Nucleon Structure at Jefferson Lab
I) the 6 GeV findings

Rolf Ent, 12th HANUC Lecture Week, Mar. 25, 2009

- 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

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

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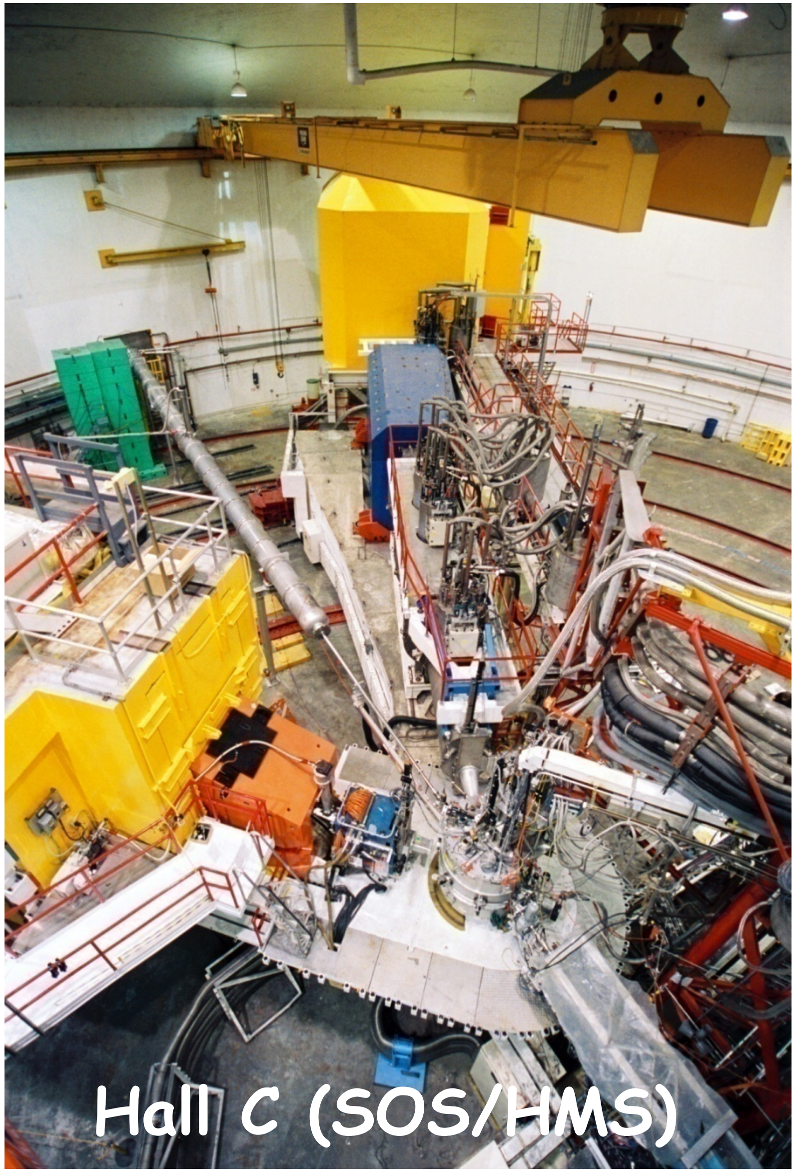
Pushing the Limits of the Standard Model of Nuclear Physics

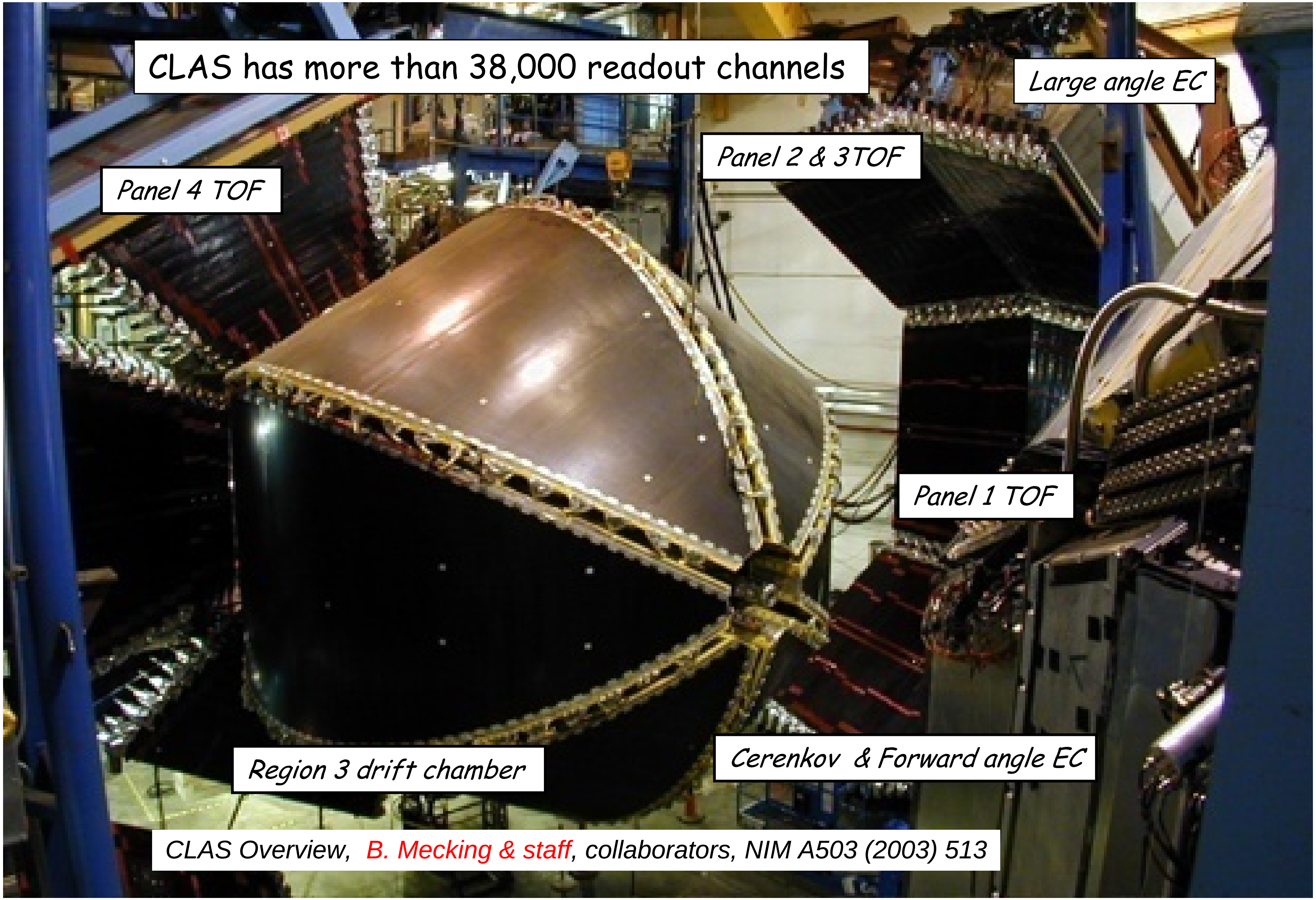
- **What are the properties of the force which binds quarks into nucleons and nuclei at distances where this force is strong and the quark confinement mechanism is important?**

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

Halls A/B/C Base Equipment

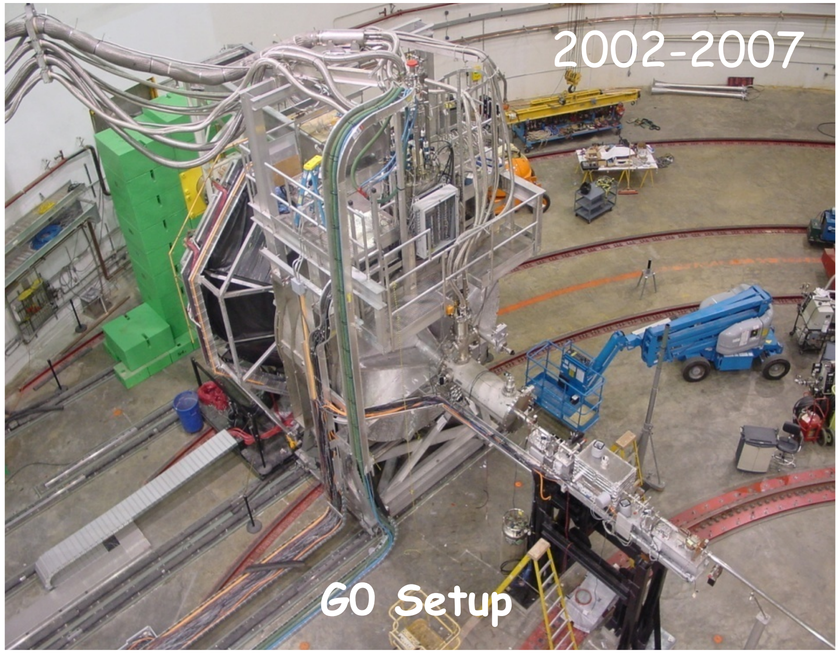


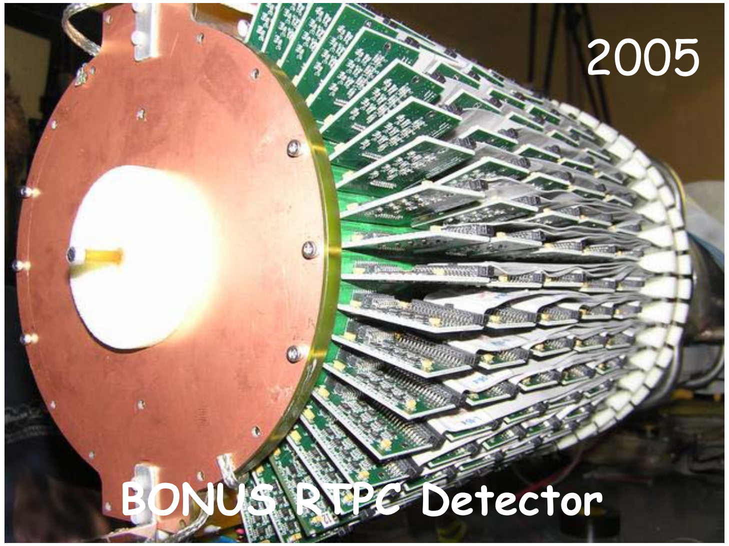
Hall B - *CLAS* (forward carriage and side clamshells retracted)

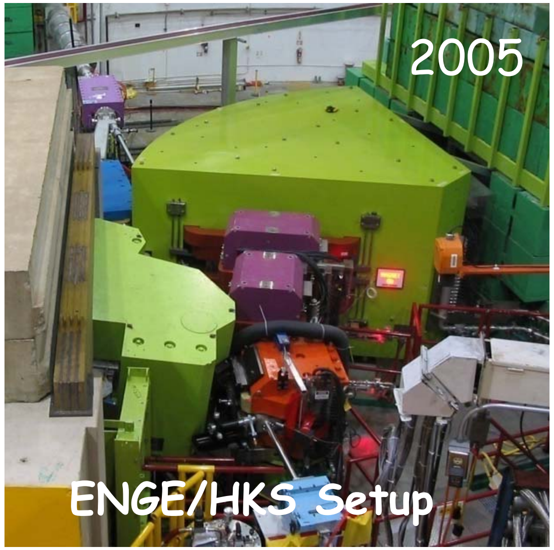


CLAS Overview, B. Mecking & staff, collaborators, NIM A503 (2003) 513

Ancillary Equipment and Experiment-Specific Apparatus







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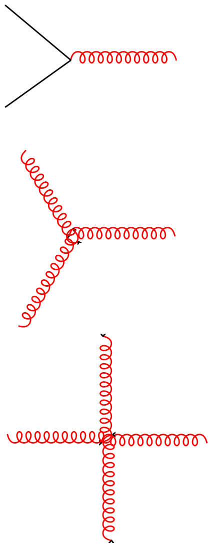
The Onset of the Parton Model

QCD and Nuclei

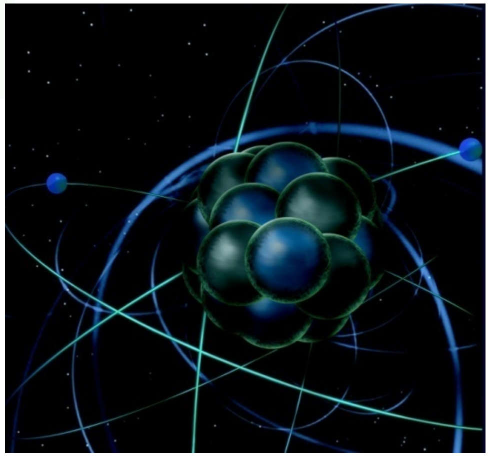
Gluons mediate the strong (color) force, just like photons mediate the electromagnetic force, but … gluons interact with themselves … which gives QCD unique properties



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

$$F^a_{\mu\nu} \equiv \delta_\mu A^a_\nu - \delta_\nu A^a_\mu - g f^{abc} A^b_\mu A^c_\nu$$

$$D_\mu \equiv \delta_\mu + igA^a_\mu \frac{\lambda_a}{2}$$



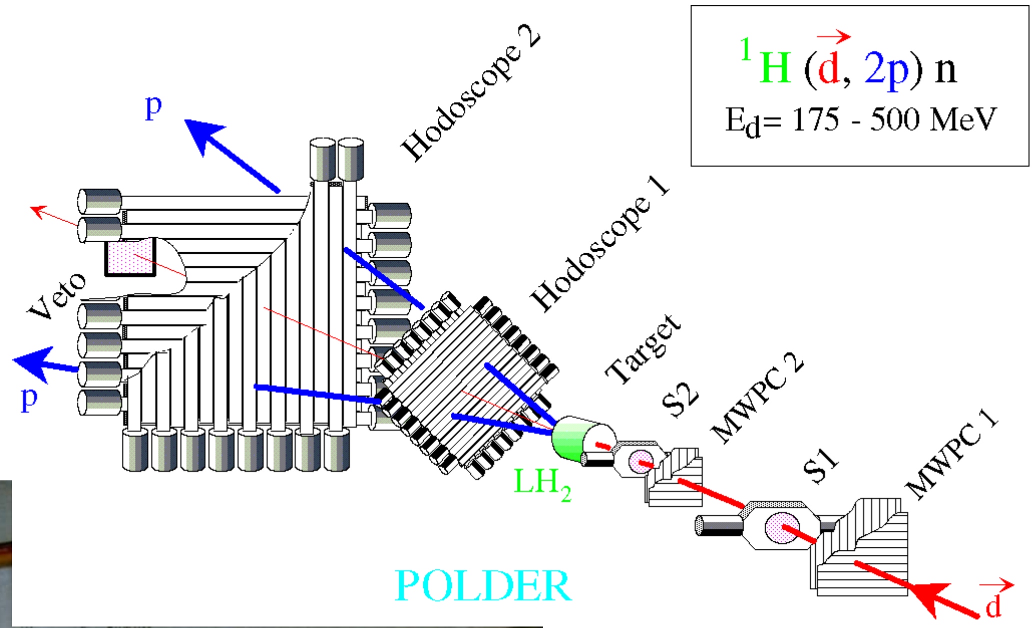
<u>QCD Lagrangian: quarks and gluons</u>

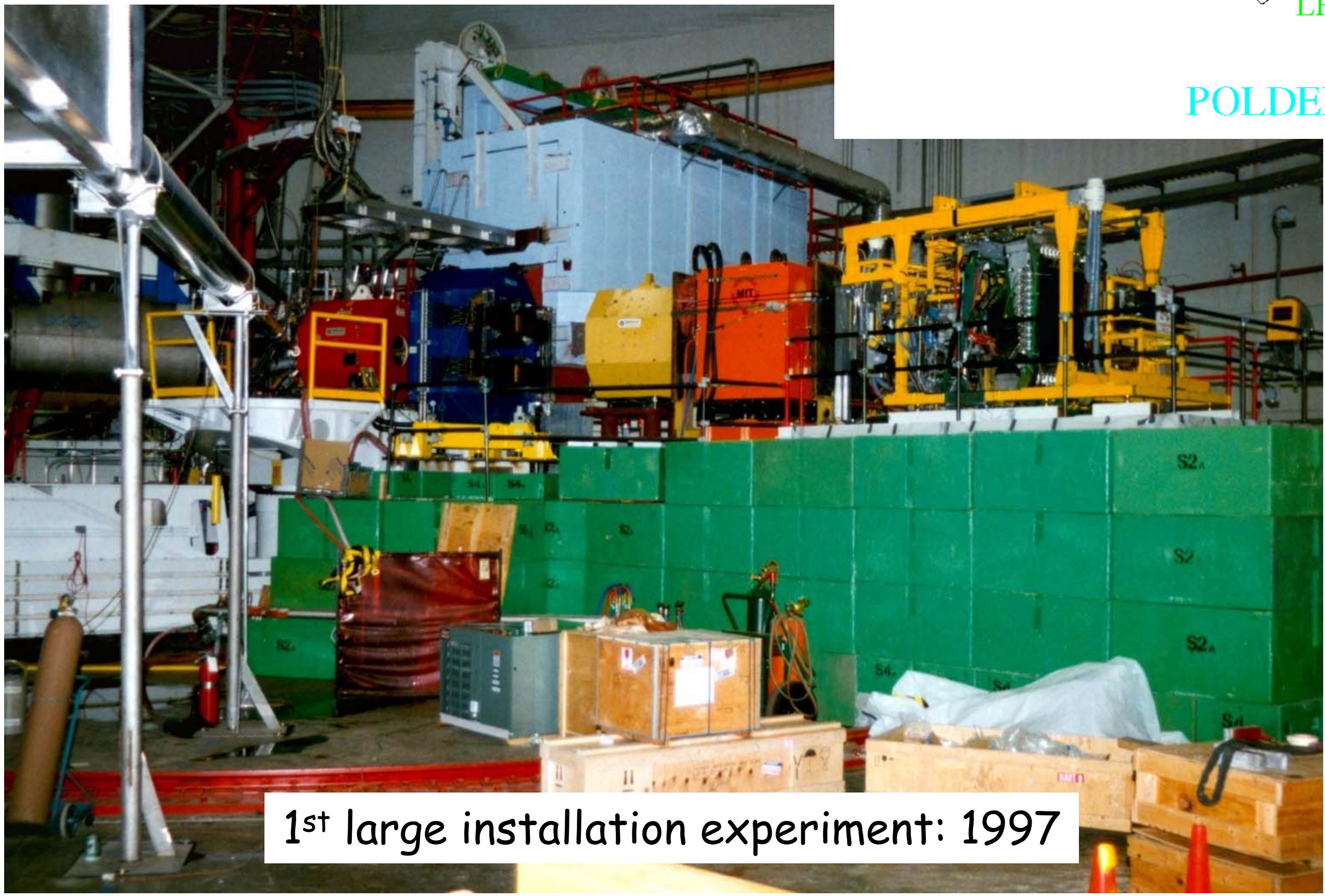
Nuclear Physics Model is an effective (but highly successful!) model using free nucleons and mesons as degrees of freedom.

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

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

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

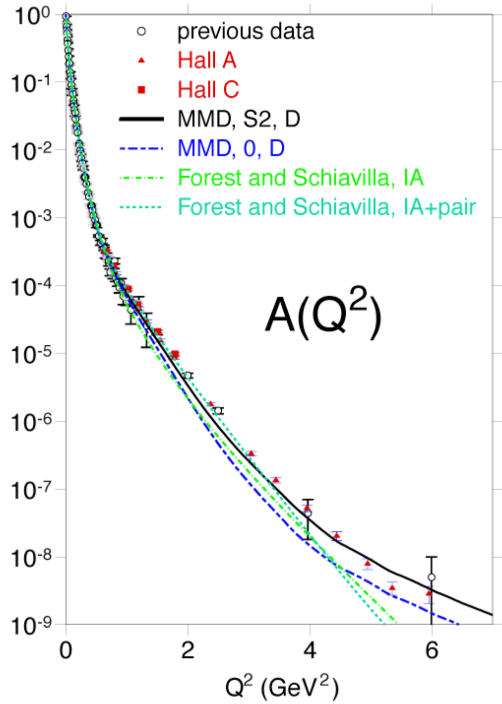


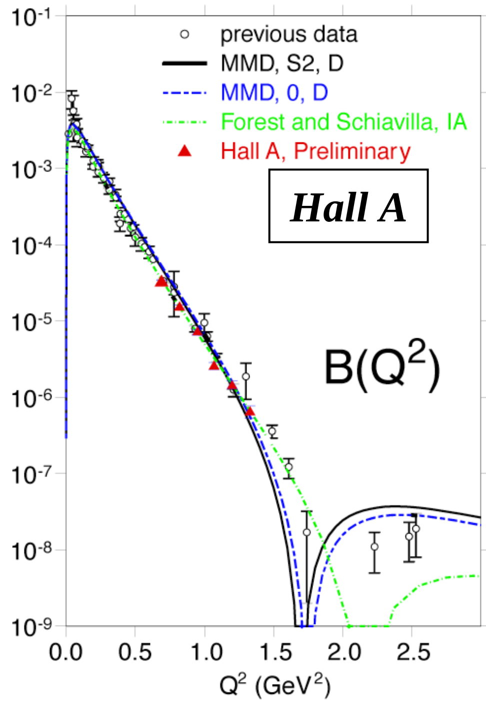


1st large installation experiment: 1997

"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:

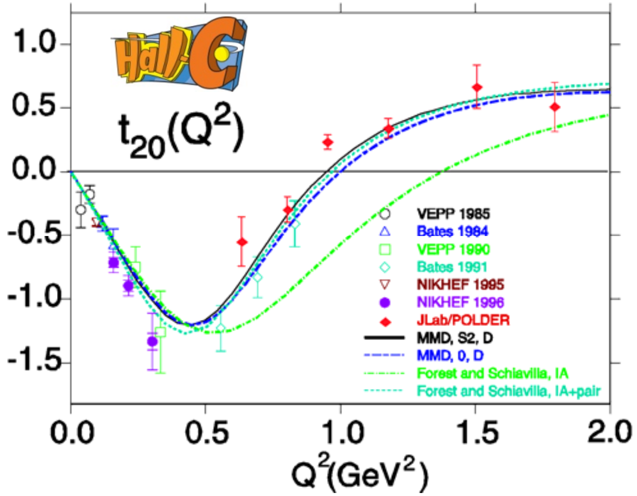
$$\frac{d\sigma}{d\Omega} = \sigma_M \left[A + B \tan^2 \frac{\theta}{2}\right]$$

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

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

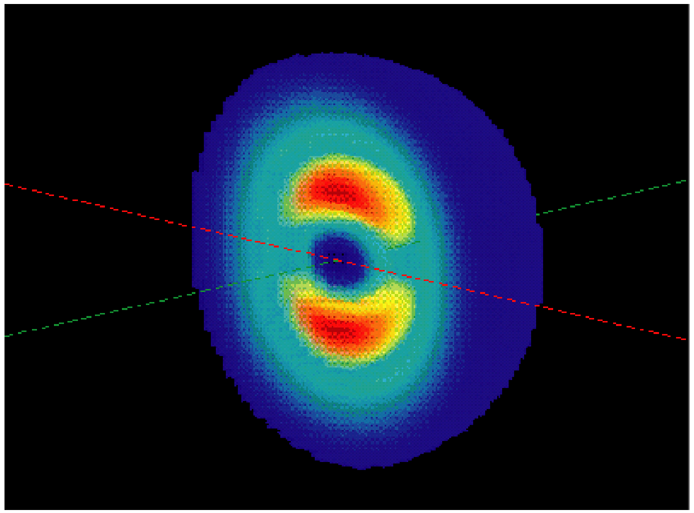
- 3rd observable needed to separate G_C and G_Q

