Fundamental Structure of Hadrons

Zein-Eddine Meziani

April 06, 2005

DOE Science Review for JLab 12 GeV Upgrade

The Science Problem ?

Quantum Chromodynamics (QCD) in the confinement regime:

How does it work?

- What do we know?

QCD works in the perturbative (weak) regime

Many experimental tests led to this conclusion, example:

Nucleon as a laboratory

- Proton is not pointlike (Nobel Prize: Hofstadter); Elastic electron scattering
- Quarks and gluons/Partons are the constituents; Deep Inelastic electron Scattering (Nobel prize: Friedman, Kendall and Taylor, 1991).

Theory celebrated recently

Asymptotic freedom (Nobel prize: Gross, Politzer and Wilczek, 2004).

but

Confinement in QCD is still a puzzle and among the 10 top problems in Physics! (Gross, Witten,....)

Strings 2000

Why Jlab 12 GeV?

- Transition from pQCD to Strong QCD needs data with high precision for a quantitative understanding of confinement

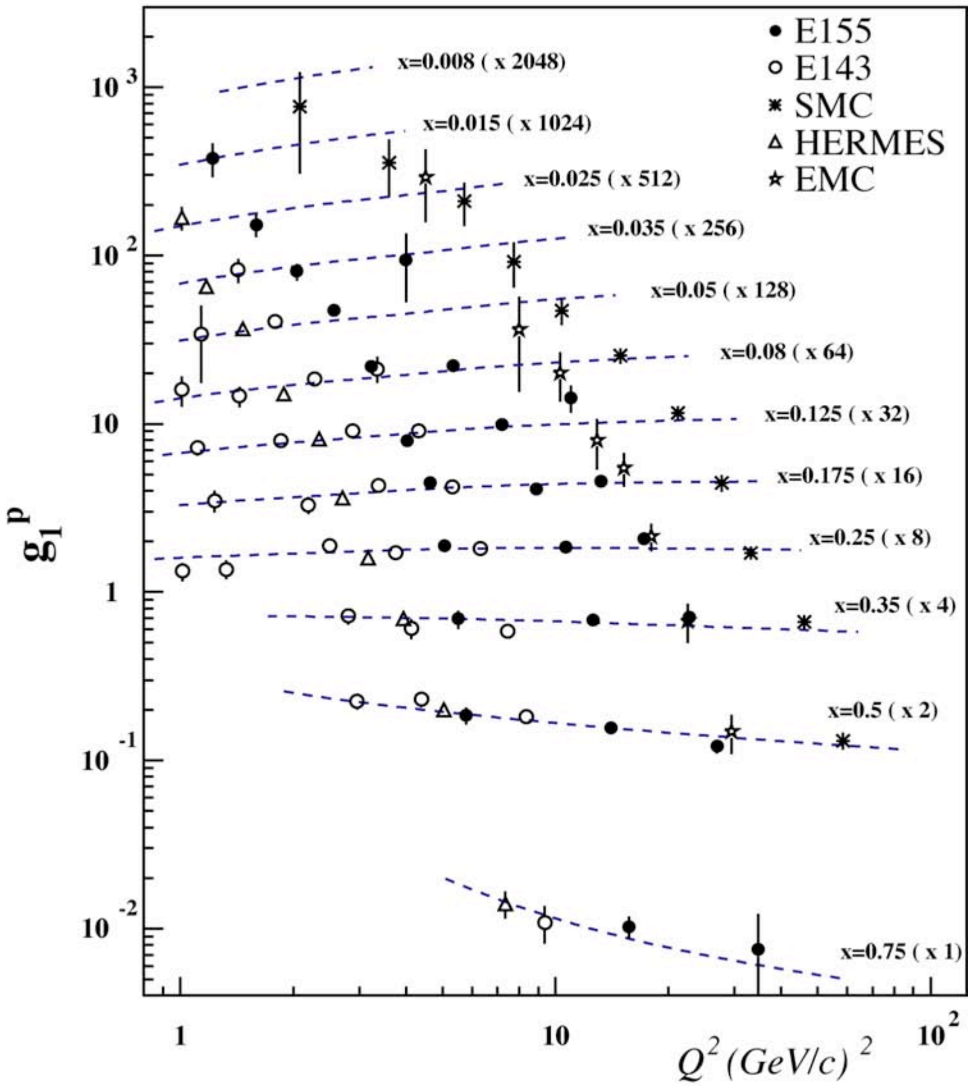
What quantities do we measure?

