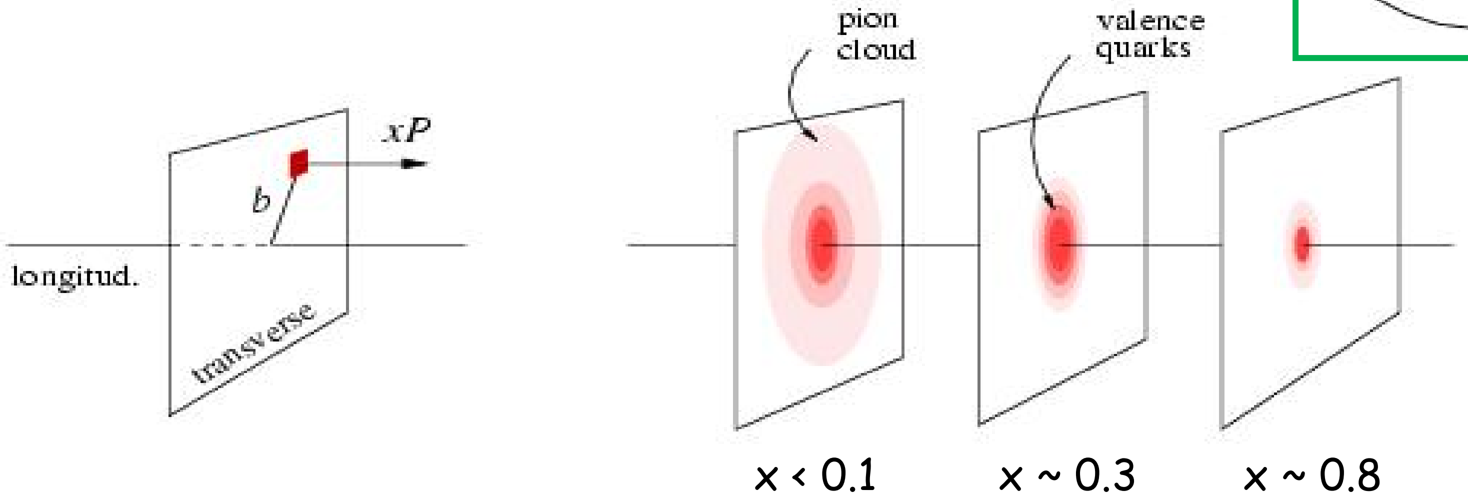
1. Allows for a unified description of form factors and parton distributions