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



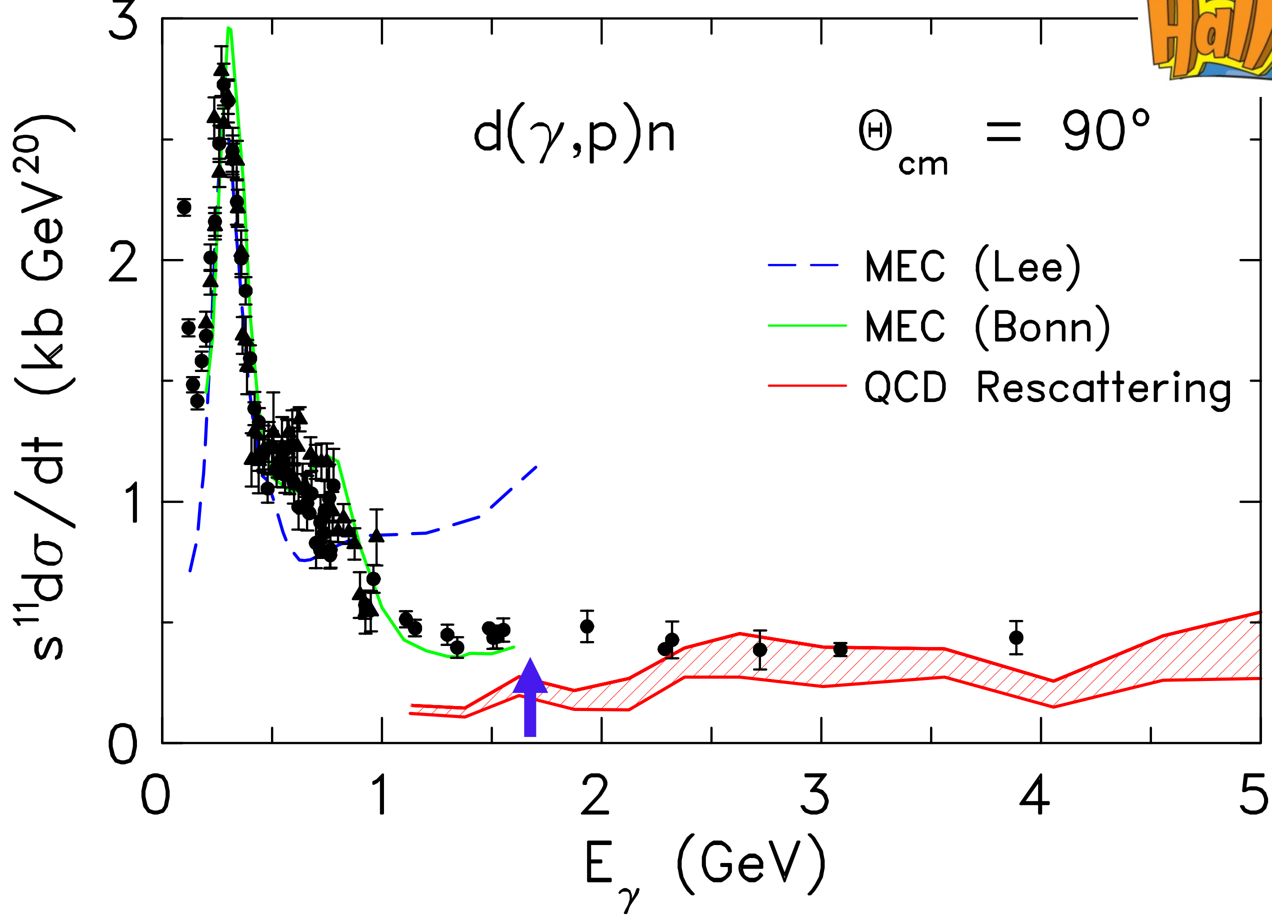
Combined Data -> Deuteron's Intrinsic Shape

The nucleon-based description works down to < 0.5 fm



Is there a Limit for Meson-Baryon Models?

Not really but …



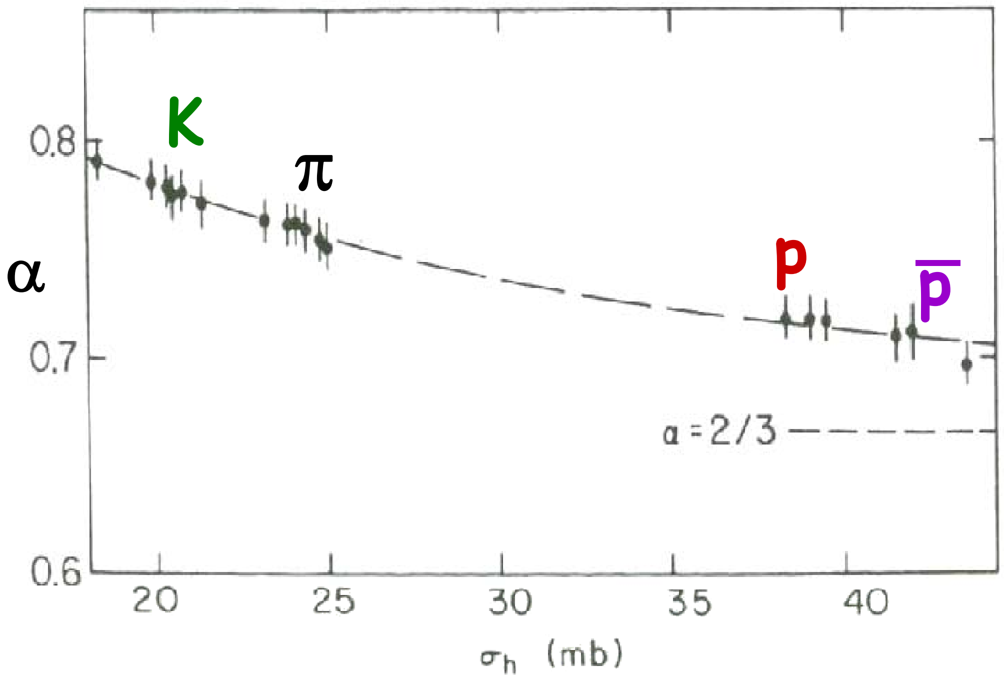
… there might be a more economical QCD description.

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

quark-gluon description
sets

Use the Nuclear Arena to Study QCD

Total Hadron-Nucleus Cross Sections



Hadron- Nucleus
total cross section

Fit to $\sigma(A) = \sigma_0 A^{\alpha}$

Hadron momentum
60, 200, 250 GeV/c

α = 0.72 - 0.78, for p, π, k

α < 1 interpreted as due to the strongly interacting nature of the probe

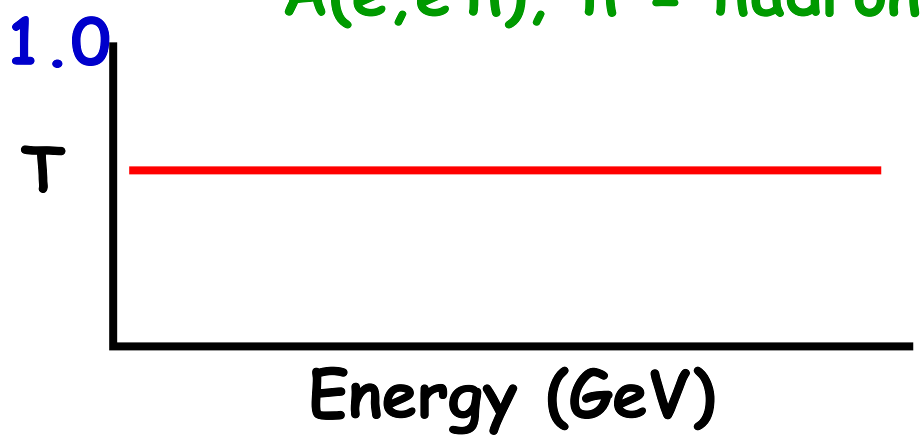
A. S. Carroll *et al.* Phys. Lett 80B 319 (1979)

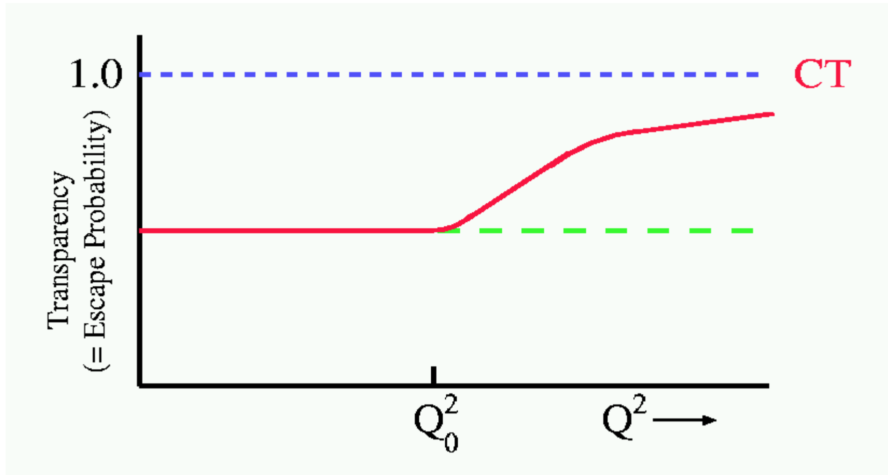
Physics of Nuclei: Color Transparency

Traditional nuclear physics expectation:
transparency nearly energy independent.

Quantum ChromoDynamics:

A(e,e'h), h = hadron





Ingredients

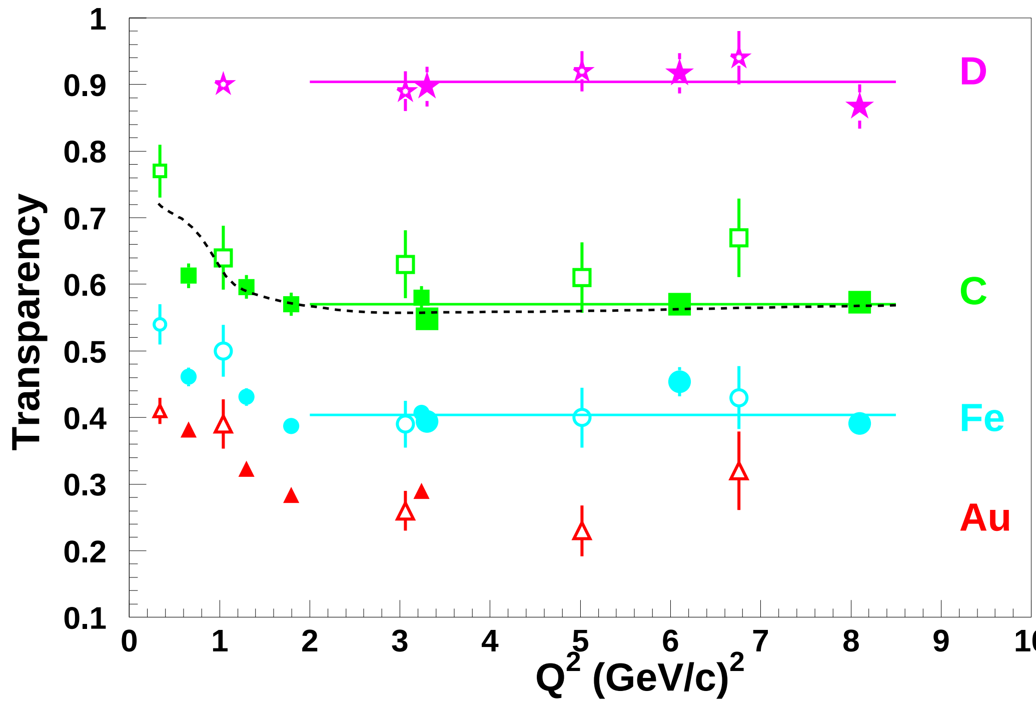
- σ_{hN} h-N cross-section
- Glauber multiple scattering approximation

(or better transport calculation!)

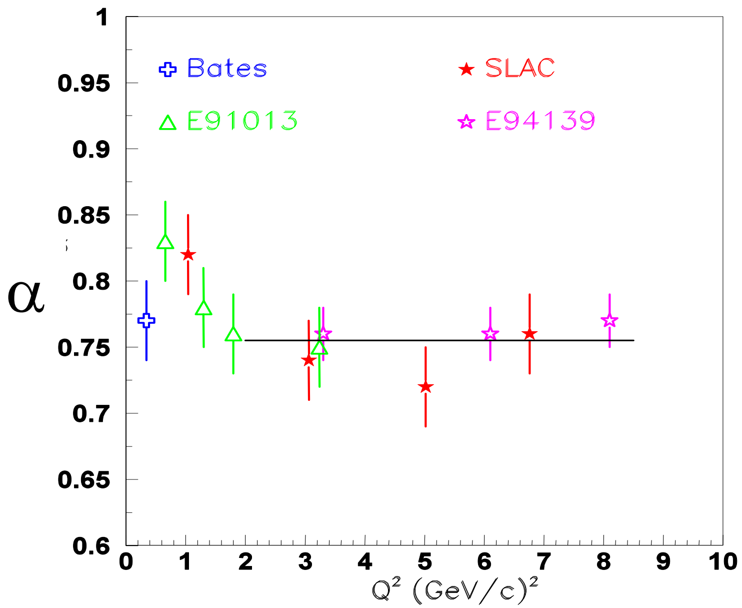
- Correlations & Final-State Interaction effects

From fundamental considerations (quantum mechanics, relativity, nature of the strong interaction) it is predicted (Brodsky, Mueller) that fast protons scattered from the nucleus will have decreased final state interactions

Search for Color Transparency in Quasi-free A(e,e'p) Scattering



Fit to $\sigma = \sigma_o A^\alpha$



Constant value line fits give good description:

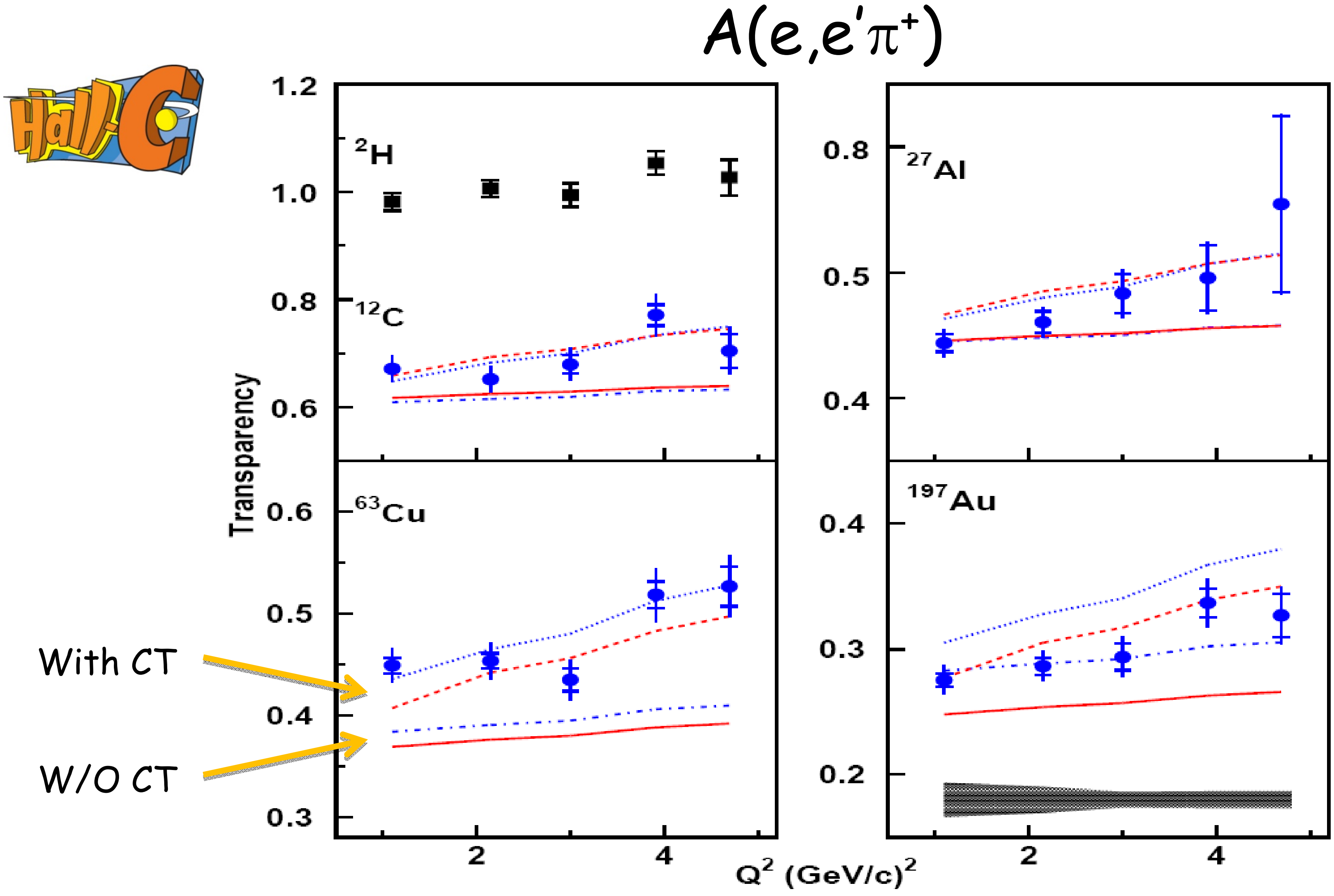
$$\chi^2/df = 1$$

Conventional Nuclear Physics Calculation by Pandharipande *et al.* (no sign of CT) also gives good description

α = constant = 0.75

Close to proton-nucleus total cross section data!

Physics of Nuclei: Color Transparency



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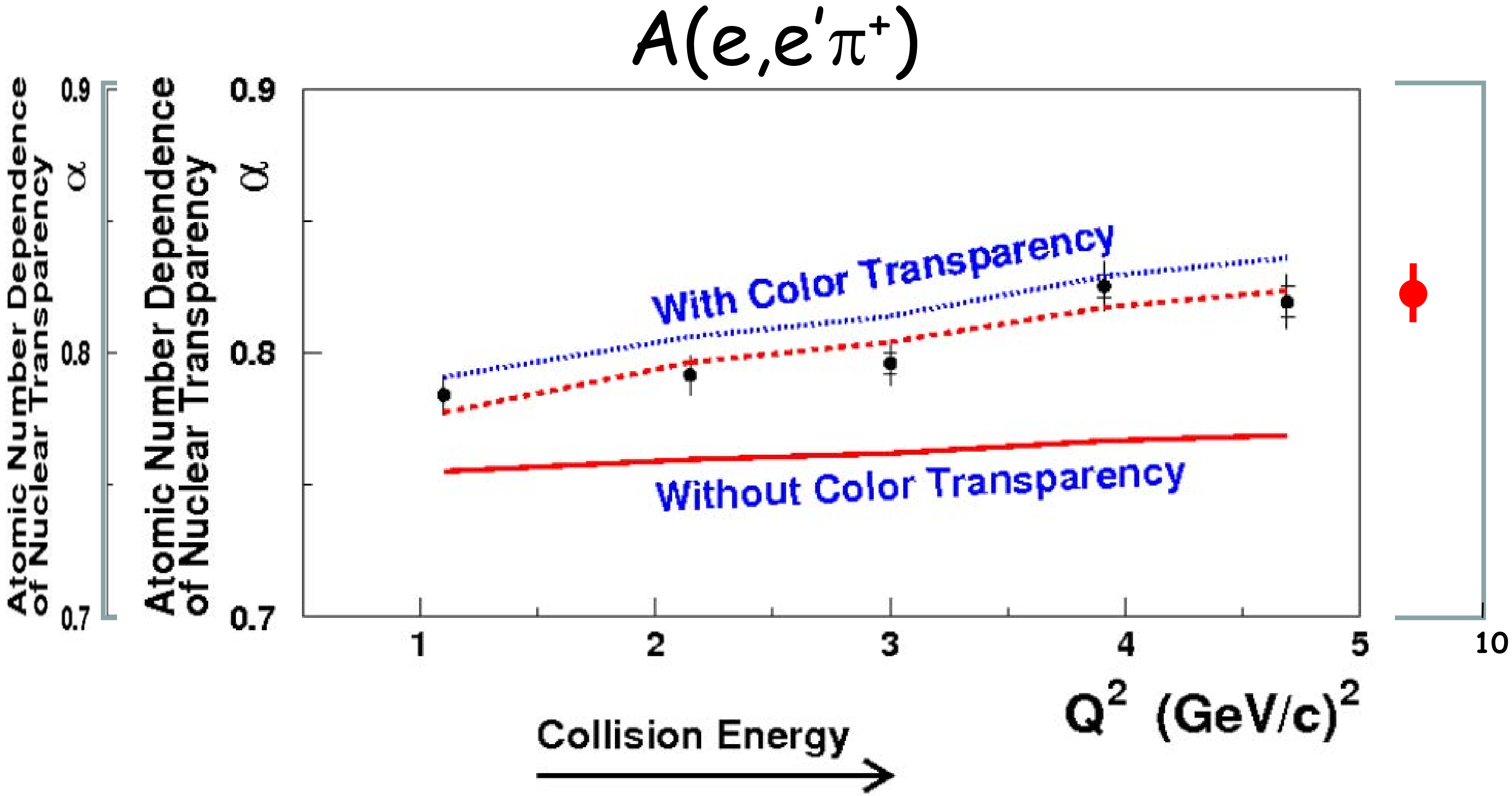

Total pion-nucleus cross section slowly disappears, or …
pion escape probability increases → Color Transparency?
→ Unique possibility to map out at 12 GeV (up to Q^2 = 10)

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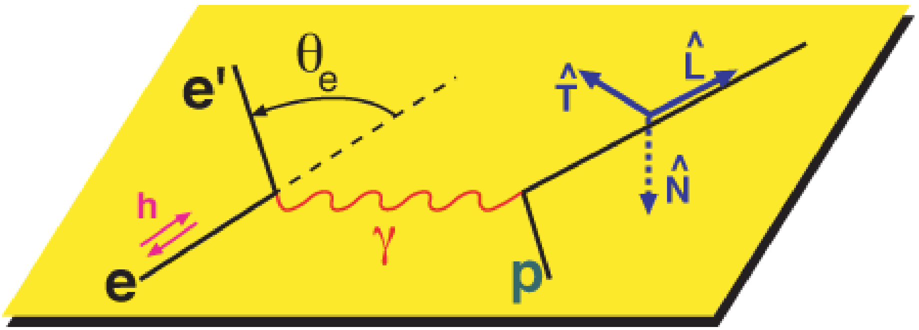
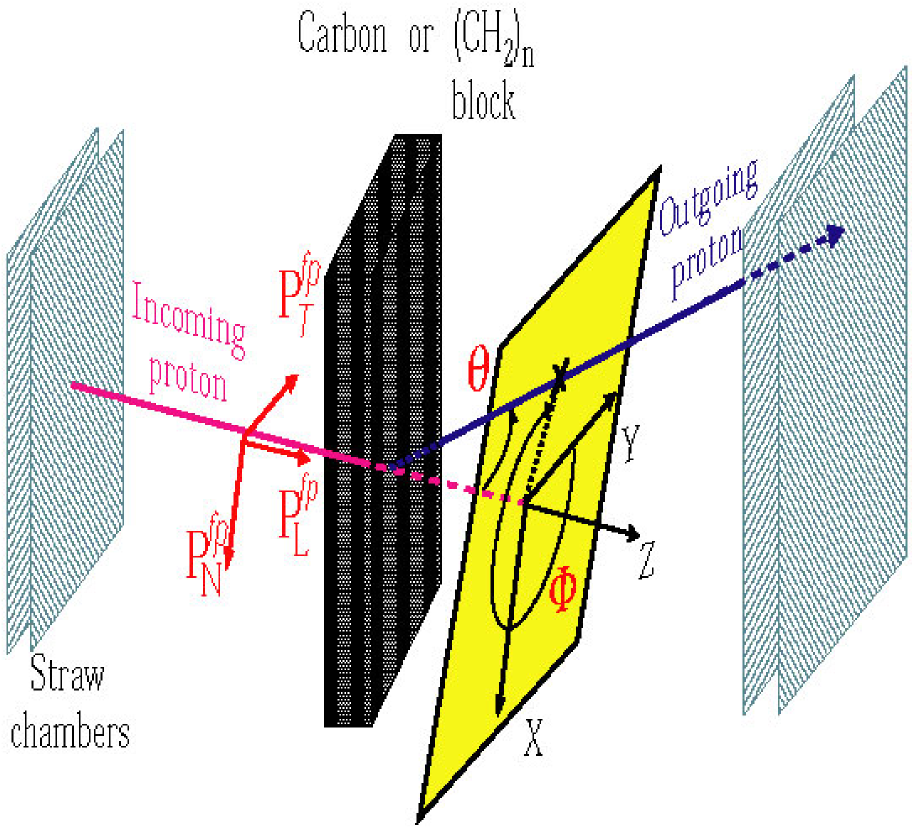
Revolutionized Polarized Beam Experiments!