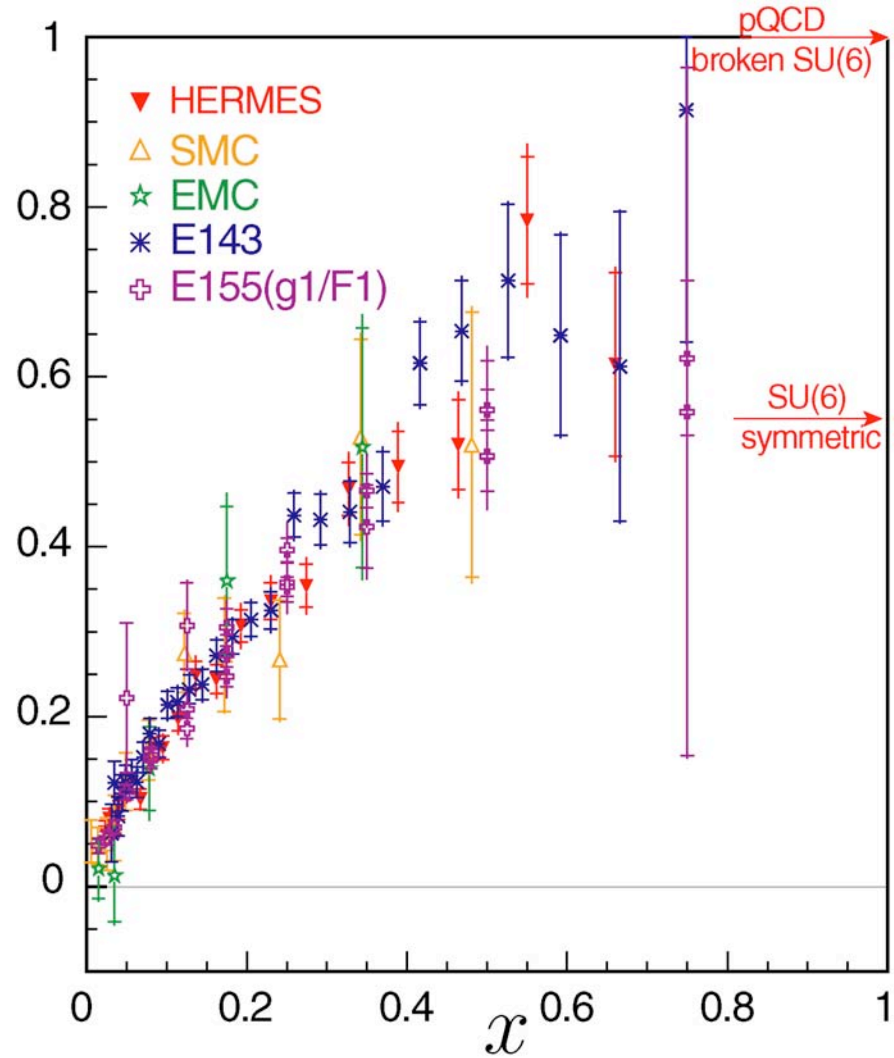
- Nucleon structure functions: [System responds incoherently]
  - Determine the helicity-dependent and -independent parton distributions at large x with flavor decomposition
  - Determine higher moments of structure functions to compare to Lattice QCD

- Hadron form factors : pion, nucleon [System responds coherently]