2. Describe correlations of quarks/gluons

3. Allows for Transverse Imaging

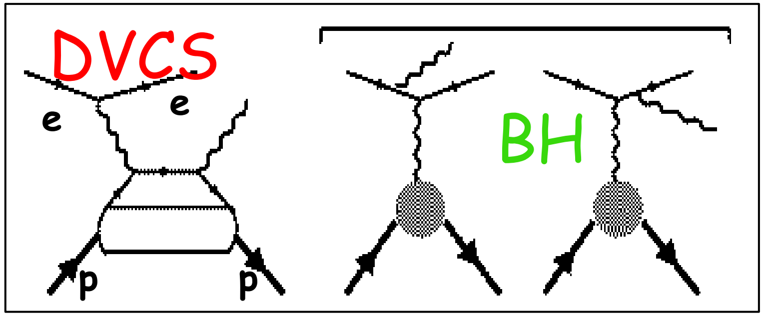
Fourier transform in momentum transfer



gives transverse spatial distribution of quark (parton) with momentum fraction x

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

Accessing GPDs through DVCS



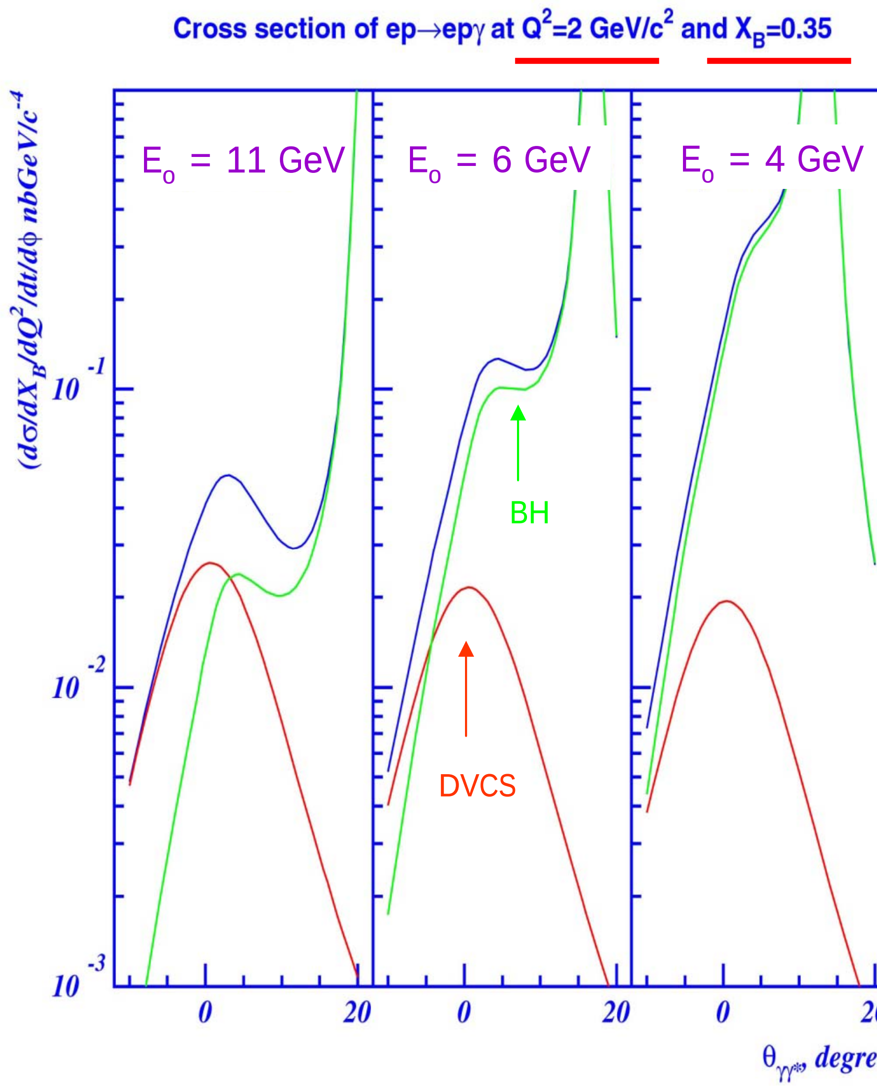
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |T^{DVCS} + T^{BH}|^2$$