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

Focal Plane Polarimeter



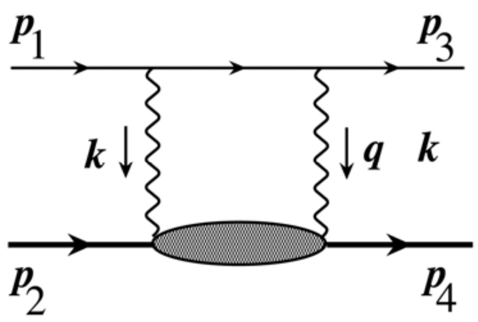
$$\frac{G_E}{G_M} = -\frac{P'_x}{P'_z}\frac{(E_i + E_f)}{2m}\tan\frac{\Theta_e}{2}$$

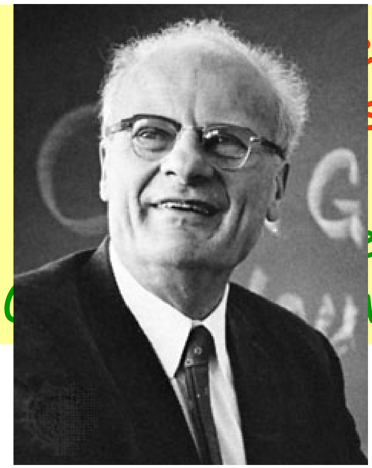


No error contributions from
- analyzing power
- beam polarimetry

Proton charge and magnetism in 2006

2-γ exchange important

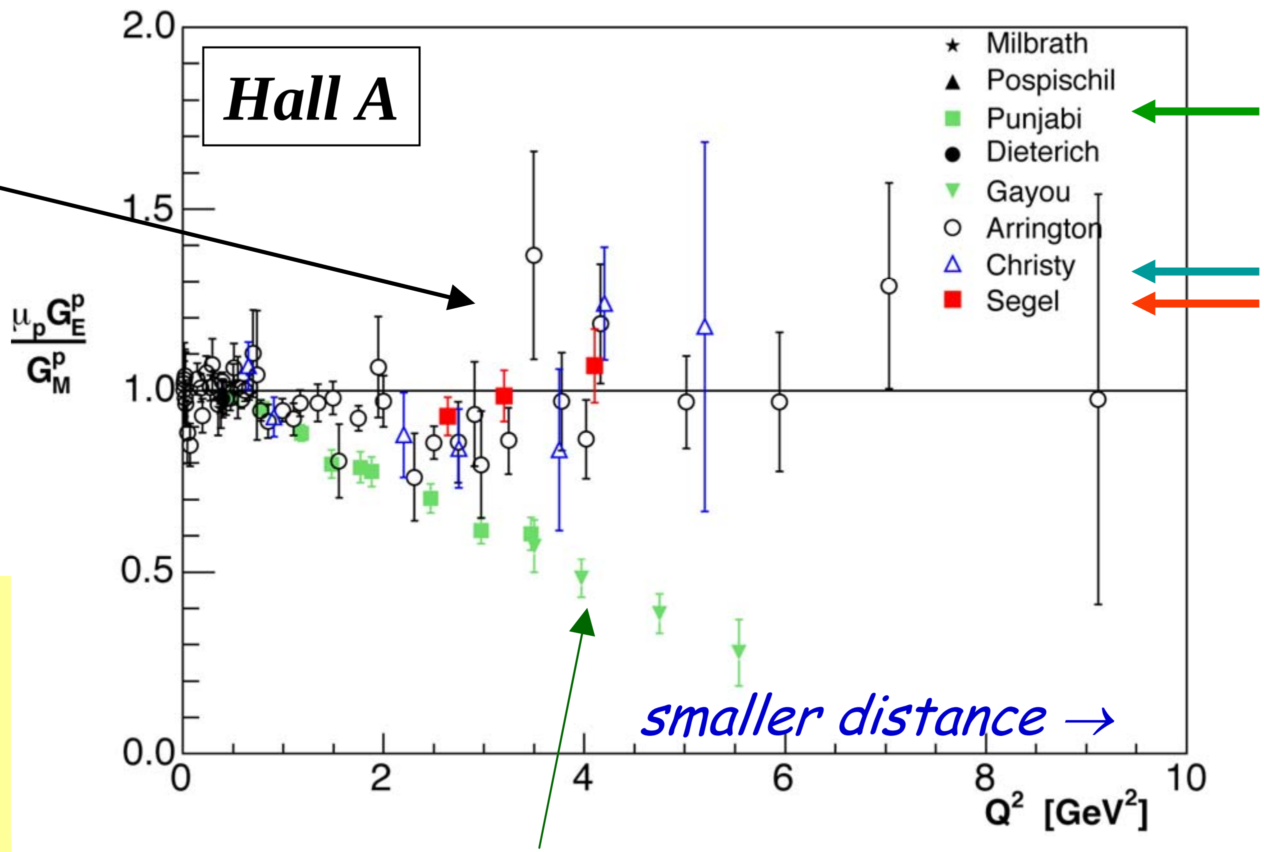




′ + p
stant

′ + $\vec{p}$
with Q^2

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



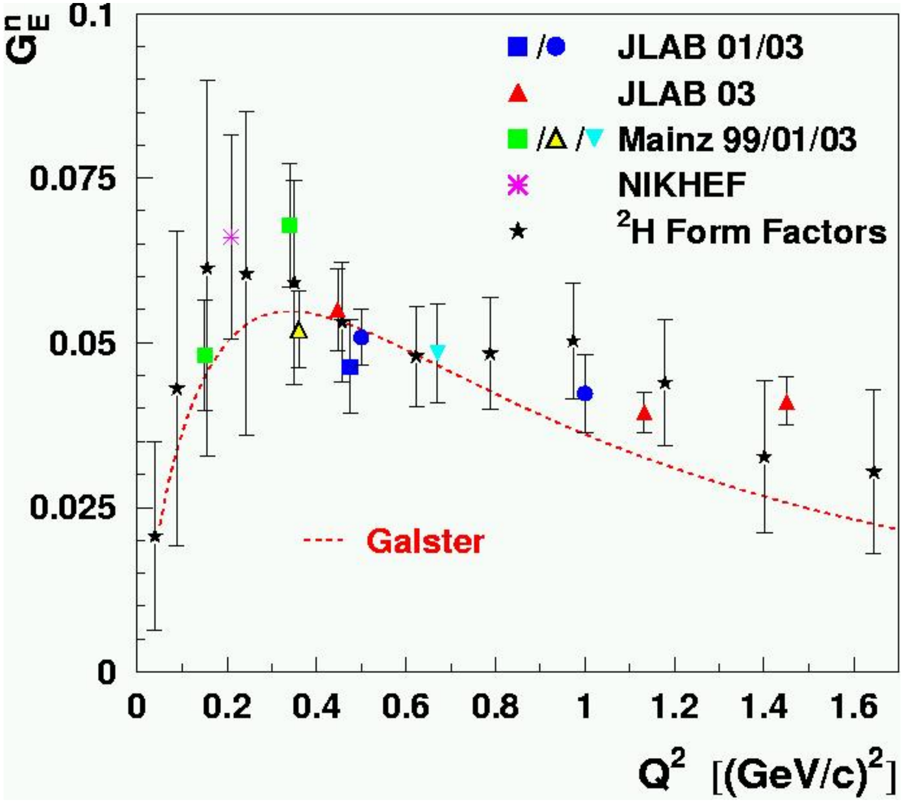
charge depletion in interior of proton

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

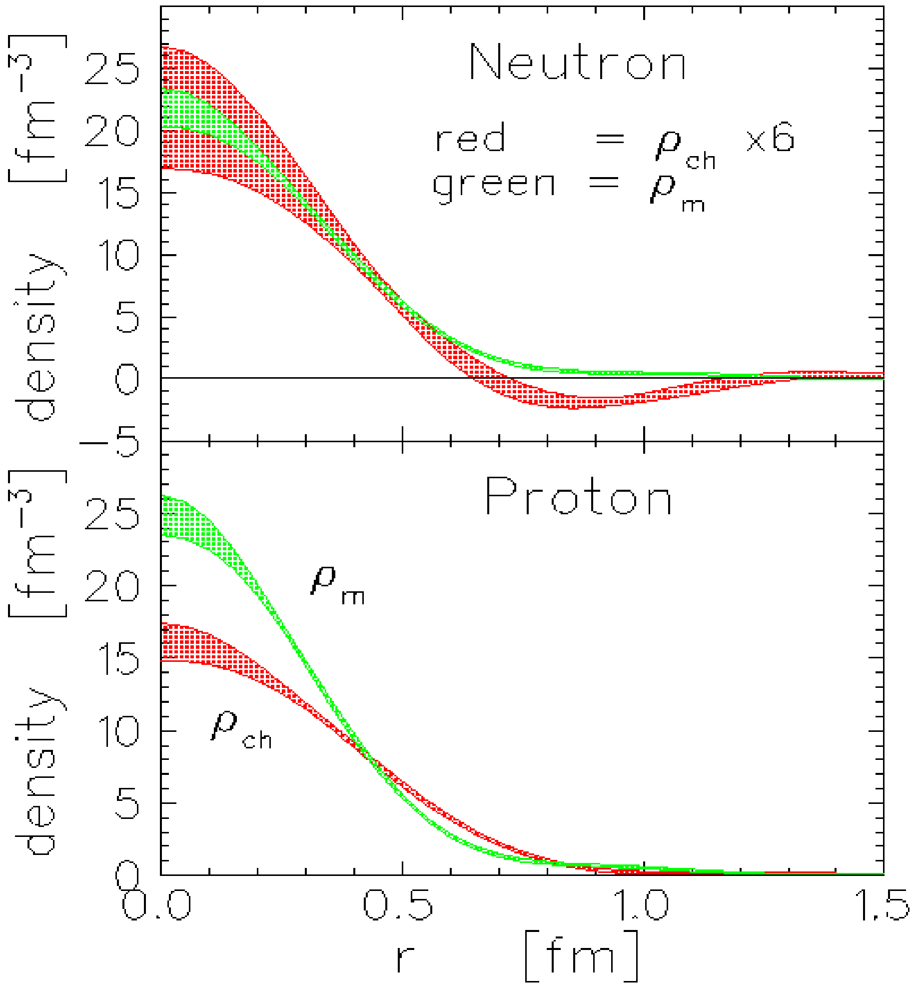
Hall A What about the neutron?

Neutron has no charge, but does have a charge distributions: n = p + π^-, n = ddu.
Use polarization and $^2H(e,e'n)$ 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

Hall B

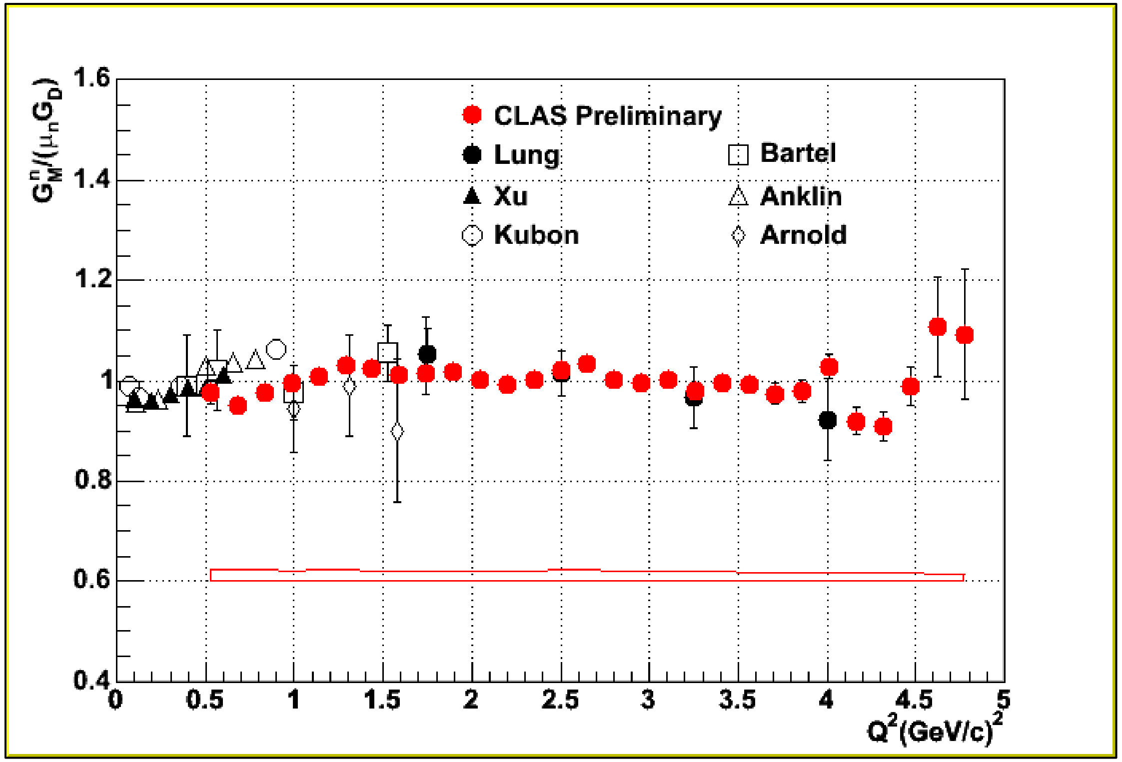
Magnetic Form Factor of the Neutron

CLAS

- Use dual target (hydrogen & deuterium)
- Measure simultaneously $e^2H \rightarrow enX$ and $e^2H \rightarrow epX$, as well as $ep \rightarrow e\pi^+n$ for in-situ calibration of neutron detection efficiency in CLAS EC and TOF.

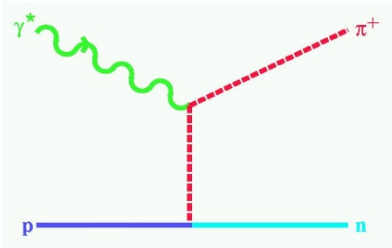
$$R_D = \frac{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'n)_{QE}]}{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'p)_{QE}]} = a \cdot R_{free}$$

$$= a \cdot \frac{\frac{(G_E^n)^2+\tau(G_M^n)^2}{1+\tau} + 2\tau(G_M^n)^2\tan^2(\frac{\theta}{2})}{\frac{(G_E^p)^2+\tau(G_M^p)^2}{1+\tau} + 2\tau(G_M^p)^2\tan^2(\frac{\theta}{2})}$$

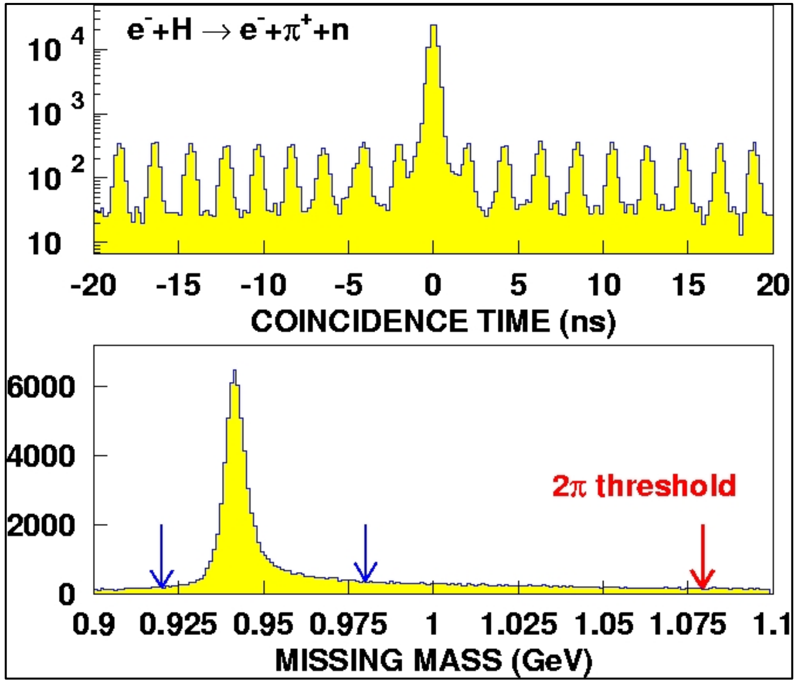


Pion's charge distribution

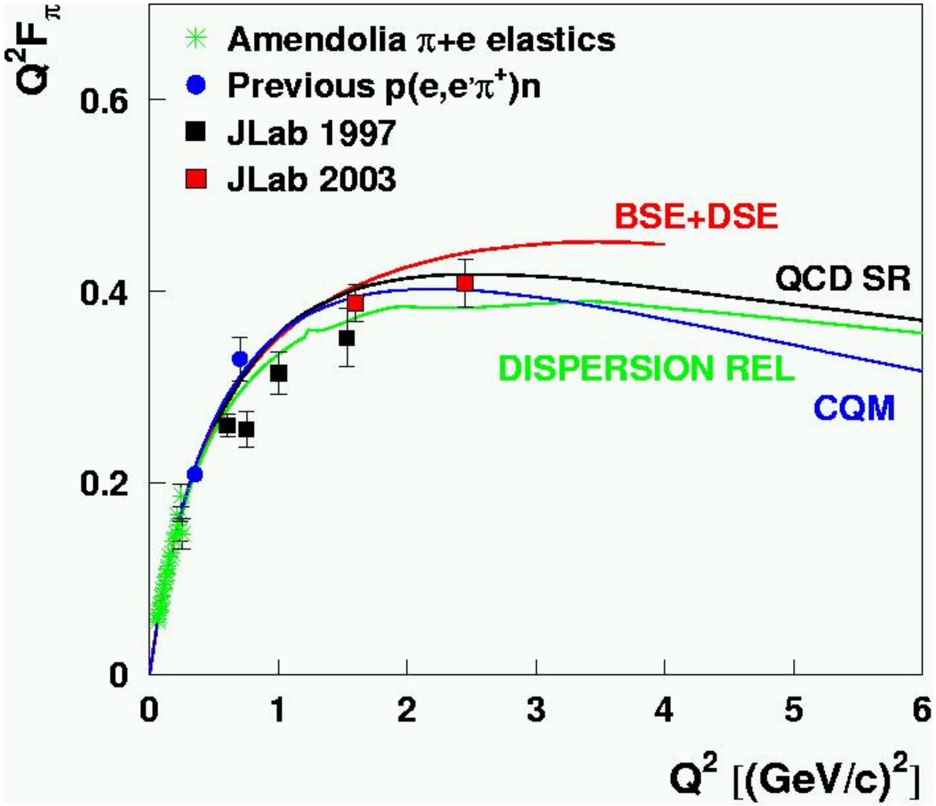
- At low Q^2 (< 0.3 $(GeV/c)^2$): use π + e scattering → R_{rms} = 0.66 fm
- At higher Q^2: use $^1H(e,e'\pi^+)n$



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



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



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

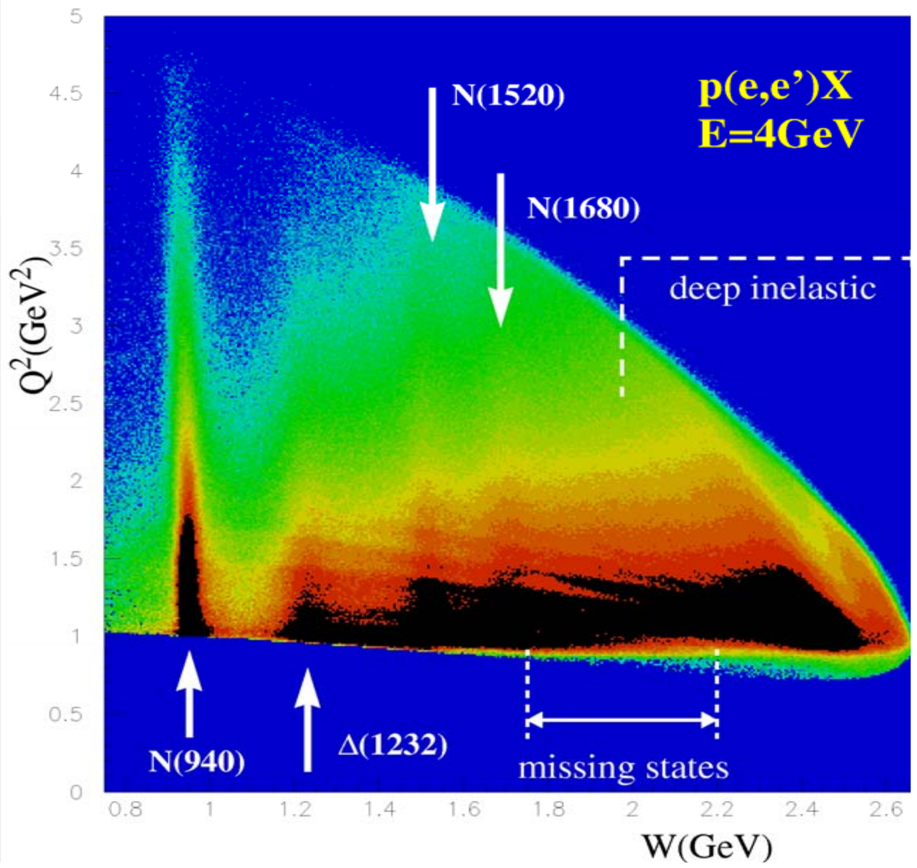
Hall B

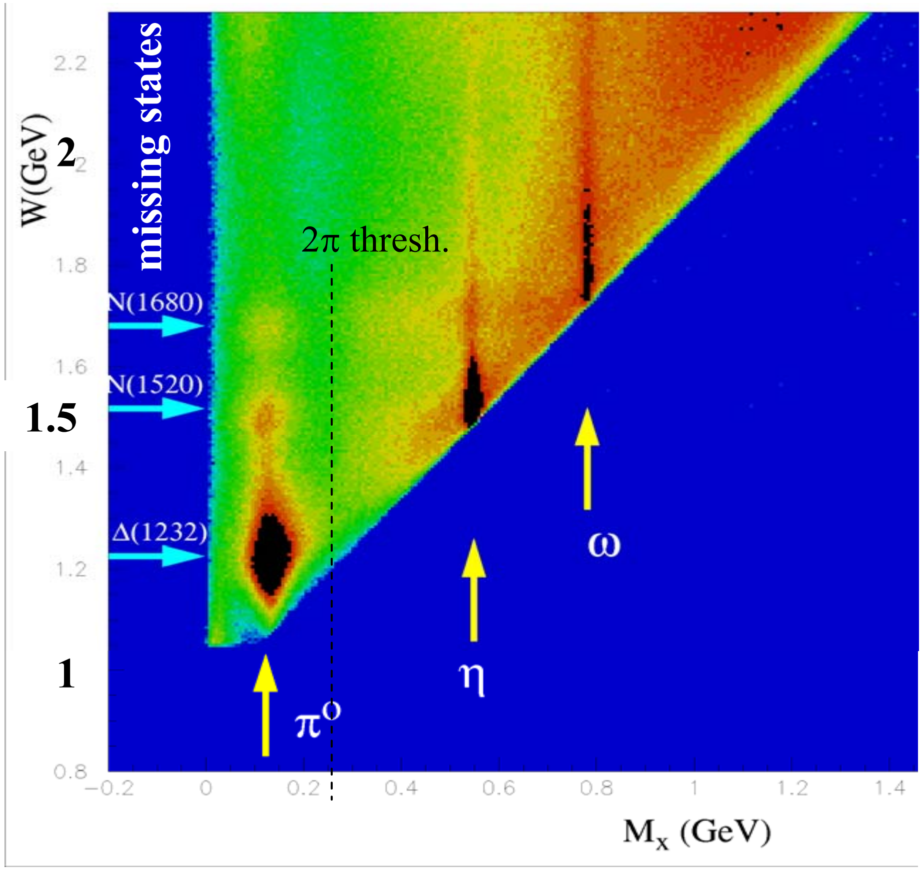
Electron Scattering

CLAS

p(e,e')X

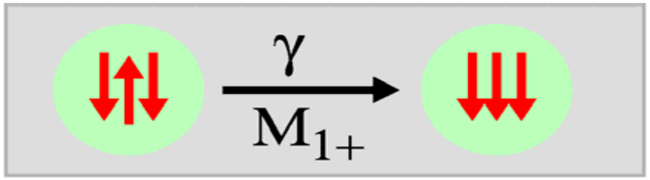
p(e,e'p)X



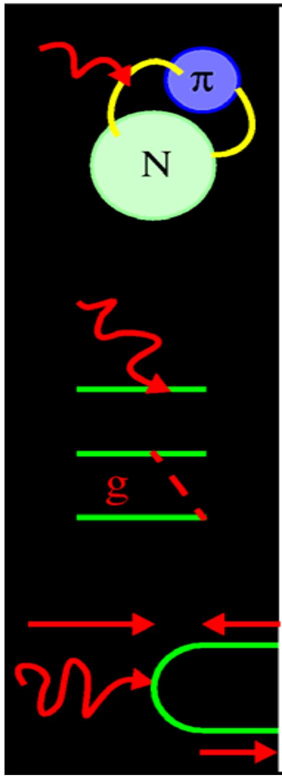


➢ Resonances cannot be uniquely separated in inclusive scattering → measure exclusive processes.