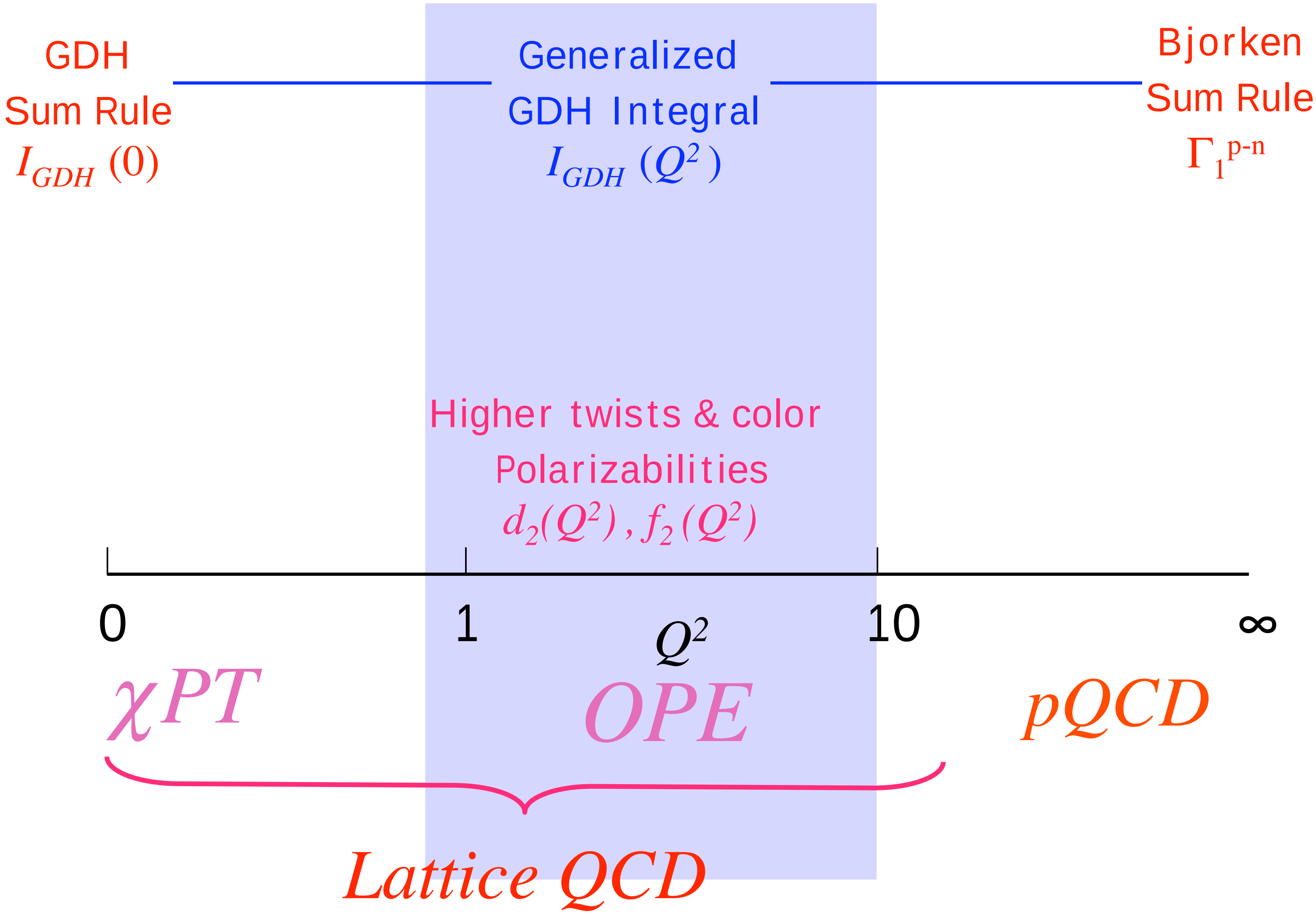
Examples of existing data and physics issues