T^{BH}: given by elastic form factors F_1, F_2

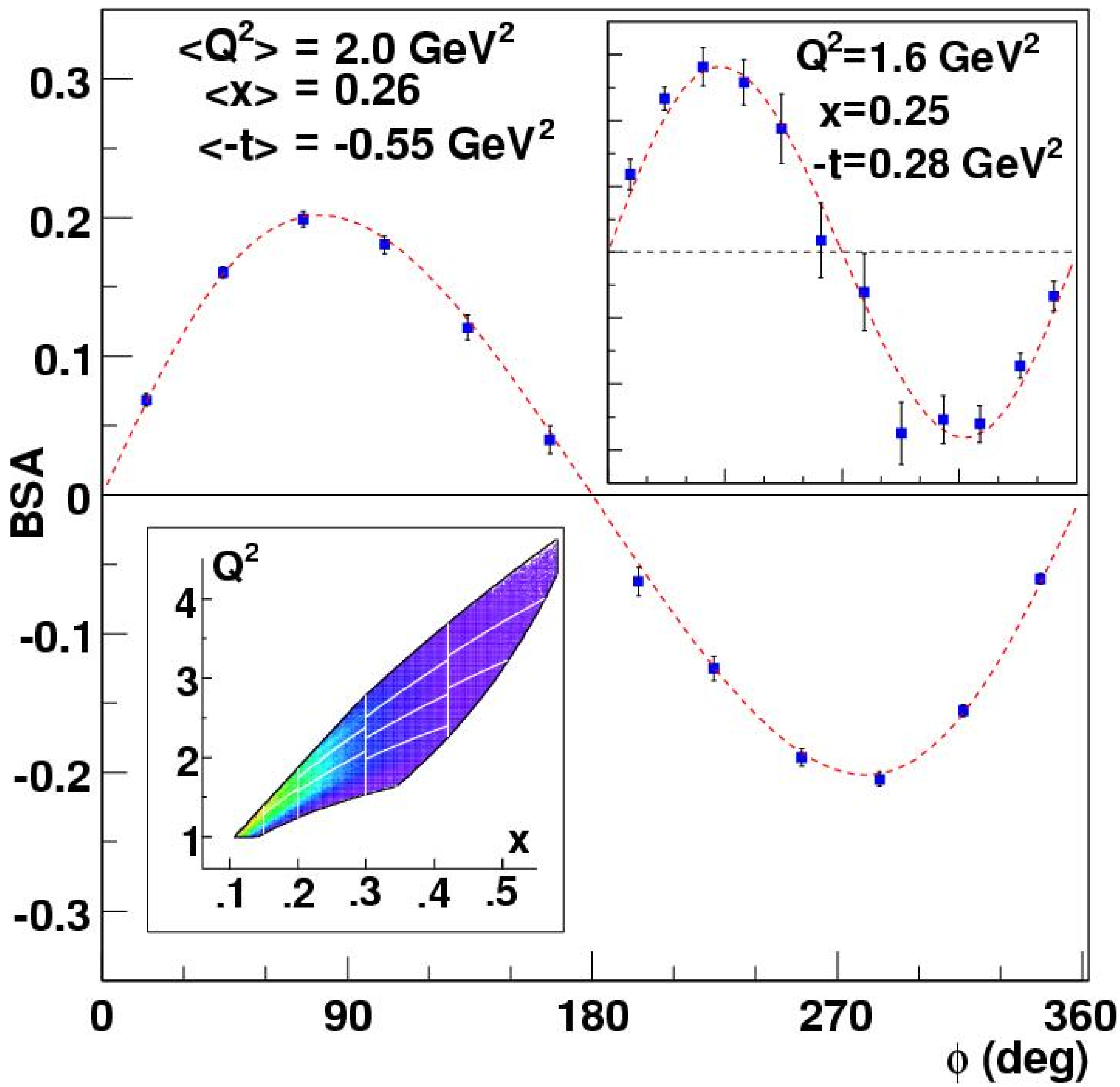
T^{DVCS}: determined by GPDs

$$\boxed{I \sim (T^{BH})\mathrm{Im}(T^{DVCS})}$$

BH-DVCS interference generates *beam and target polarization asymmetries* that carry the proton structure information. → **Transverse size of quark (parton) with longitudinal momentum fraction x**