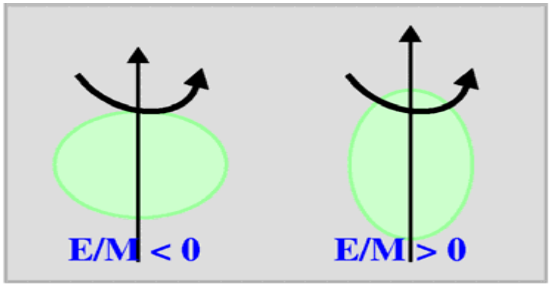
The γNΔ(1232) Quadrupole Transition



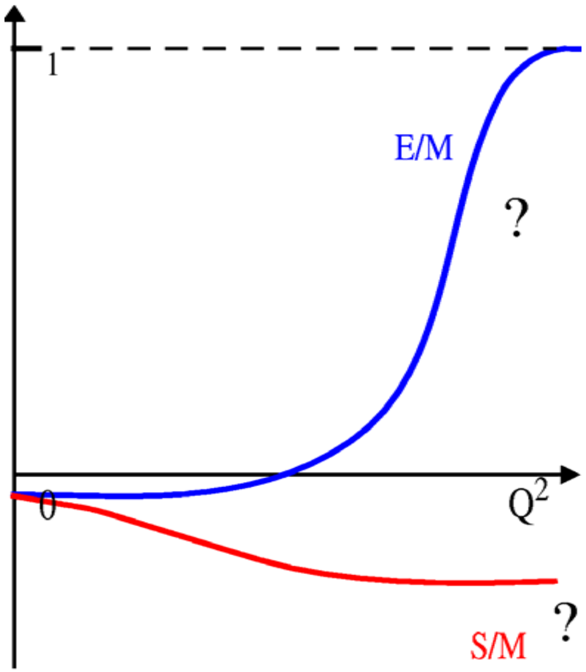
SU(6): $E_{1+}=S_{1+}=0$



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

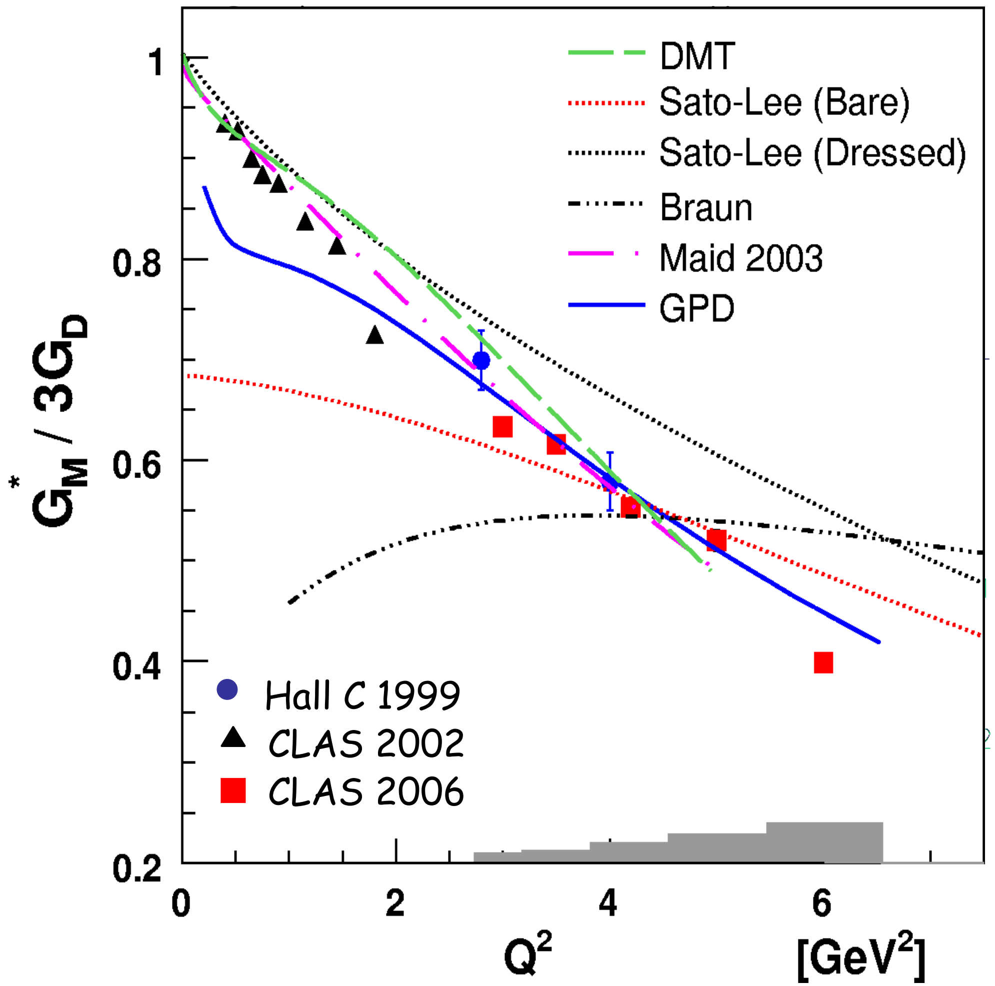


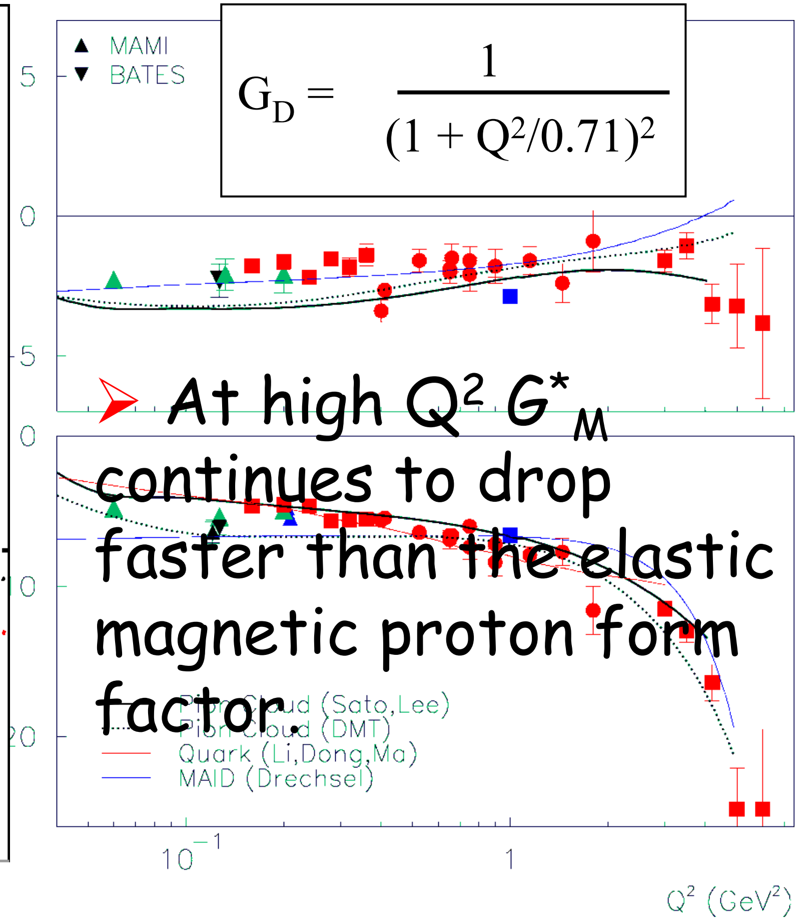
(A. Buchmann, E. Henley, 2000)



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

(The N-Δ Transition)



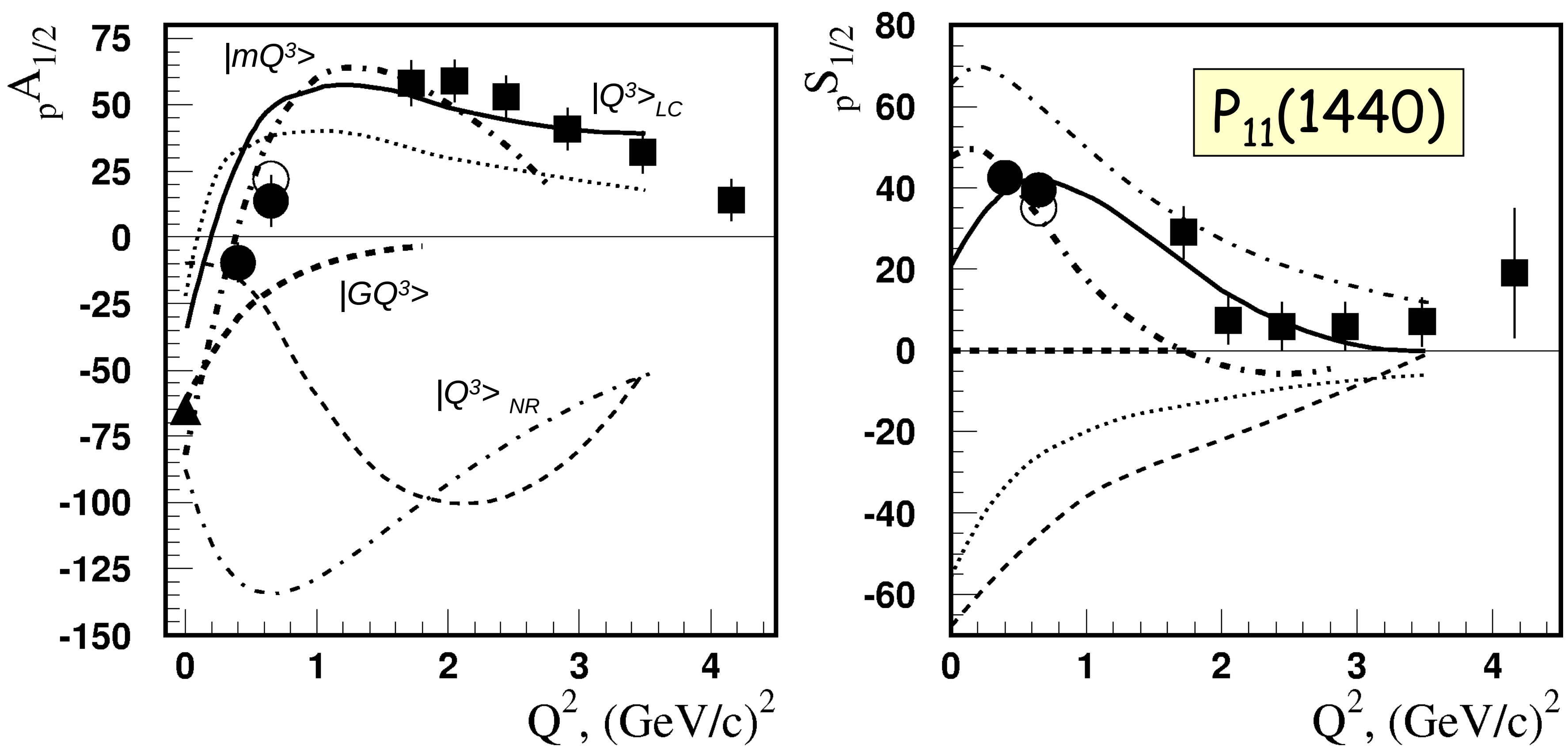


$$G_D = \frac{1}{(1 + Q^2/0.71)^2}$$

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

Hall B **Transition amplitudes $\gamma_V p \rightarrow N_{1/2^+}(1440)$** CLAS

(The Elusive Roper Resonance)



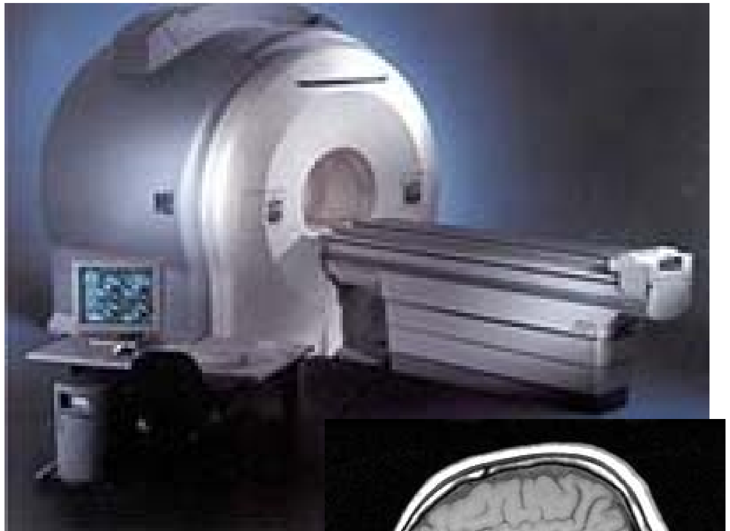
At large distances the Roper resonance shows behavior similar to what is predicted in a model containing large meson contributions, at short distances the data are consistent with behavior expected from a constituent quark picture.

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:

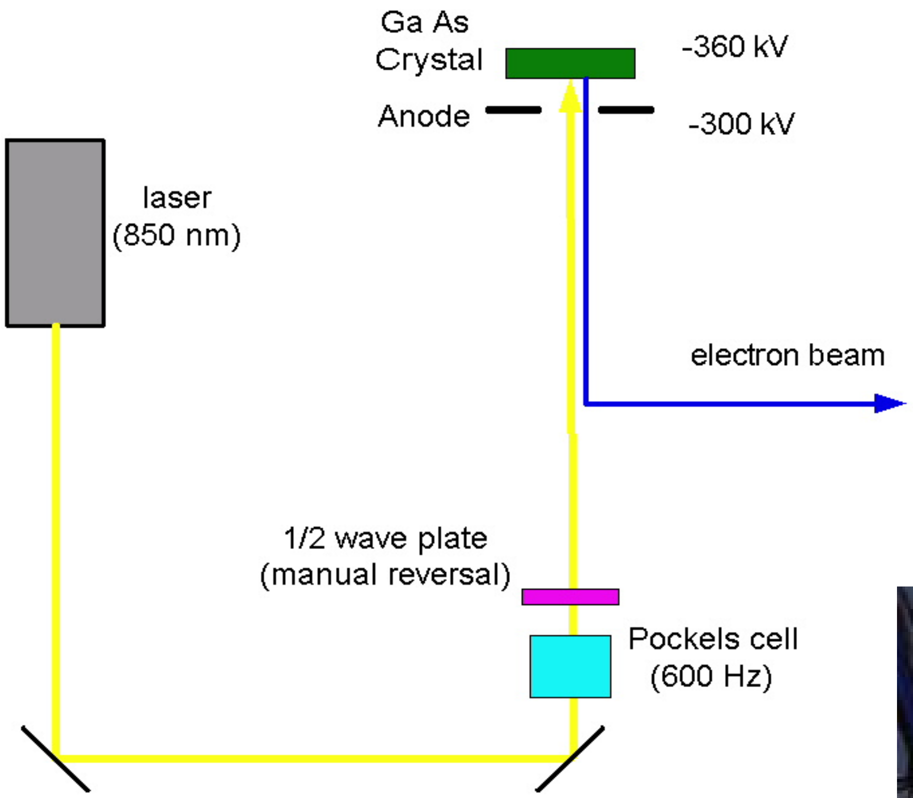
$\mu_p \sim 2.8\ \mu_N$

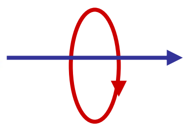
$\mu_n \sim -1.8\ \mu_N$

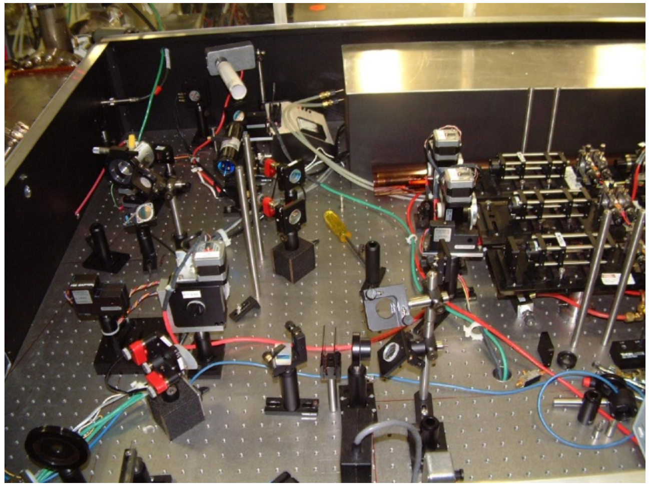
How do the quark contributions add up?

How are charge and magnetism distributed?

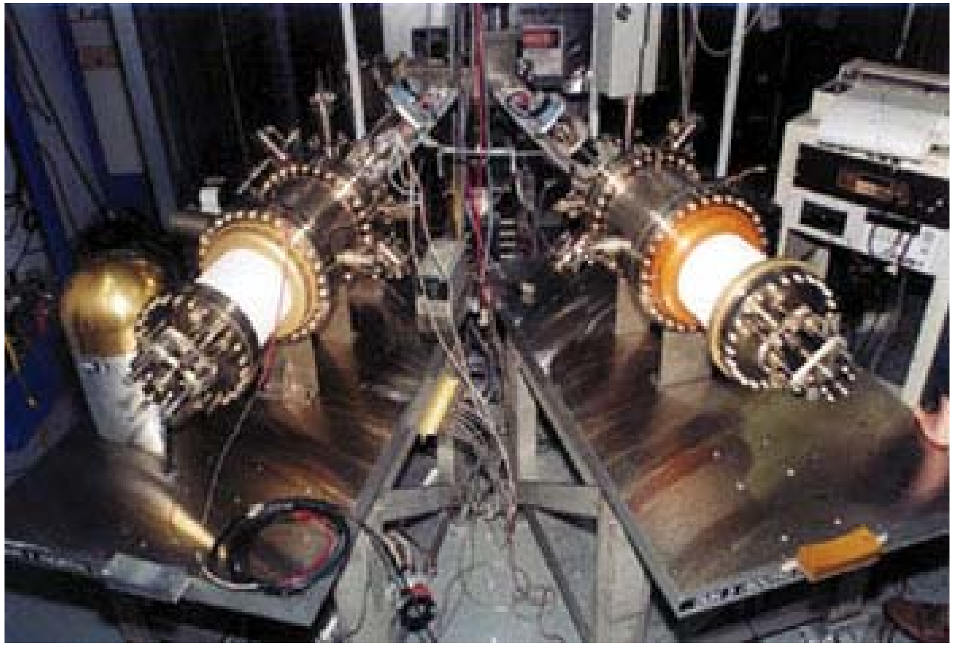
JLab: Polarized Electrons!!!