World data on g_1^p

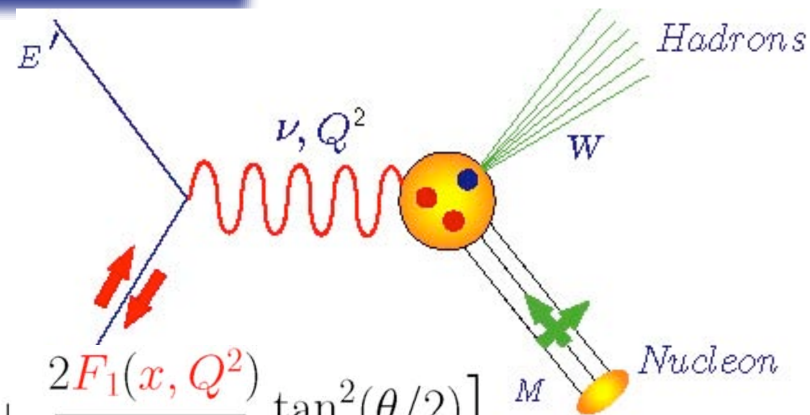




Examples of observables and theory tools



Inclusive DIS



- Unpolarized structure functions $F_1(x,Q^2)$ and $F_2(x,Q^2)$
  - ➡ Proton & neutron measurements provide d/u distributions ratio

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

- Polarized structure functions $g_1(x,Q^2)$ and $g_2(x,Q^2)$
  - ➡ Proton & neutron measurements combined with d/u provide the spin-flavor distributions $\Delta u/u$ & $\Delta d/d$

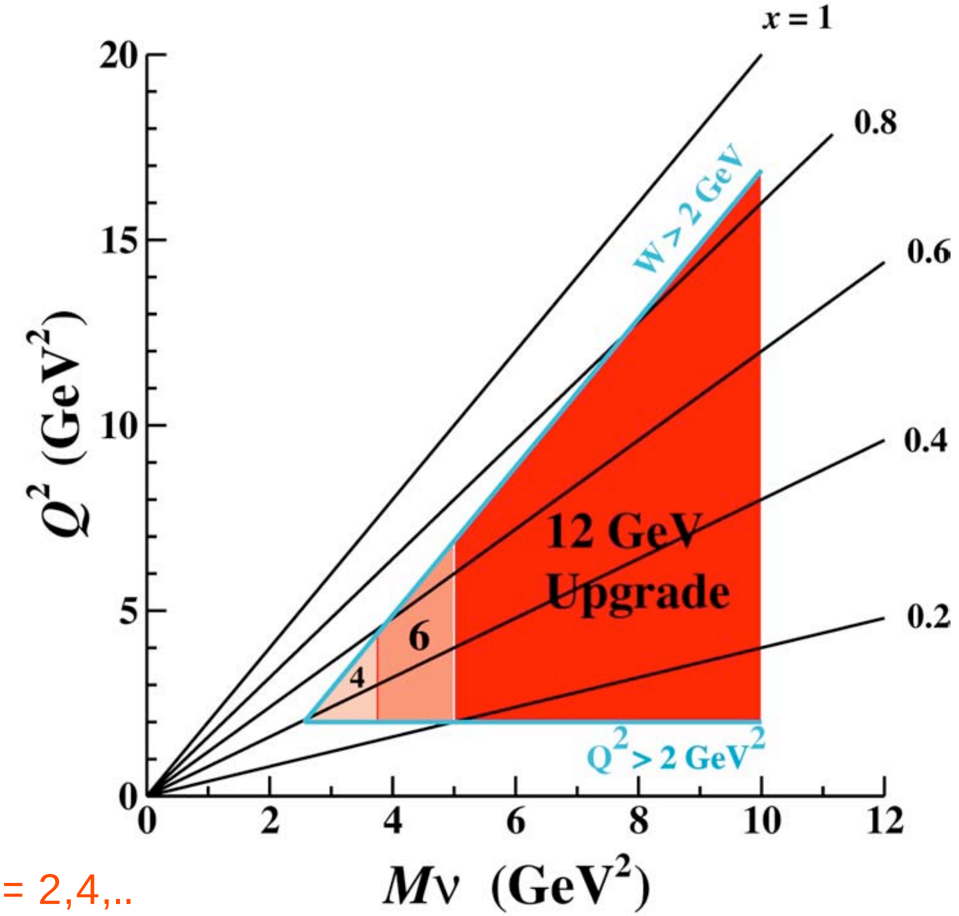
Q^2 : Four-momentum transfer
x : Bjorken variable
ν : Energy transfer
M : Nucleon mass
W : Final state hadrons mass

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

12 GeV upgrade kinematical reach

- Access to very large x (x > 0.4)
  - Clean region
    - No strange sea effects
    - No explicit hard gluons to be included
- Quark models can be a powerful tool to investigate the structure of the nucleon
- Comparison with lattice QCD is possible for higher moments of structure functions.