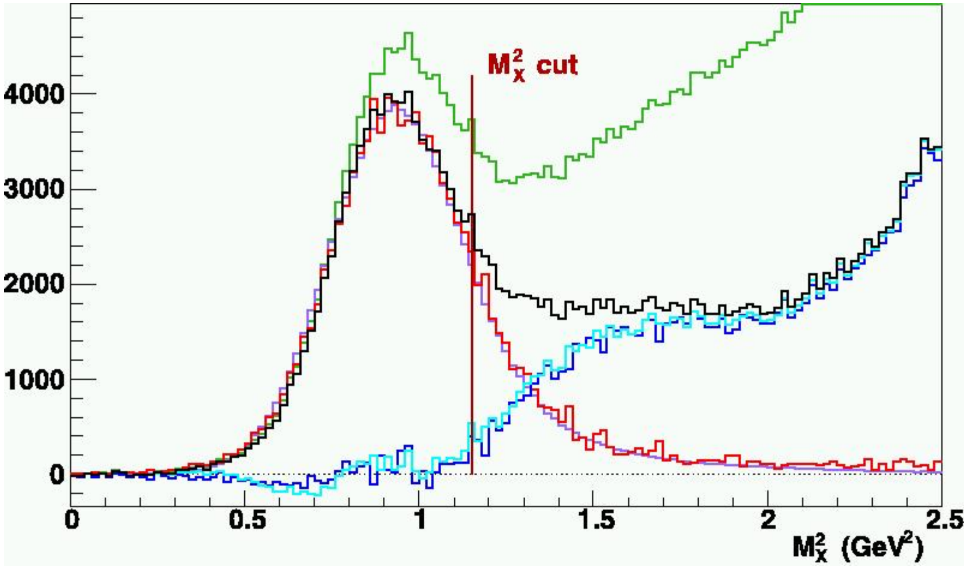
Next Round of DVCS Experiments: Hall B

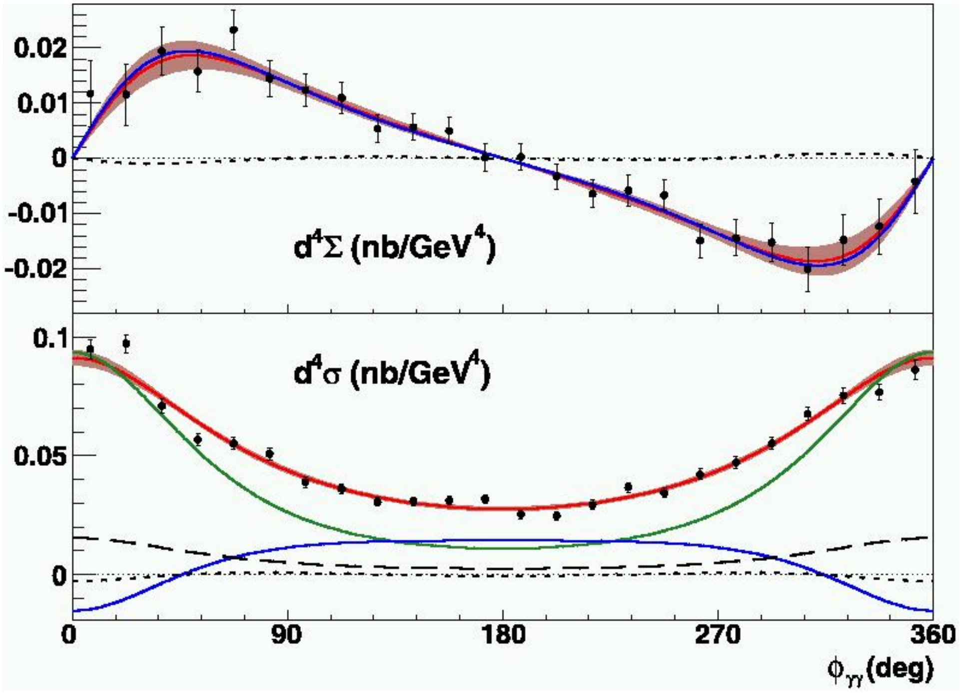


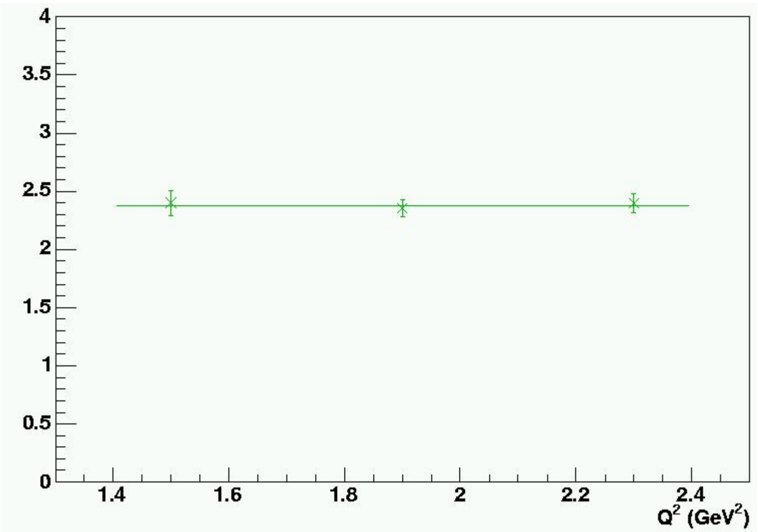
Range in (x,Q^2,t)

Next Round of DVCS Experiments: Hall A

- First explicit demonstration of exclusivity in the DVCS reaction, due to excellent missing-mass resolution.
- For a selected bin in Q^2 and t, the helicity-dependent (top) and helicity-independent (bottom) cross sections, compared with the twist-2 (blue, long-dashed) and twist-3 (dotted) contributions.
- Q^2-variation of the twist-2 term
  → indication of scaling