Electron retains circular polarization of laser beam



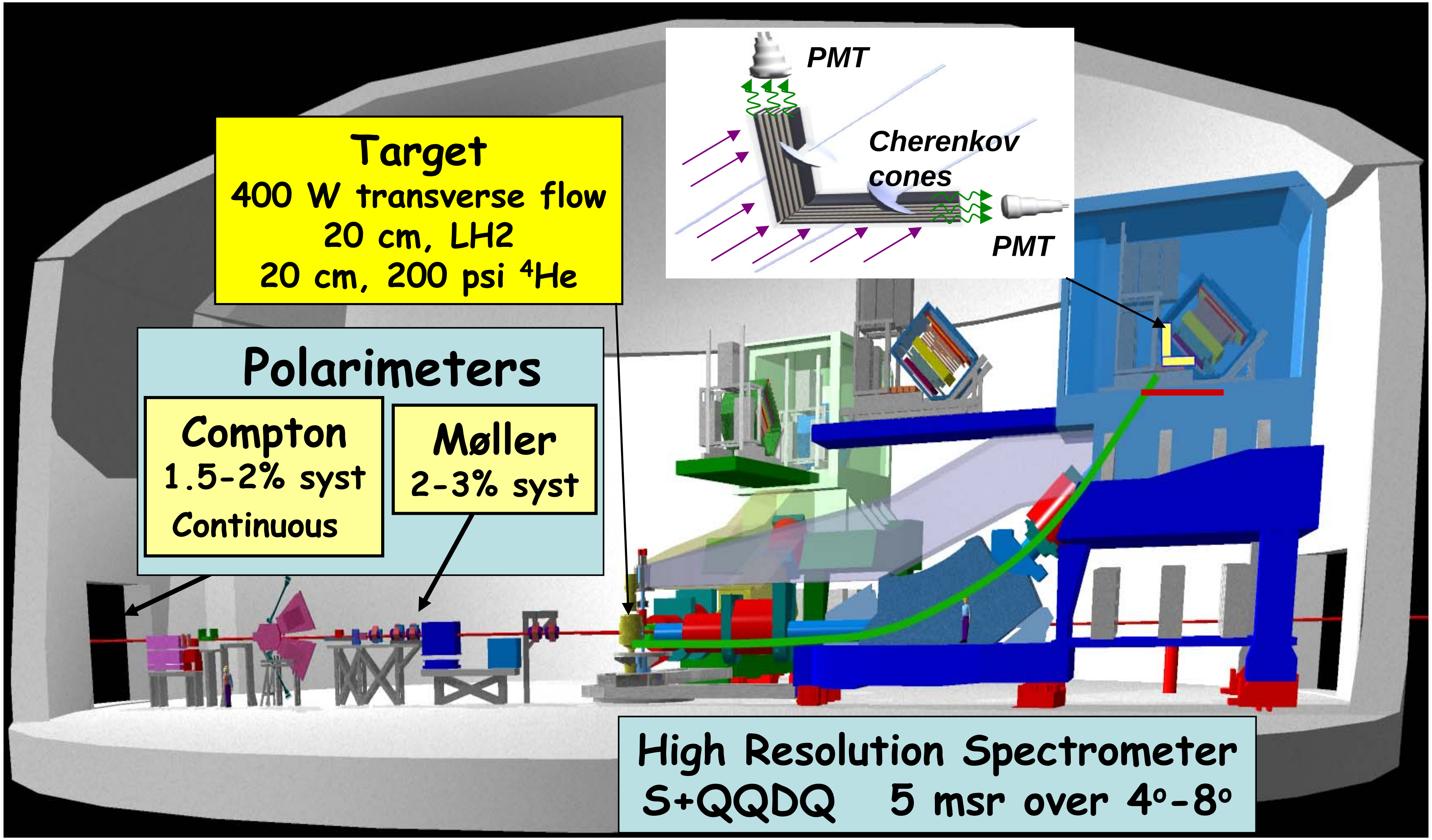
Reverse polarization of beam at rate of 30 Hz

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



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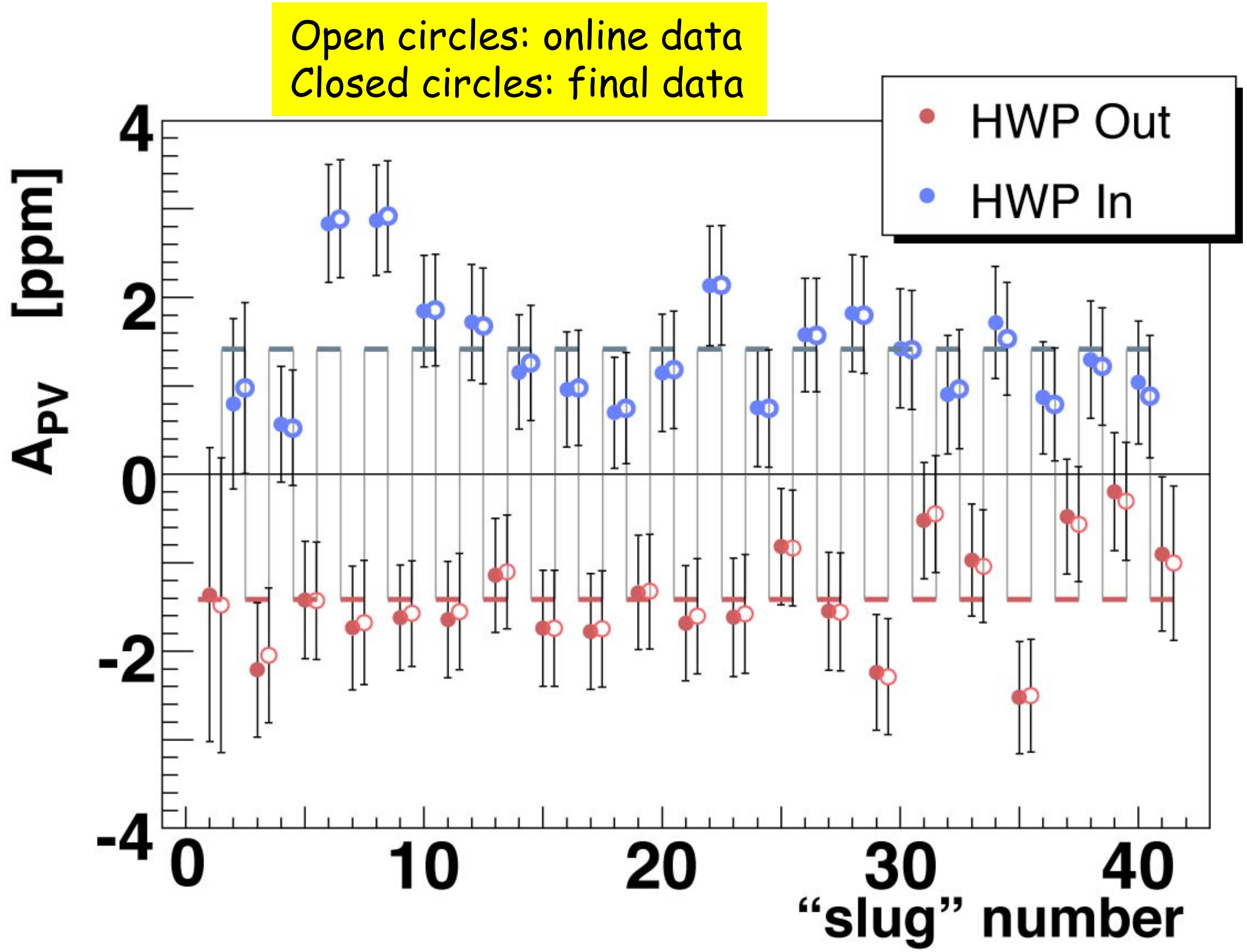
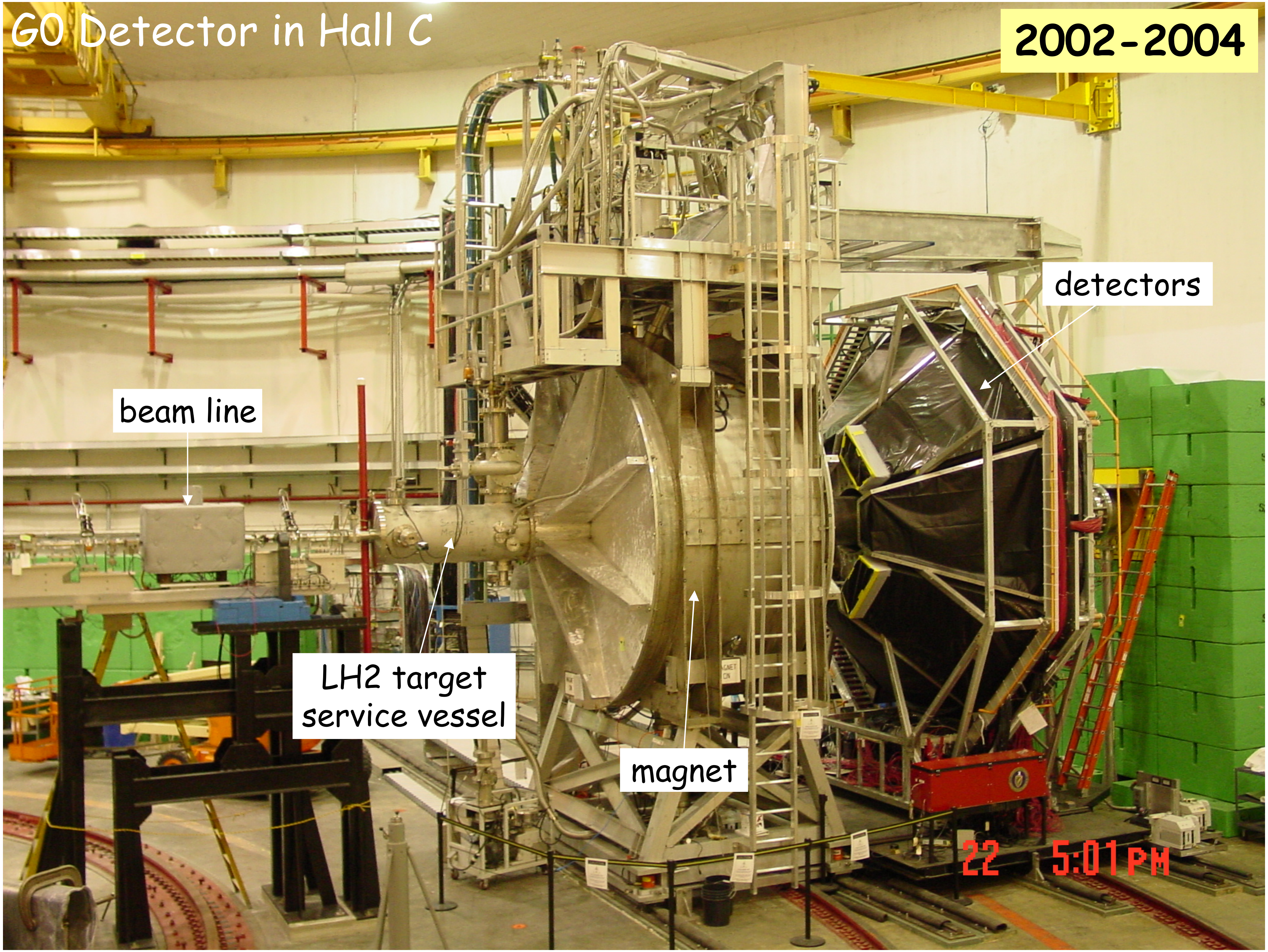
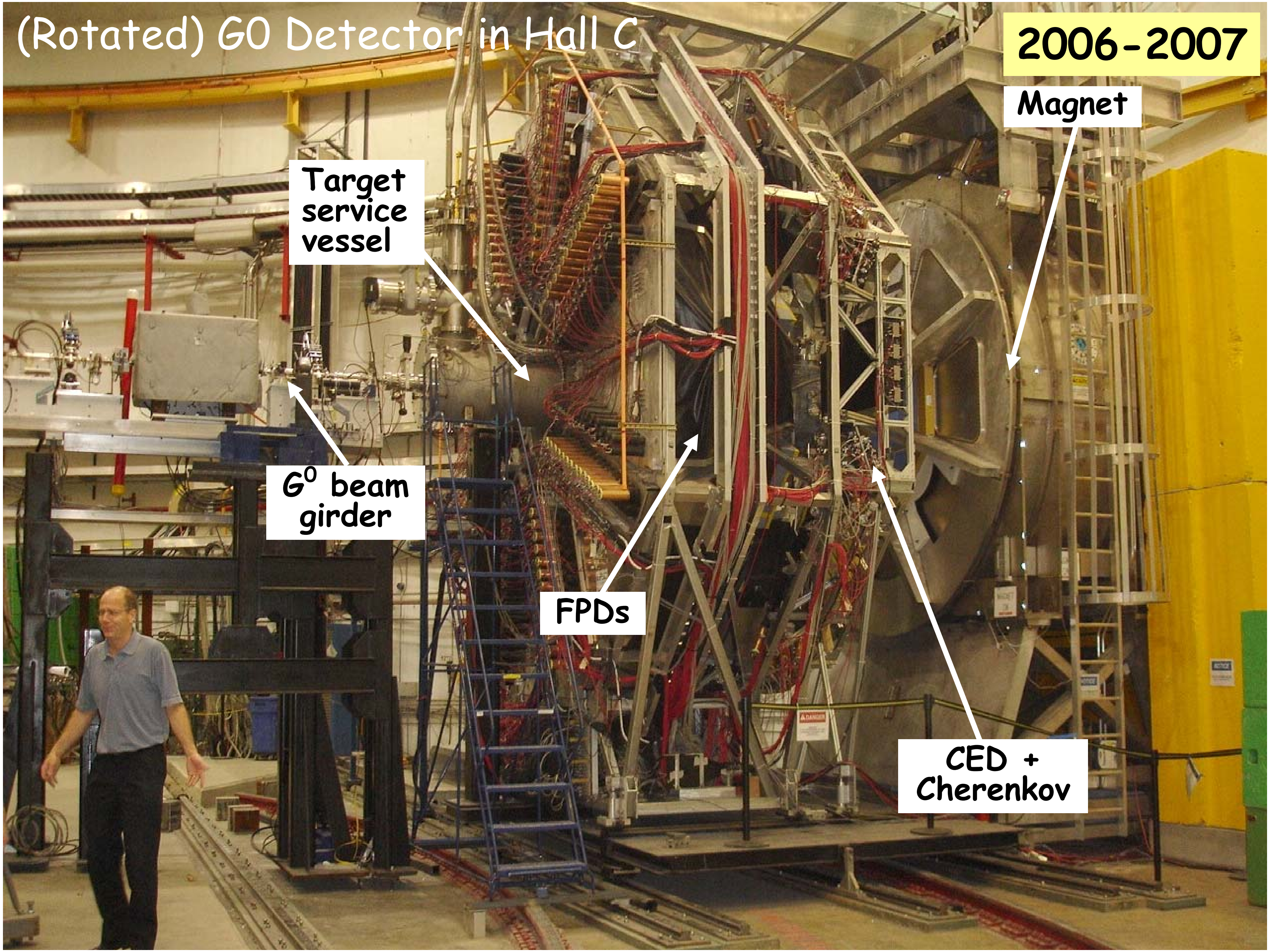
The HAPPEx Program: Strange Quark Contributions to the Proton




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
Magnet
Target service vessel
G0 beam girder
FPDs
CED + Cherenkov

JLab polarized beam

G0 forward running beam:

- strained GaAs (P_B ~ 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

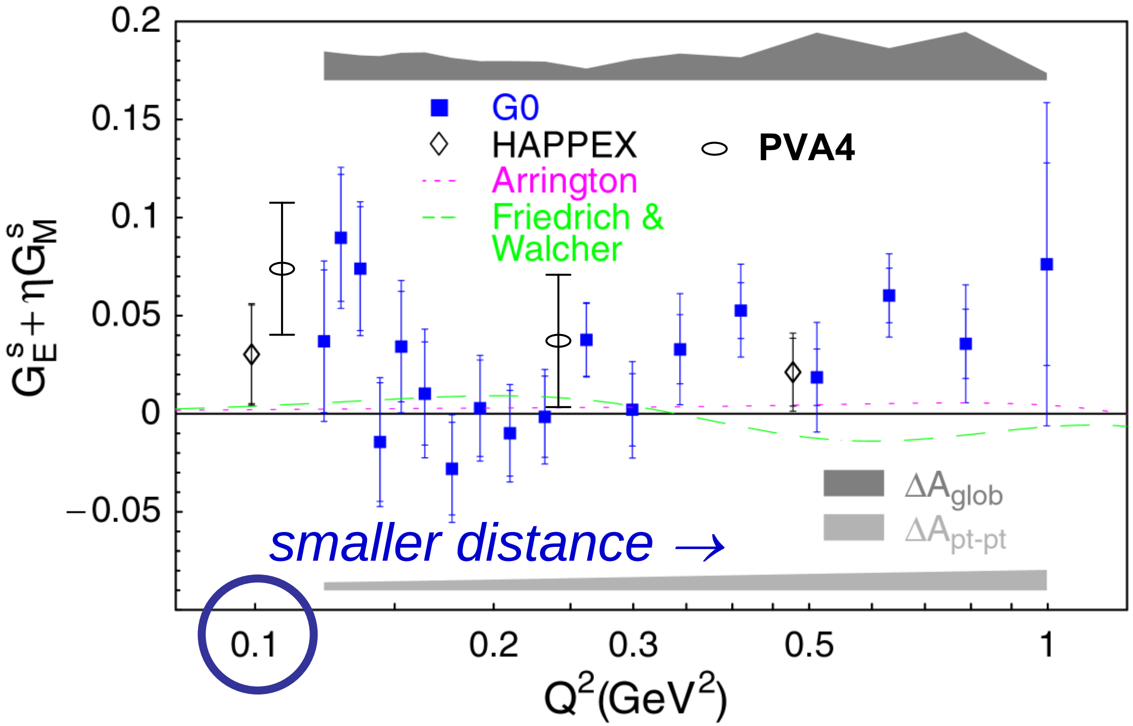
The spatial distribution of quarks and the proton's magnetism

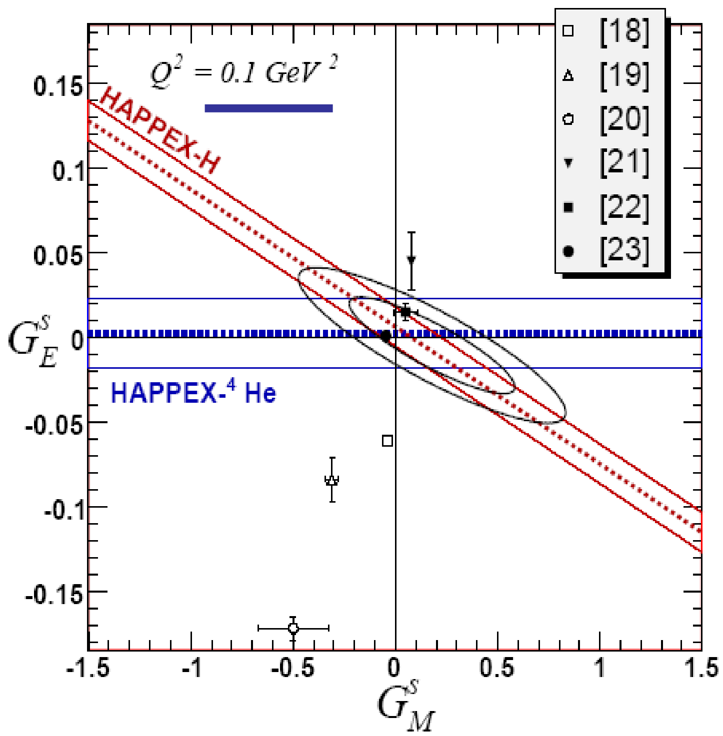
Hall A

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

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.

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

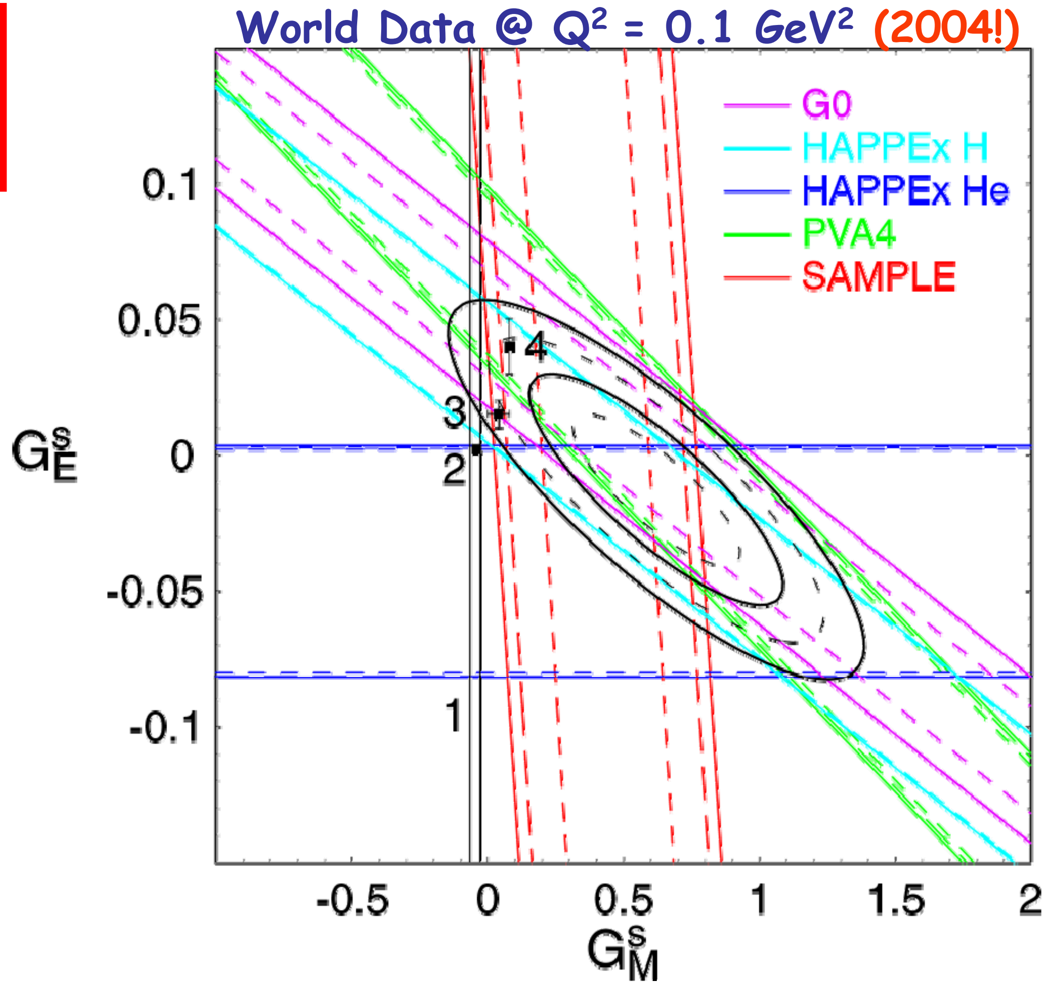
<u>Contours</u>

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



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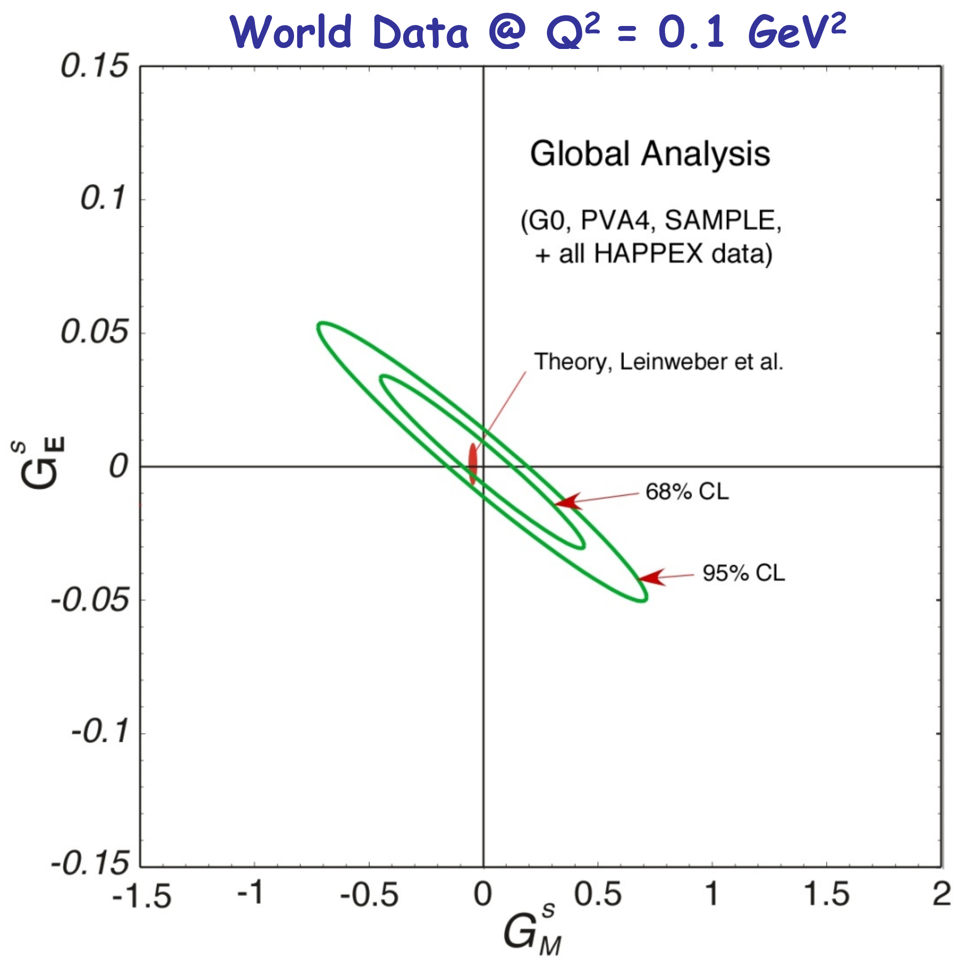
Contours
- 1σ, 2σ
- 68.3, 95.5% CL

Theory
- Leinweber, et al.
- PRL **94** (05) 212001;
- hep-lat/0601025

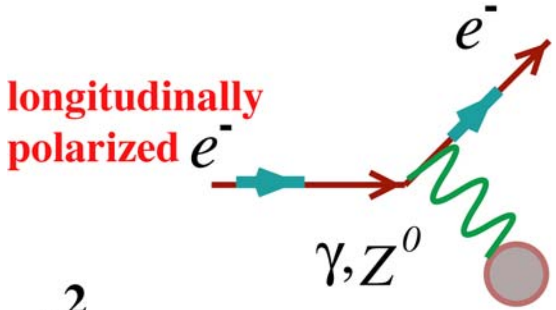
… or include recent HAPPEx-H and -He data



PV Asymmetries

Weak Neutral Current (WNC) Interactions at $Q^2 \ll M_Z^2$

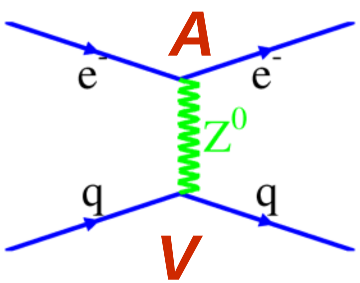
Longitudinally Polarized Electron Scattering off Unpolarized Fixed Targets



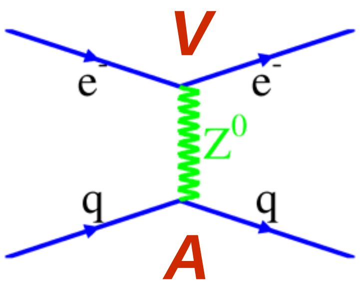
$$\sigma \;\alpha\; |A_\gamma + A_{weak}|^2$$

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha} (g_A^e g_V^T + \beta g_V^e g_A^T)$$

Electron-Quark Phenomenology



$$C_{1i} \equiv 2 g_A^e g_V^i$$



$$C_{2i} \equiv 2 g_V^e g_A^i$$

$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2(\theta_W) \approx -0.19$$
$$C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2(\theta_W) \approx 0.35$$
$$C_{2u} = -\frac{1}{2} + 2\sin^2(\theta_W) \approx -0.04$$
$$C_{2d} = \frac{1}{2} - 2\sin^2(\theta_W) \approx 0.04.$$

Use precision data to get new update on C_{1q} couplings…

→ Dramatic improvement in knowledge of weak couplings!