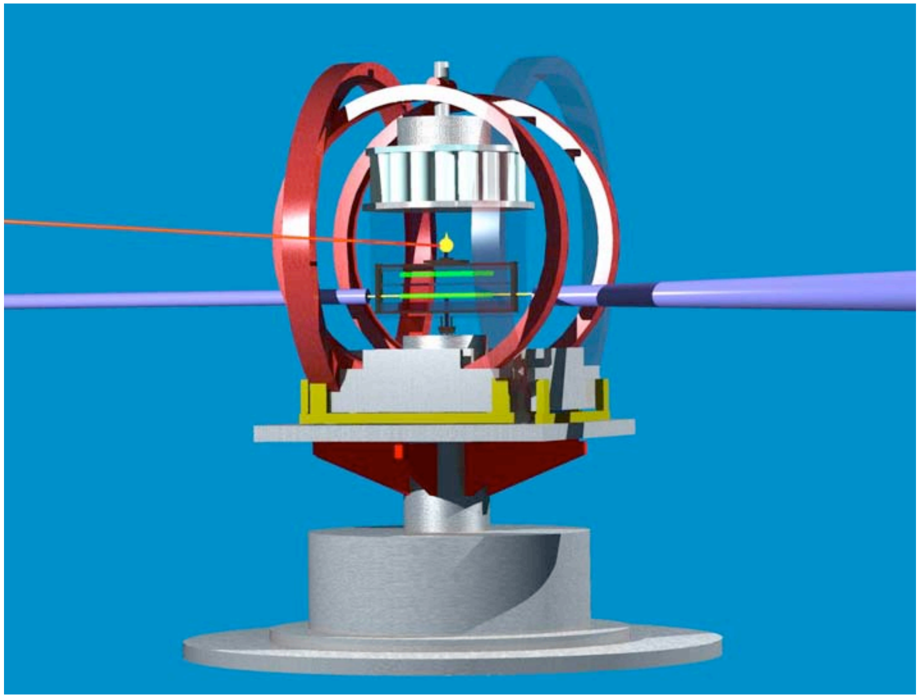


$$M_n(Q^2) = \int_0^1 dx\, x^{n-2}\, F_2(x, Q^2) \qquad n = 2,4,..$$

$$M_n(Q^2) = \int_0^1 dx\, x^{n-1}\, g_1(x, Q^2), \qquad n = 1, 3, 5...$$

The tools

- A high duty cycle, high current, polarized 12 GeV electron beam
- A high luminosity Hall.
- A large acceptance Hall.
- Polarized targets