Next Round of DVCS Experiments: Hall B

Asymmetries, $0.4 < -t < 0.6$ GeV^2

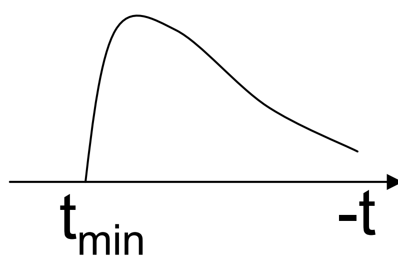
$\alpha = A_{LU}(90)$ as a function of t

Target Unpolarized
Beam Longitudinally Polarized

- Φ distributions compatible with (leading-twist) parameterization

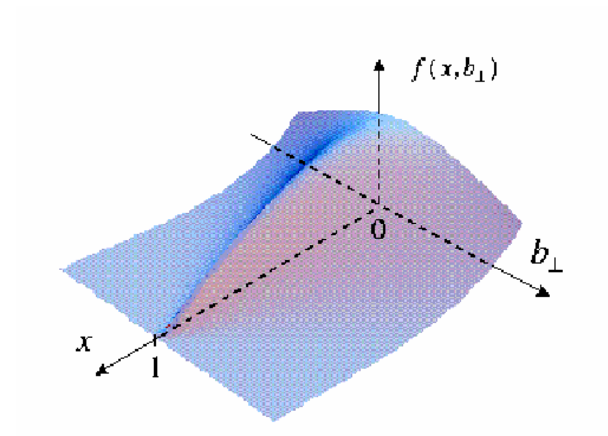
$$A(\phi) = \frac{\alpha \sin\phi}{1 + \beta \cos\phi}$$

- $\alpha = A_{LU}(90)$



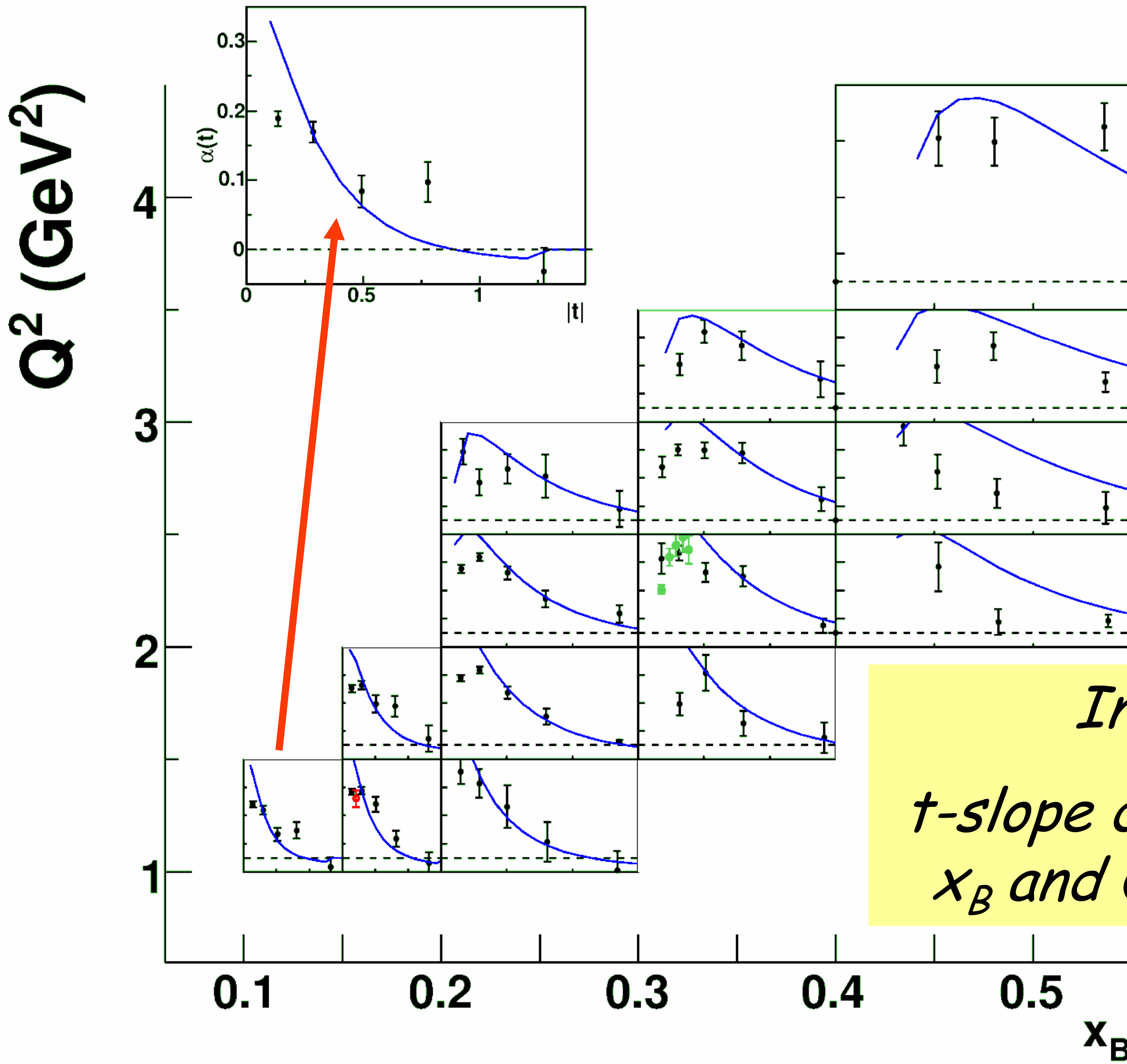
t-slope decreases as x_B and Q^2 increase