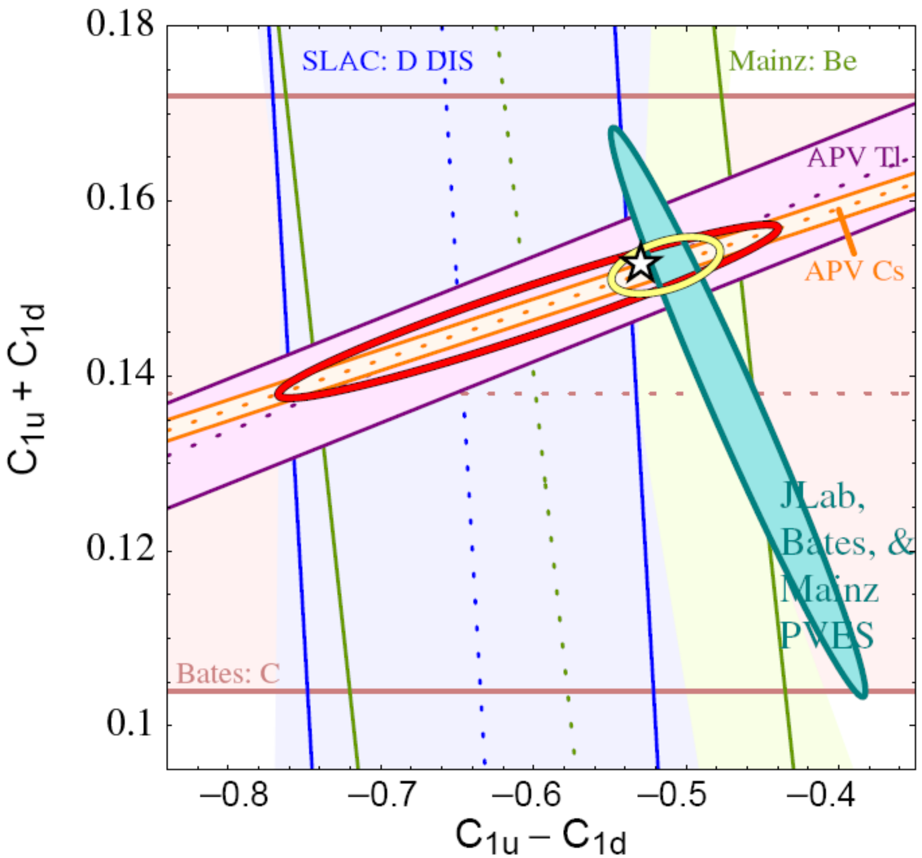
$$\mathcal{L}_{SM}^{PV} = -\frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}^{SM} \bar{q}\gamma^\mu q$$

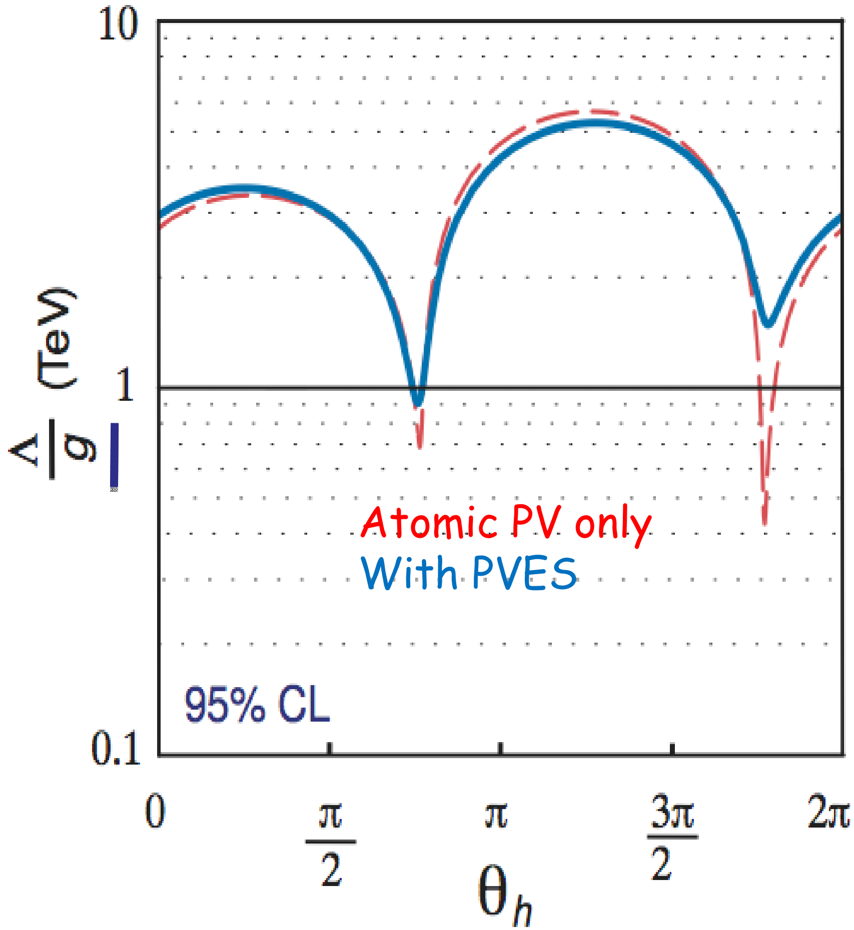
Erler et al., PR D68 (2003)

$$\mathcal{L}_{NP}^{PV} = \frac{g^2}{4\Lambda^2} \bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

Full isospin coverage for limits on new physics!

$$h_V^u = \cos\theta_h \qquad h_V^d = \sin\theta_h$$



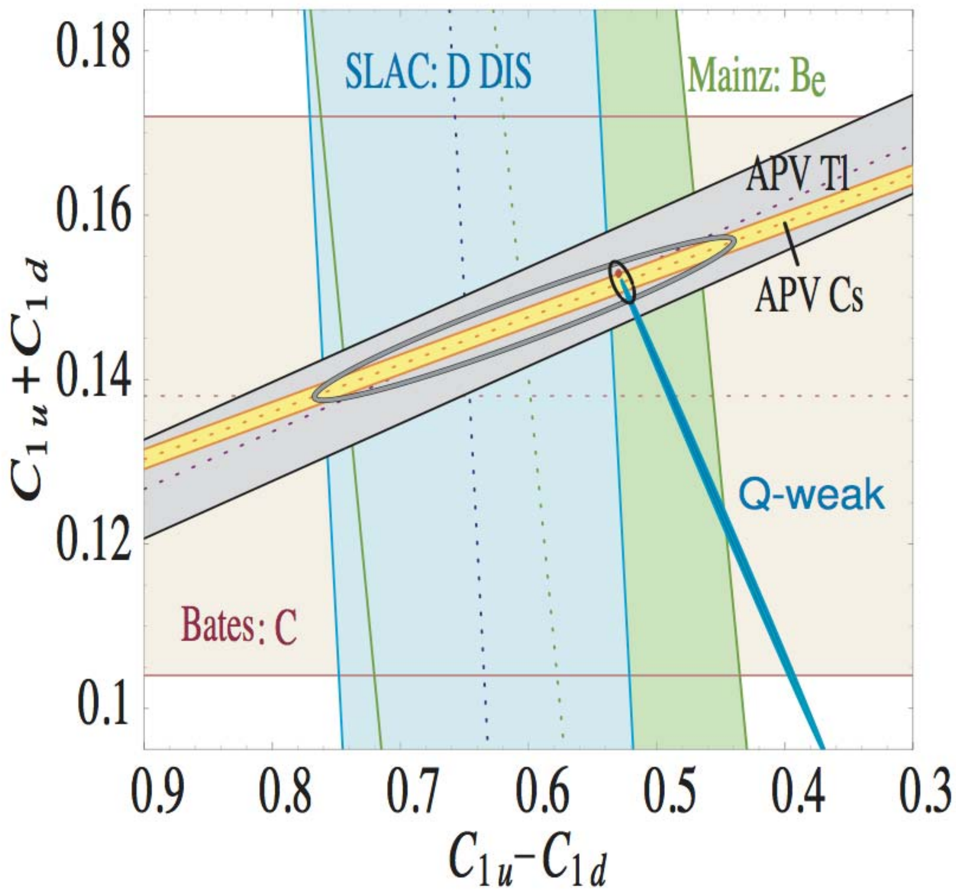


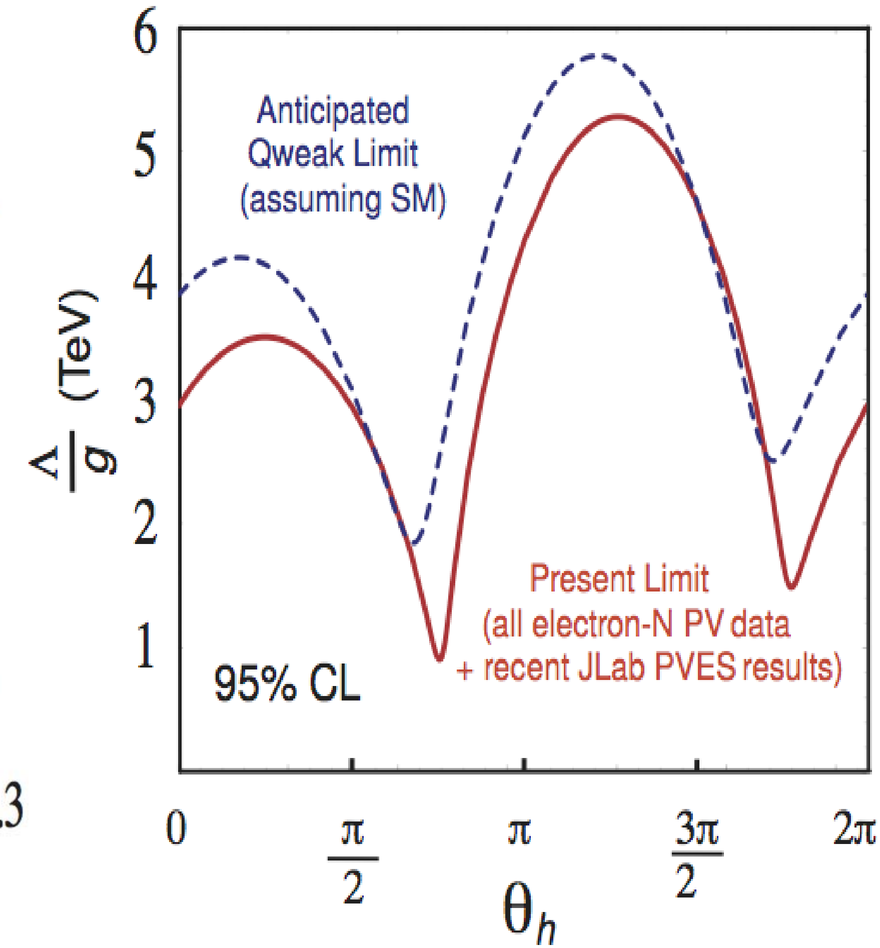
Factor of 5 increase in precision of Standard Model test

New Physics Scale > 0.9 TeV

Possible Impact of Qweak Experiment (2010-2012)

Qweak constrains new physics to beyond 2 TeV





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?**

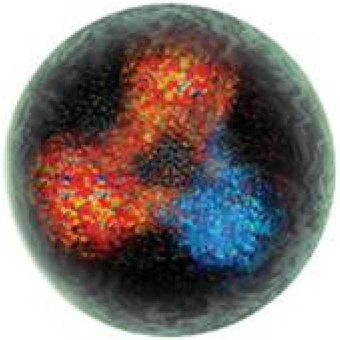
Pushing the Limits of the Standard Model of Nuclear Physics

- **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

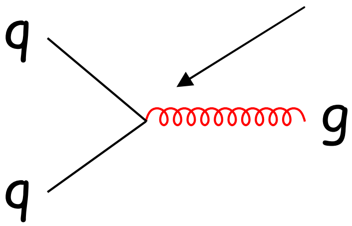
The Double-Faced Strong Force

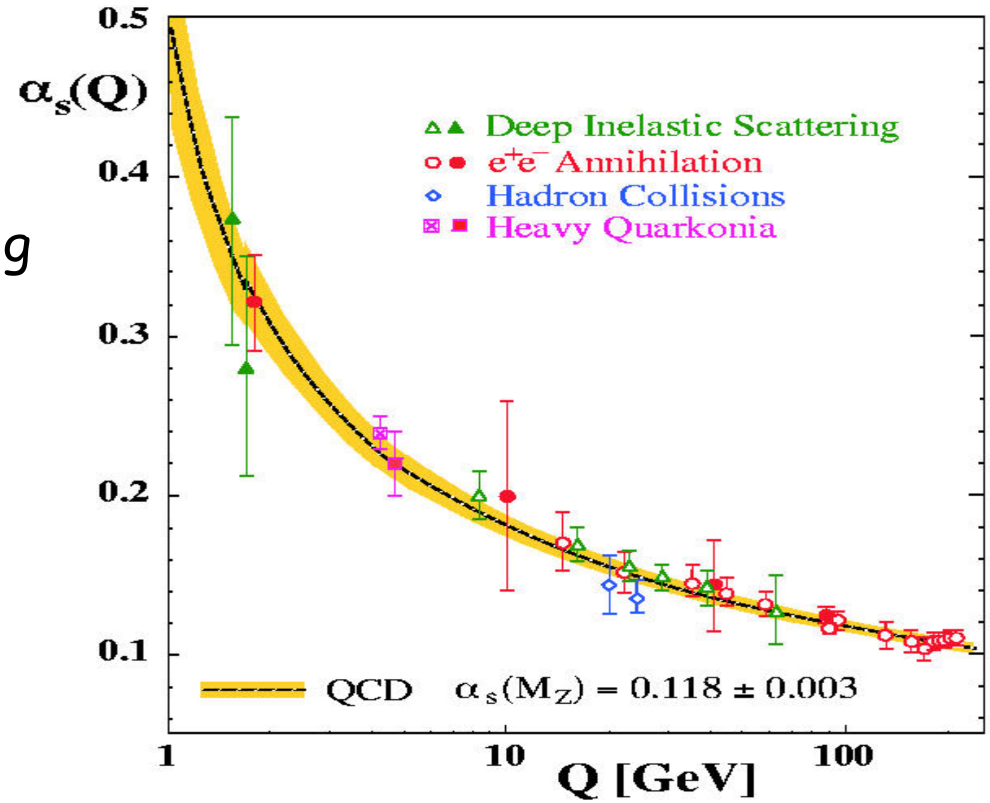


Confinement
Nucleons
$Q < \Lambda$
$\alpha_s(Q) > 1$

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

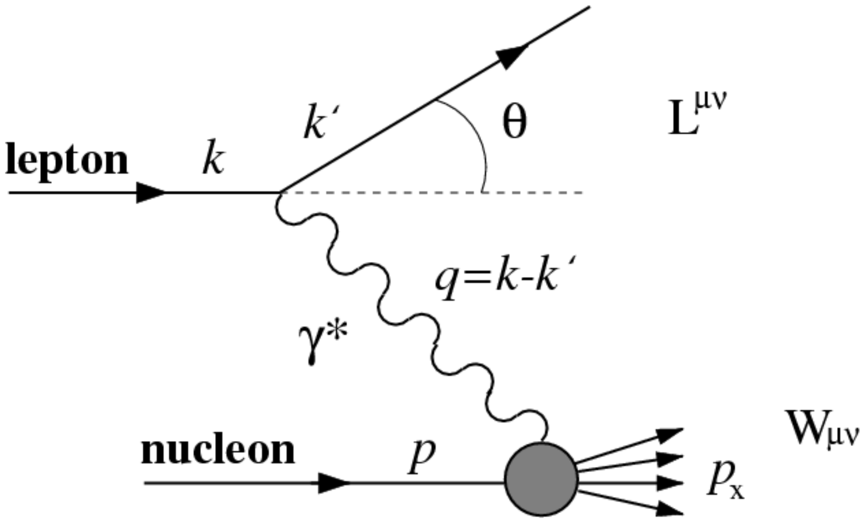
Mass and Radius of the
Proton are (almost)
completely governed by

$\Lambda_{QCD} \approx 0.213$ GeV

Quark Model

Quark Parton Model

Inclusive $^1H(e,e')$ Scattering - Formalism



Cross section for inclusive lepton (electron) scattering:

$$\frac{d\sigma}{d\Omega dE'} = \frac{\alpha^2}{Q^4}\frac{E}{E'} L_{\mu\nu} W^{\mu\nu}$$

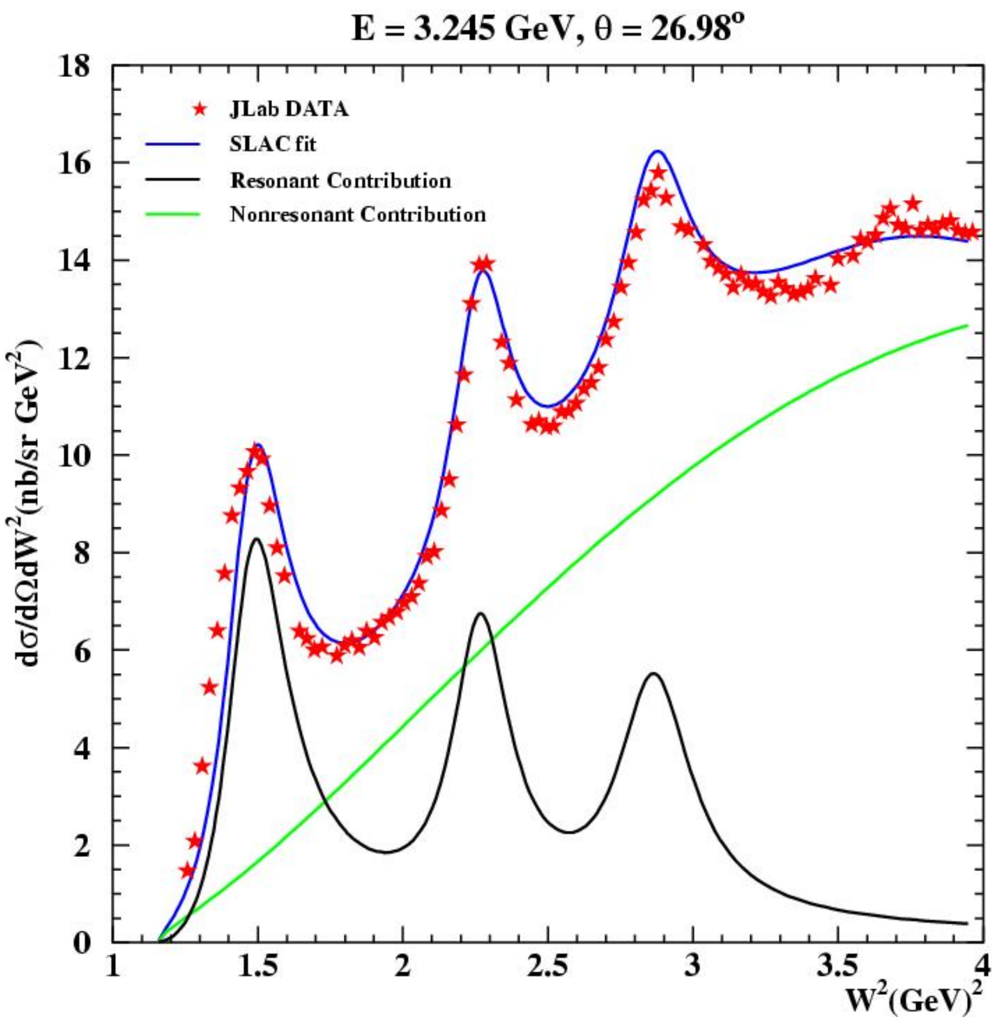
In terms of virtual photon polarization ε:

$$\frac{d\sigma}{d\Omega dE'} = \Gamma(\sigma_T + \varepsilon\sigma_L) = \Gamma\sigma_T(1+\varepsilon R)$$

Or, in terms of structure functions $W_1(\nu,Q^2)$ and $W_2(\nu,Q^2)$:

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2 (E')^2}{Q^4}\left[W_2(\nu,Q^2)\cos^2\frac{\theta}{2} + 2W_1(\nu,Q^2)\sin^2\frac{\theta}{2}\right]$$

Inclusive $^1H(e,e')$ Scattering



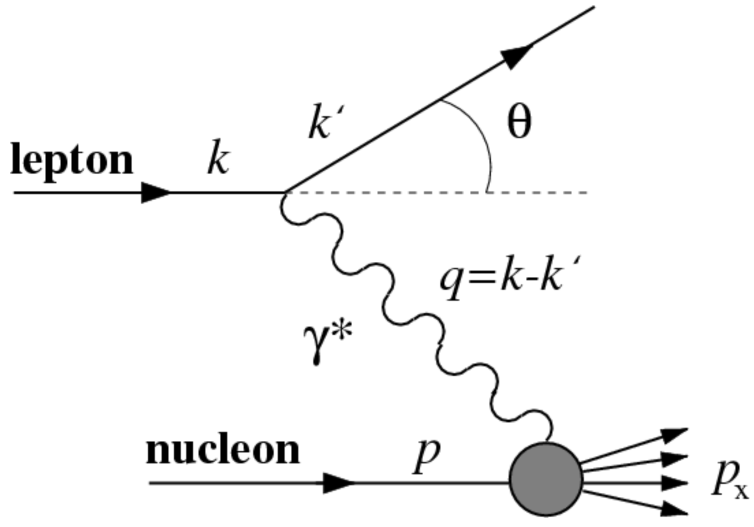
$$Q^2 = 4EE'\sin^2(\Theta/2)$$
$$\nu = E - E'$$
$$x = Q^2/(2M\nu)$$
$$W^2 = M^2 + 2M\nu - Q^2$$
$$= M^2 + Q^2(1/x - 1)$$

Define several regions:

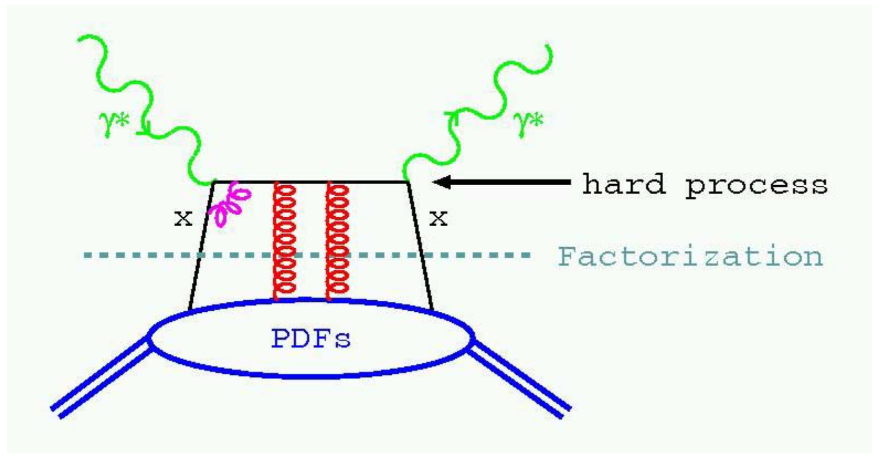
0) elastic region: $W^2 = M^2$
1) 1st resonance excitation "Δ"
2) 2nd resonance region "S"
3) 3rd resonance region "F"
4) 4th region: $3.3 < W^2 < 4$ GeV^2
5) Deep-inelastic "DIS" region $W^2 > 4$ GeV^2

Spectrum consists of Resonant and Non-Resonant Contributions

Deep Inelastic Scattering



$|\ \ |^2 =$



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)

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

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

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

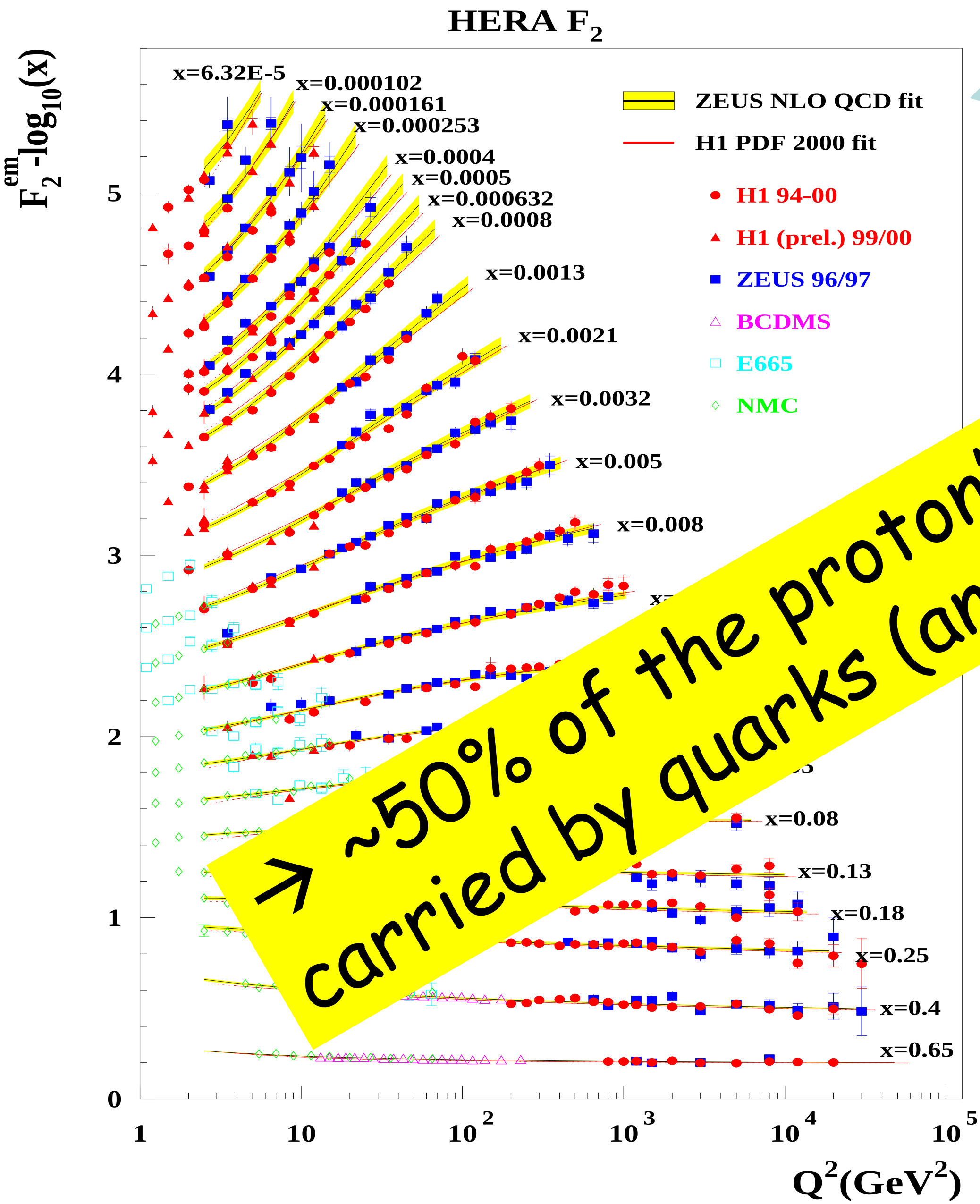
F_2 interpreted in the **quark-parton model** as the charge-weighted sum over quark distributions:

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

Empirically, DIS region is where logarithmic scaling is observed

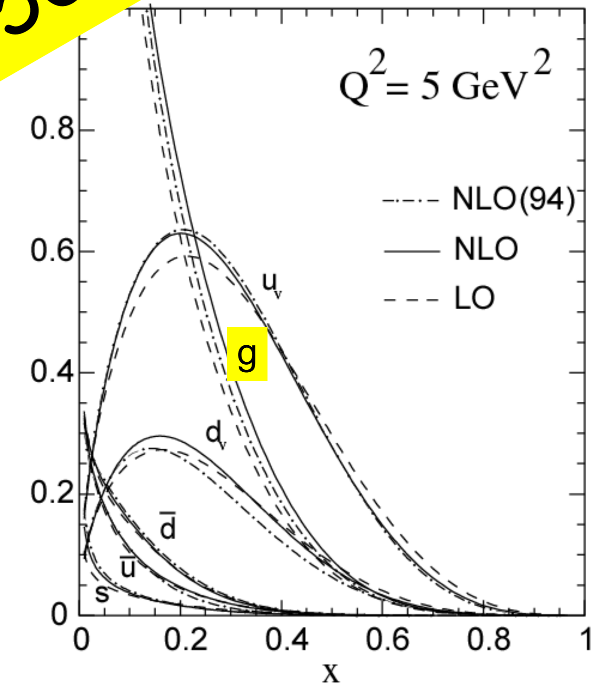
$Q^2 > 1\ \text{GeV}^2,\ W^2 > 4\ \text{GeV}^2$

World Data on F_2^p Structure Function



(DIS data only)

In general, Nex… …ading-Order (NLO… …e QCD (DGLAP… …ob of re… …d over the … …it range.



→ ~50% of the proton's momentum is carried by quarks (and ~50% by gluons)

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”

The Quark Parton Model is well defined in the limit of large Q^2 and large ν (or W^2).

Empirically, deep inelastic scattering (or quark parton model) descriptions seem to work well down to modest energy scales: $Q^2 \sim 1\ GeV^2$, $W^2 \sim 4\ GeV^2$.

Why is the Quark-Hadron Transition in QCD so smooth, and occurring at such low energy scales?

The underlying reason is the Quark-Hadron Duality phenomenon.

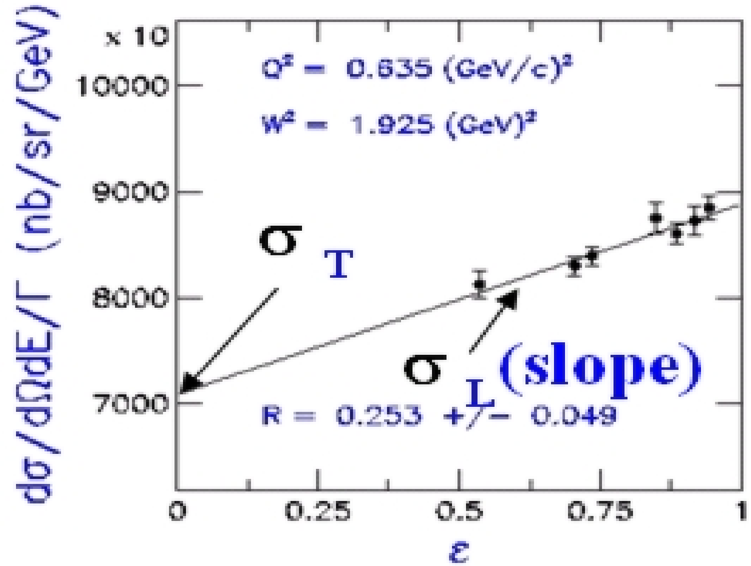
A Factory for "Rosenbluth" Separations

E.g.: Inclusive Scattering

e + p (d) → e + X

Rosenbluth Separation Technique:

$$\frac{d\sigma}{d\Omega dE'} = \Gamma(\sigma_T + \varepsilon\sigma_L)$$



Where: Γ = flux of transversely polarized virtual photons

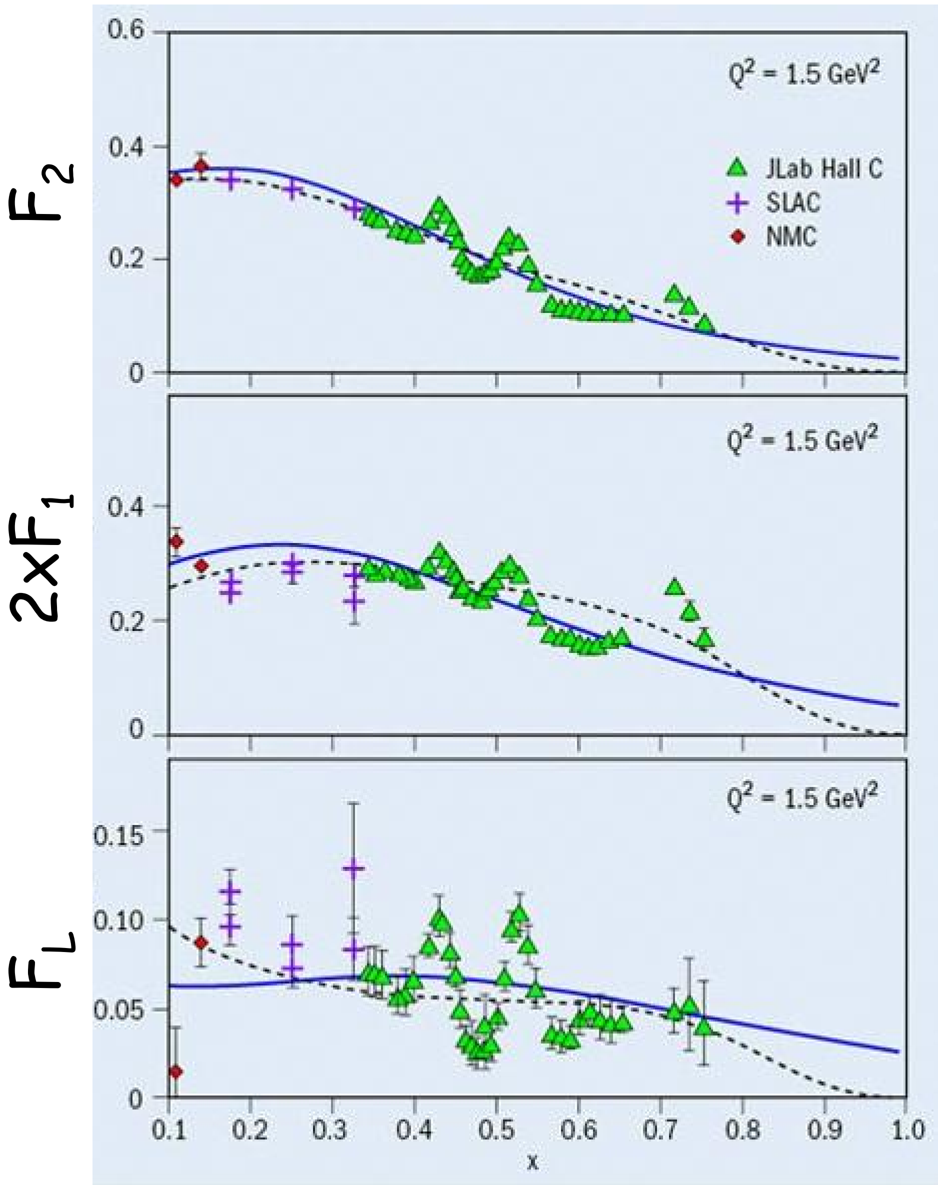
ε = relative longitudinal polarization

$$R = \frac{\sigma_L}{\sigma_T} = \frac{F_L}{2xF_1}$$

$$F_L = \left(1 + \frac{4M^2x^2}{Q^2}\right)F_2 - 2xF_1$$

longitudinal (F_L) — **mIxEd** (F_2) — Transverse (F_1)

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

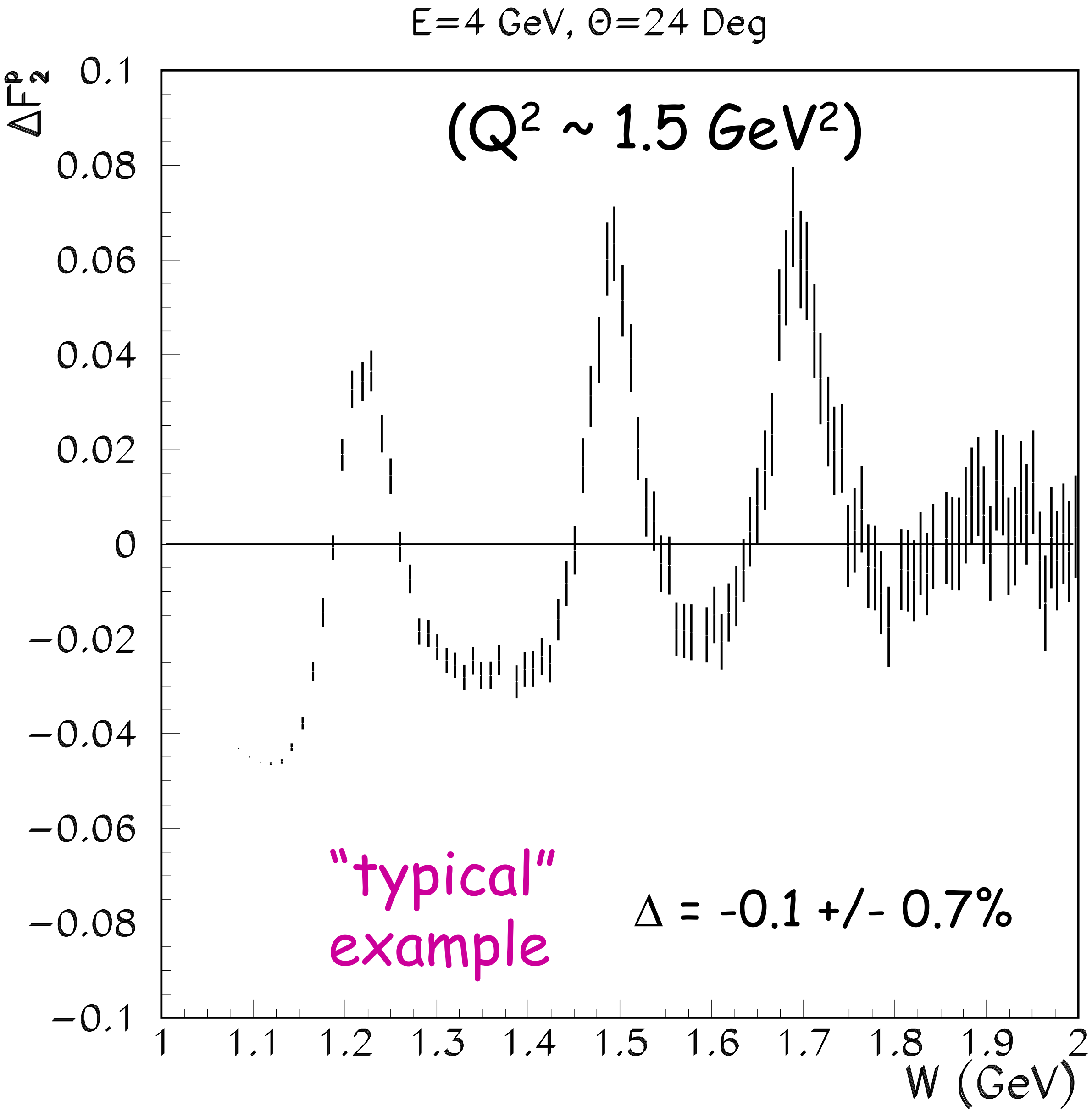


- The resonance region is, on average, well described by NNLO QCD fits.
- This implies that Higher-Twist (FSI) contributions cancel, and are on average small. "Quark-Hadron Duality"
- The result is a smooth transition from Quark Model Excitations to a Parton Model description, or a smooth quark-hadron 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



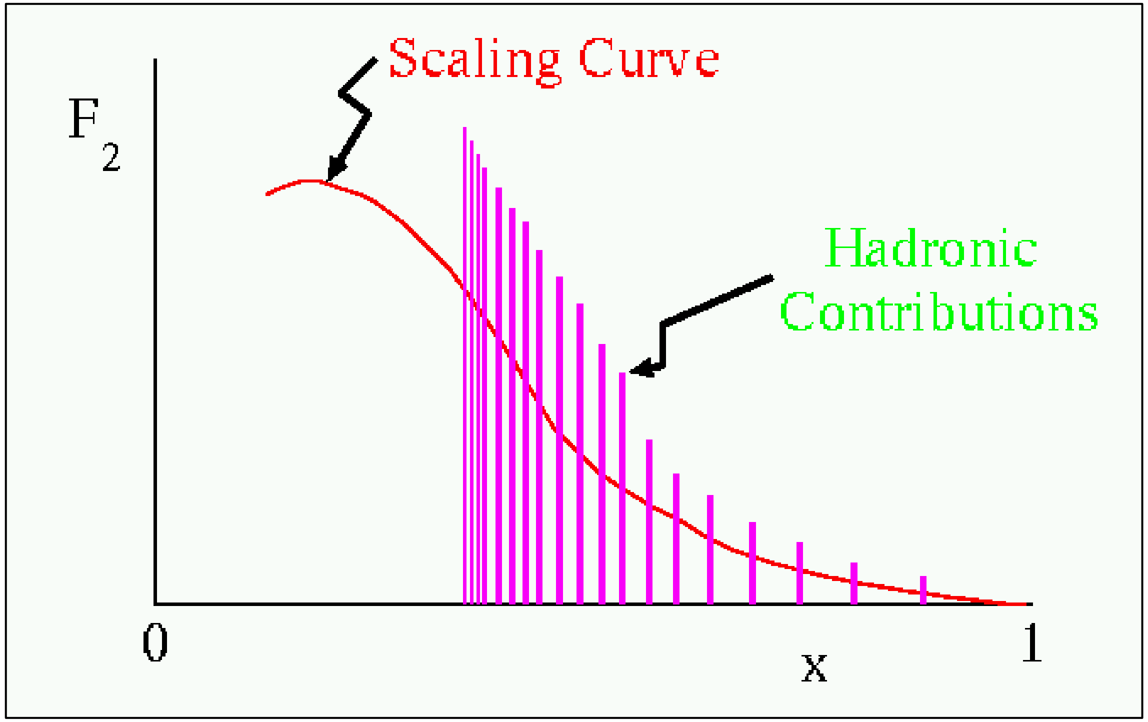
- Evidence of resonance transitions is "bumps and valleys" around the expected parton model behavior.
- Similar as standard textbook example of $e^+e^- \rightarrow$ hadrons
- **"Resonances build the parton subprocess cross section because of a separation of scales between hard and soft processes."**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

Quark-Hadron Duality – Theoretical Efforts

N. Isgur et al : $N_c \rightarrow \infty$

$q\bar{q}$ infinitely narrow resonances

qqq only resonances



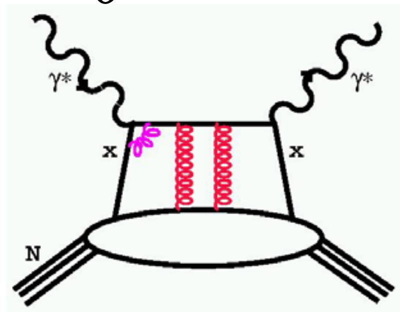
- Distinction between Resonance and Scaling regions is **spurious**
- Bloom-Gilman Duality must be invoked even in the Bjorken Scaling region → **Bjorken Duality**

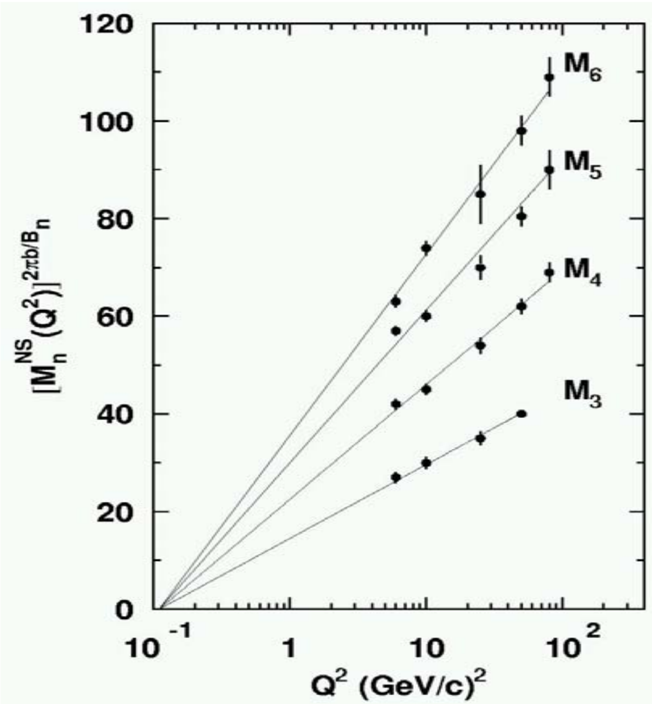
QCD and the Operator-Product Expansion

- Moments of the Structure Function $M_n(Q^2) = \int_0^1 dx\ x^{n-2} F(x,Q^2)$
- Operator Product Expansion

$$M_n(Q^2) = \sum_{k=1}^{\infty} (nM_0^2/\ Q^2)^{k-1}\ B_{nk}(Q^2)$$

higher twist — logarithmic dependence





At High Q^2 : $\ln(Q^2)$ dependence of moments one of first "proofs" of QCD → Λ(QCD)