- Comparison to Vanderhaeghen, Guichon, Guidal GPD Model Calculation →



Next Round of DVCS Experiments: Hall B

$\alpha = A_{LU}(90)$ as a function of t



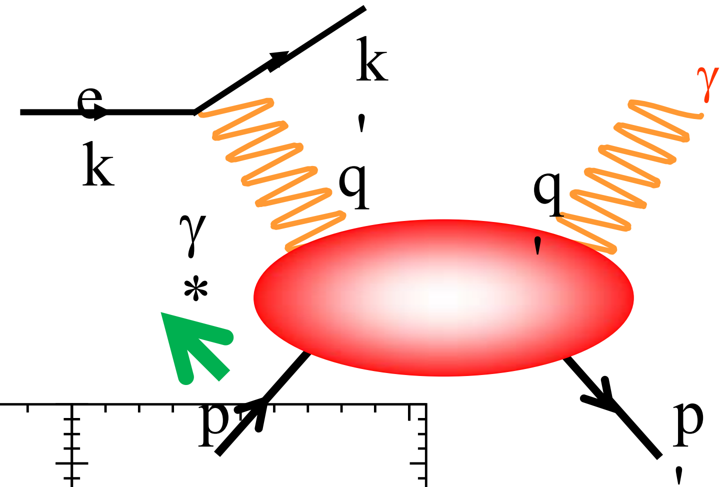
Indeed:

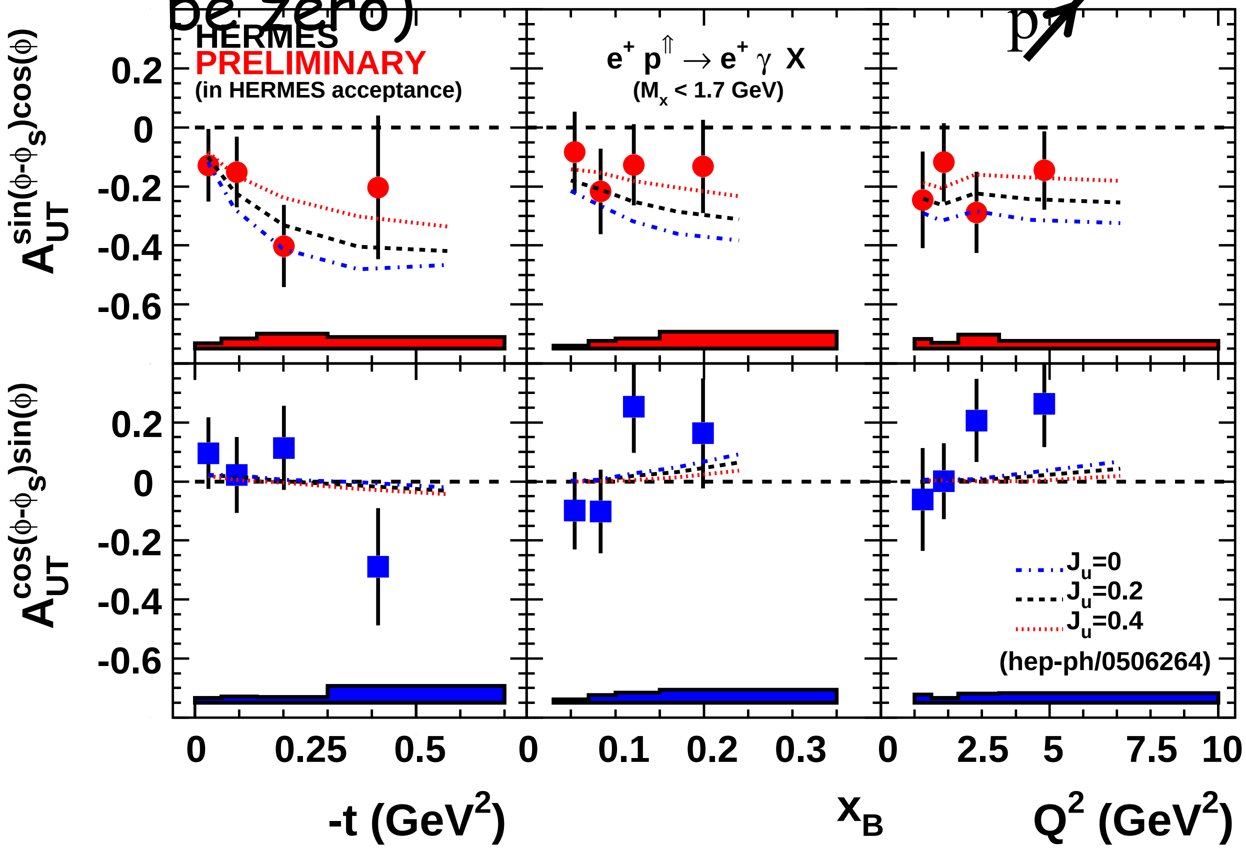
t-slope decreases as x_B and Q^2 increase

Next Round of DVCS Experiments: HERMES

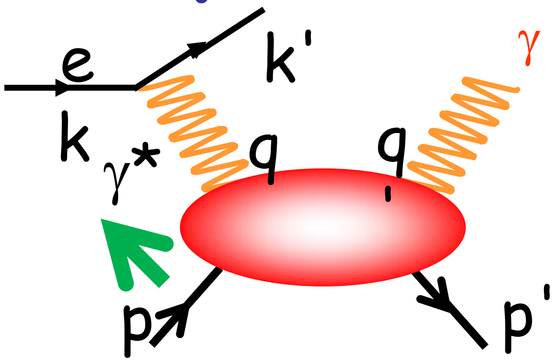
DVCS: "TTSA"

First model-dependent extraction of J_u possible (J_d assumed to be zero)





orbital angular momentum carried by quarks : solving the spin puzzle



At one value of x only

Ingredients:

1) GPD Modeling

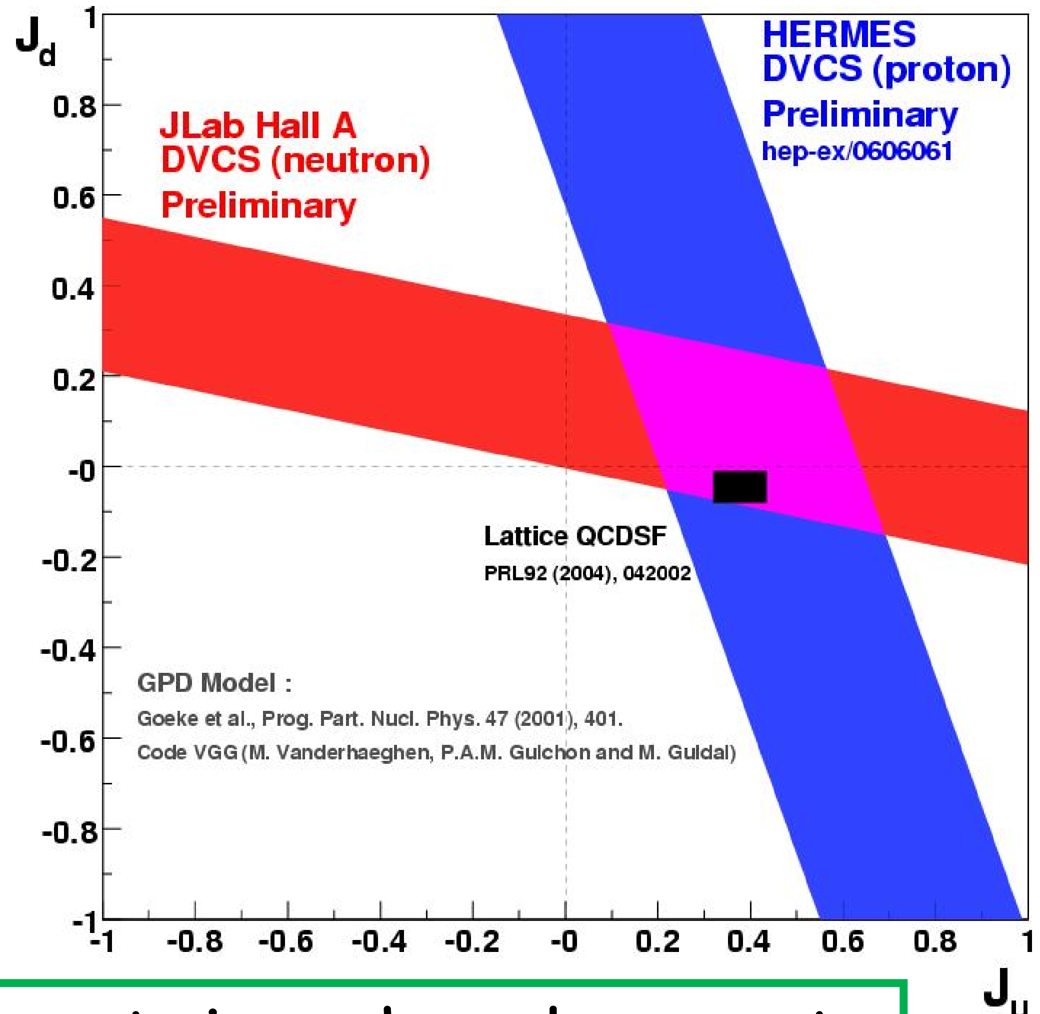
2) HERMES $^{1}H(e,e'\gamma)p$

(transverse target spin asymmetry)

3) Hall A $^{2}H(e,e'\gamma n)p$

Or independent:

Lattice QCD!



→ Tremendous progress to constrain quark angular momenta

→ 12 GeV will give final answers for quarks

10 Years of Physics Experiments at JLab

- Experiments have successfully adressed original Mission Statement:

  "The study of the largely unexplored transition between the nucleon-meson and the quark-gluon descriptions of nuclear matter"

Highlight 1: The Role of Quarks in Nuclear Physics
Probing the Limits of the Traditional Model of Nuclei

- Emphasis has slowly shifted from Base Equipment Experiments to Experiments with dedicated/additional setups and/or detectors
- Emphasis has shifted to third sub-area of intended CEBAF research:

  "What are the properties of the force which binds quarks into nucleons and nuclei at distances where this force is strong and the quark confinement mechanism is important?"

- *Highlight 2: Charge and Magnetization in Nucleons and Pions*

Charge distribution in proton differs from magnetization distribution
Elusive charge distribution of neutron well mapped out to high resolution
Strange quarks play <5% role in mass of proton → unsolved mysteries…

- *Highlight 3: The Onset of the Parton Model at Low Energies*

High quality hadronic structure function data at JLab at 6 GeV have been accumulated spanning the nucleon resonance and low-W^2 deep inelastic region. The data indicate a surprisingly smooth parton-hadron transition at relatively low Q^2, allowing, for $x > 0.1$, an unprecedented access to Parton Model physics with the 12 GeV Upgrade