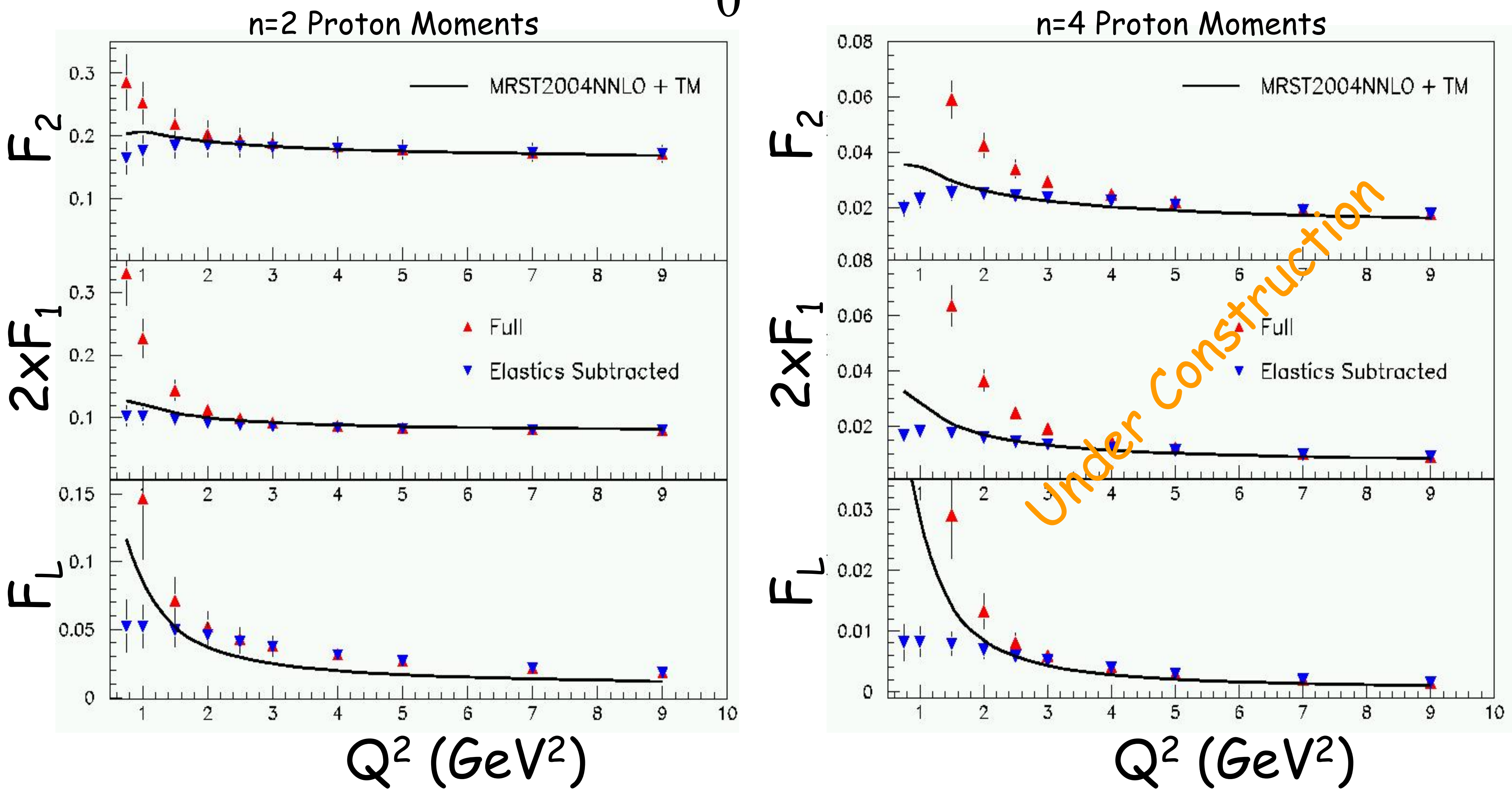
At Low Q^2 : $O(1/Q^2)$ power dependence is due to initial and final state interactions between the struck quark and target remnants

→ "Higher Twist" effects

Quark-Hadron Duality is described in the Operator Product Expansion *as higher twist effects being small or canceling*

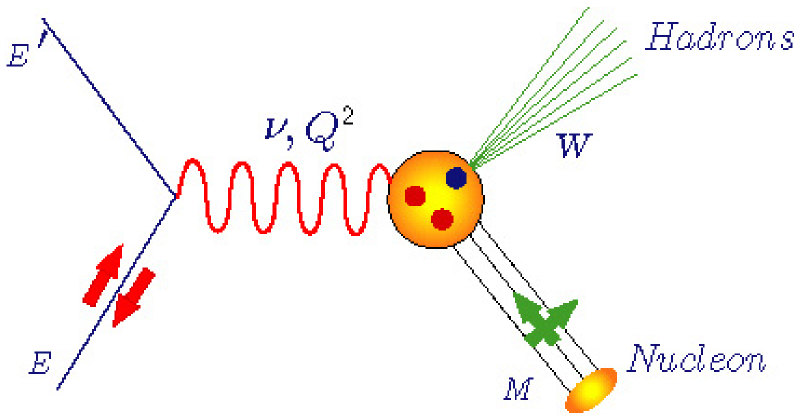
Separated Structure Function Moments up to $Q^2 = 4\ GeV^2$

$$M_n(Q^2) = \int_0^1 dx\ x^{n-2} F(x,Q^2)$$



- Higher-twist at low Q^2 mainly seems to reflect "discreteness" of low-W region
- $M_L^{(n)} = \alpha_s(Q^2)\{ \frac{4M_2^{(n)}}{3(n+1)} + \frac{2c\int dx\ xG(x,Q^2)}{(n+1)(n+2)} \}$ at leading twist and at zero proton-mass

Inclusive Electron Scattering - Formalism



Q^2 : Four-momentum transfer
x : Bjorken variable ($=Q^2/2M\nu$)
ν : Energy transfer ($y = \nu/E$)
M : Nucleon mass
W : Final state hadronic mass

U $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow + \uparrow\Uparrow) = \frac{8\alpha^2\cos^2(\theta/2)}{Q^4}\left[\frac{F_2(x,Q^2)}{\nu} + \frac{2F_1(x,Q^2)}{M}\tan^2(\theta/2)\right]$$

- Unpolarized structure functions $F_1(x,Q^2)$ and $F_2(x,Q^2)$, or $F_T(x,Q^2)$ [$=2xF_1(x,Q^2)$] and $F_L(x,Q^2)$, to separate by measuring $R = \sigma_L/\sigma_T$
- Polarized structure functions $g_1(x,Q^2)$ and $g_2(x,Q^2)$

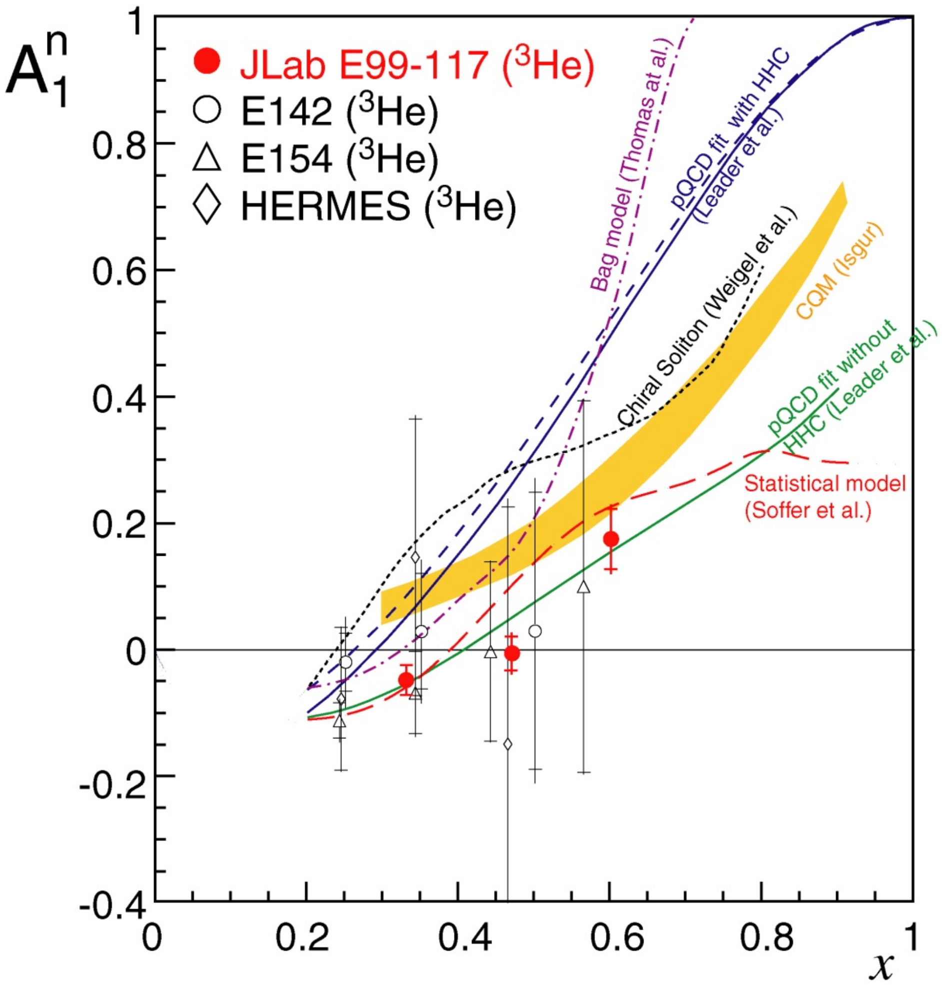
L $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2}{MQ^2}\frac{E'}{\nu E}\left[(E + E'\cos\theta)g_1(x,Q^2) - \frac{Q^2}{\nu}g_2(x,Q^2)\right]$$

T $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1(x,Q^2) + 2E g_2(x,Q^2)\right]$$

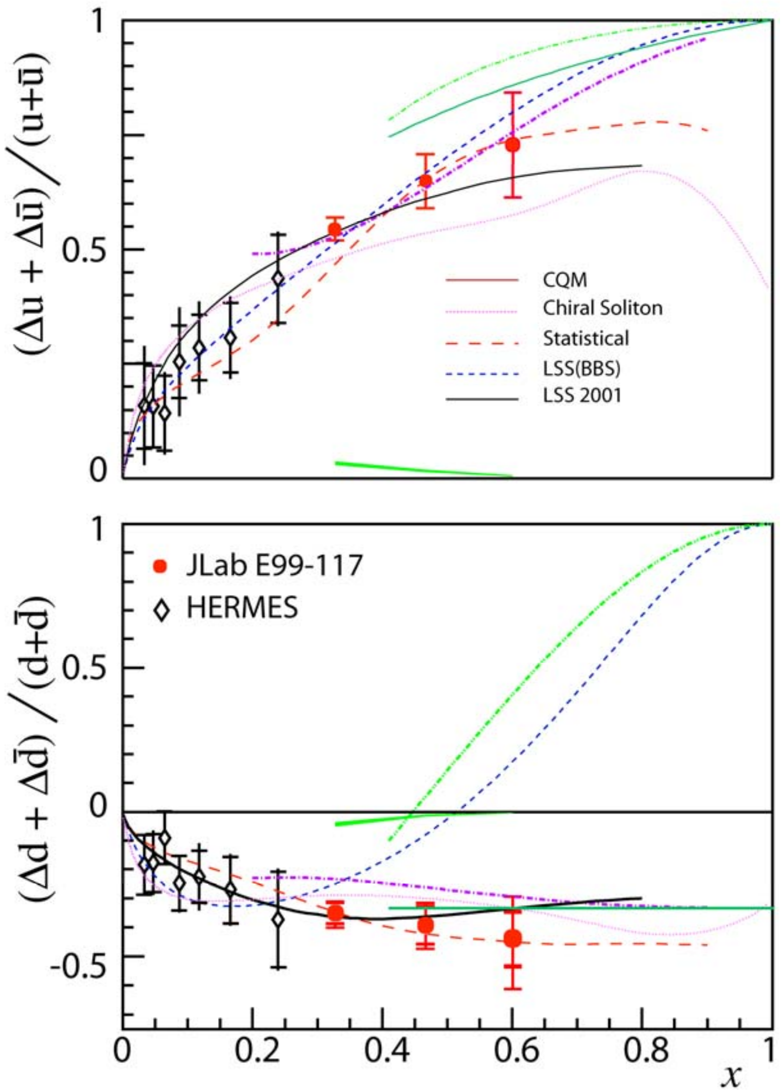
Parton Model Ideas Valid @ 6 GeV

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

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

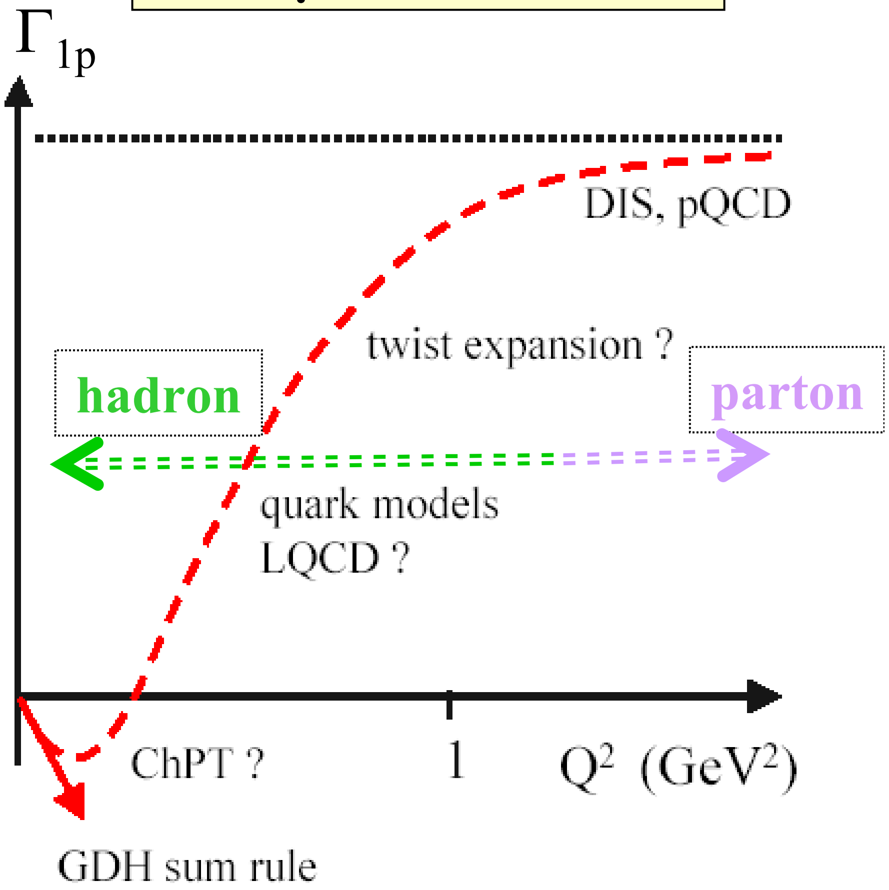
$\vec{e} + \vec{p} \rightarrow e + X$

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

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

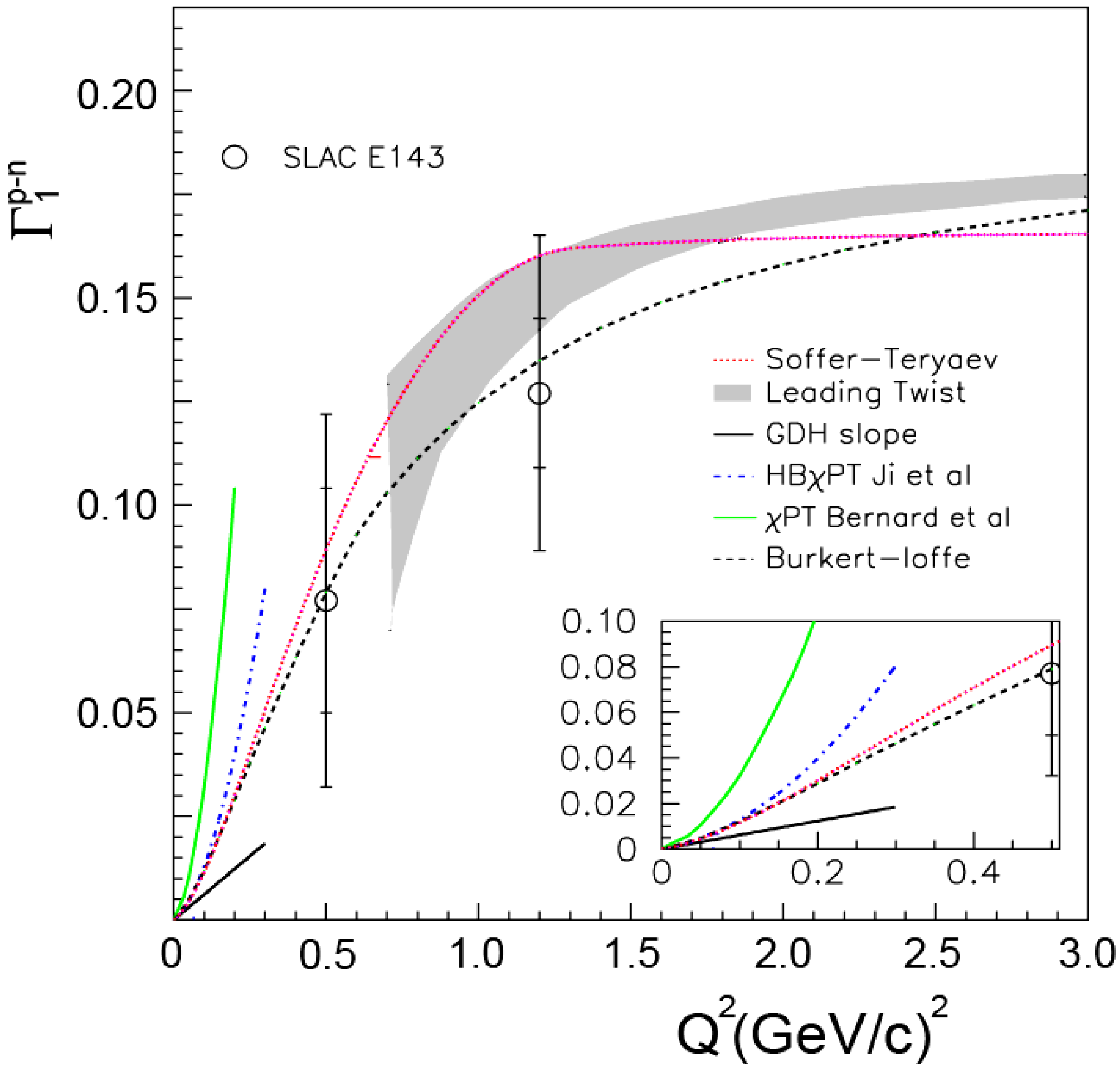


Expect rapid change of Γ_1 in transition from the hadronic to the partonic regimes.

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

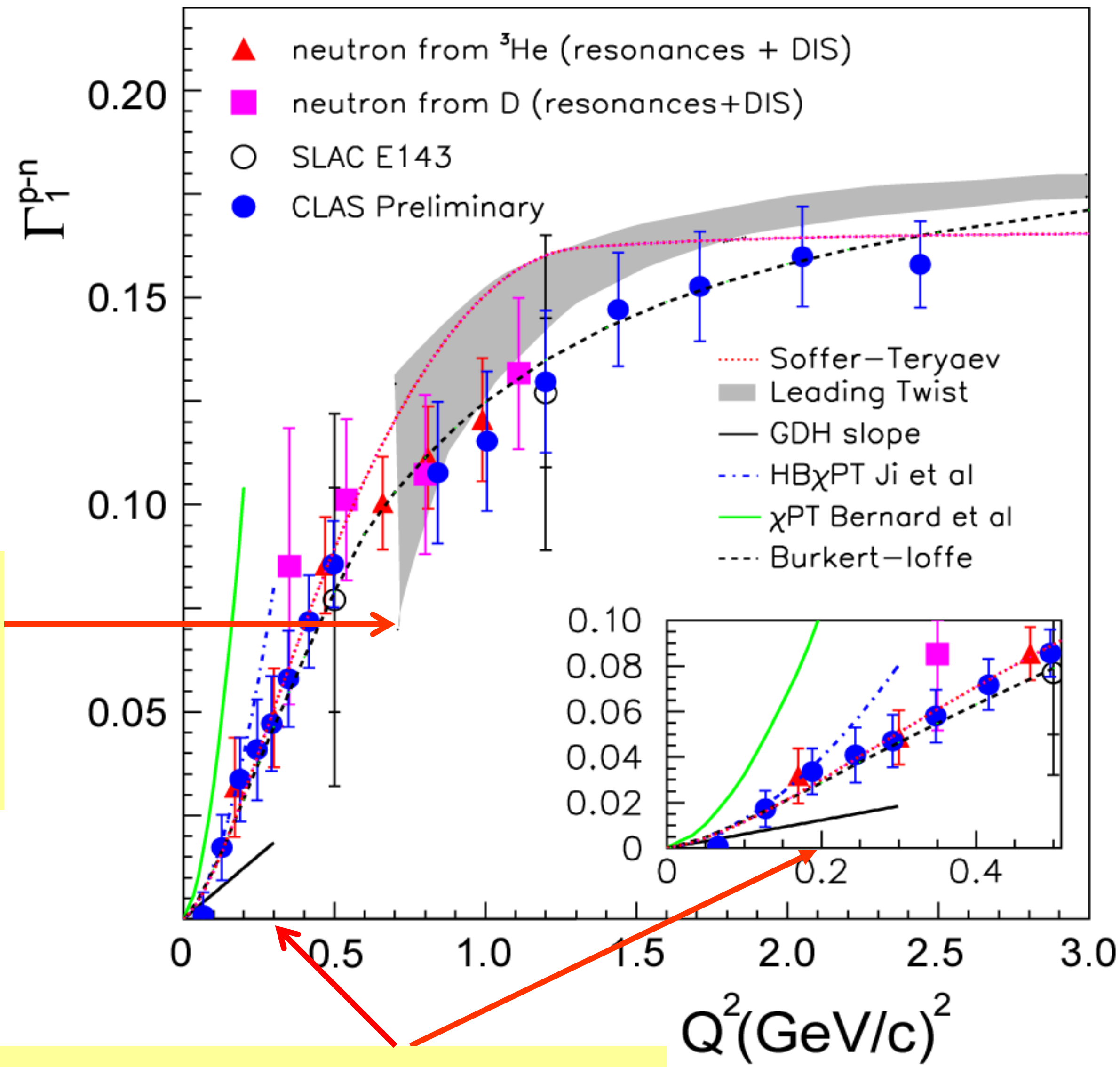
Bjorken Integral Γ_1^{p-n} (pre-JLab)

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:

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

~ 0.3

Small?

? Large ?

The Impact of Quark and Gluon Motion on the Nucleon Spin

"TMDs and GPDs"

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