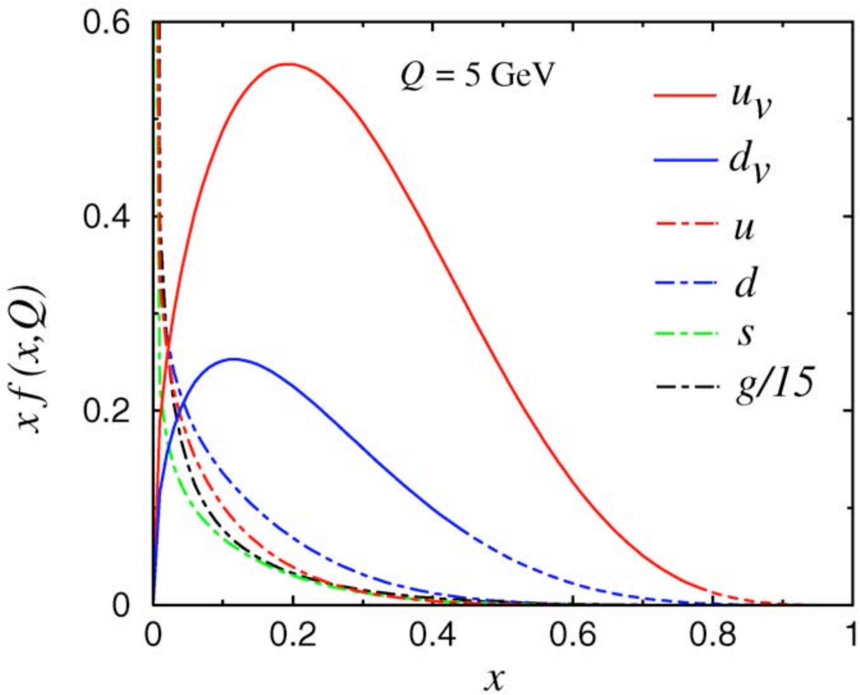


PDFs in the valence quark region

Understand the nucleon structure in the valence quark region

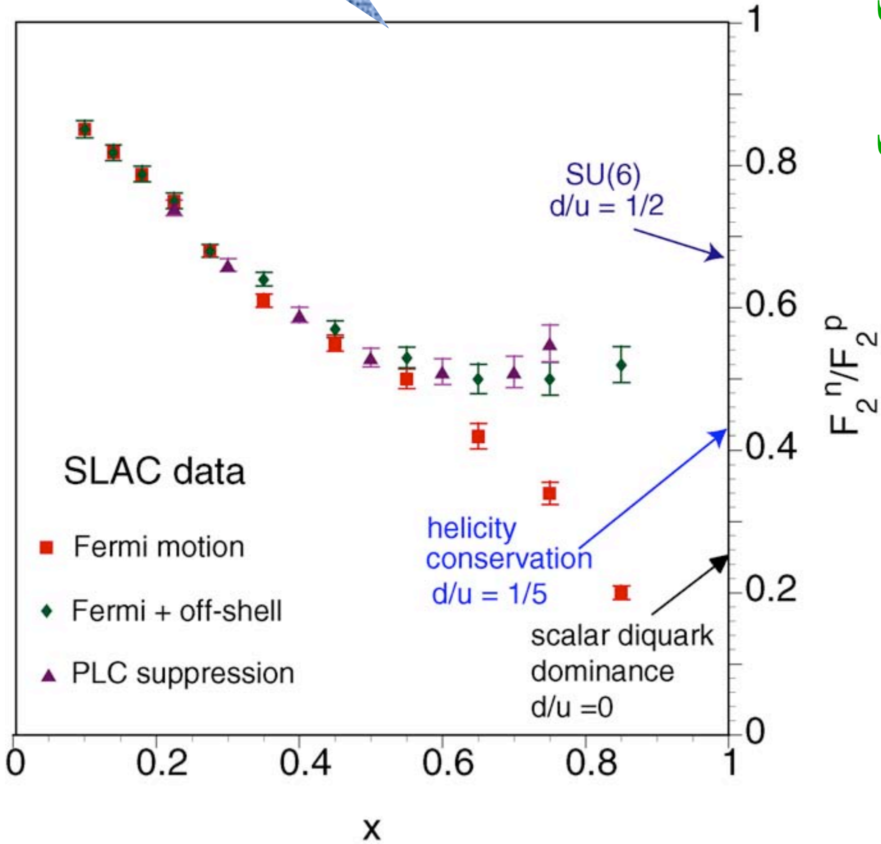
- What is required?

- Complete knowledge of parton distribution functions (PDFs).
  - Unpolarized, helicity-dependent
- Theoretically
  - large x exposes valence quarks
    - free of sea effects
  - x->1 behavior – sensitive test of spin-flavor symmetry breaking
  - important for higher moments of PDFs - compare with lattice QCD
  - intimately related with resonances, quark-hadron duality



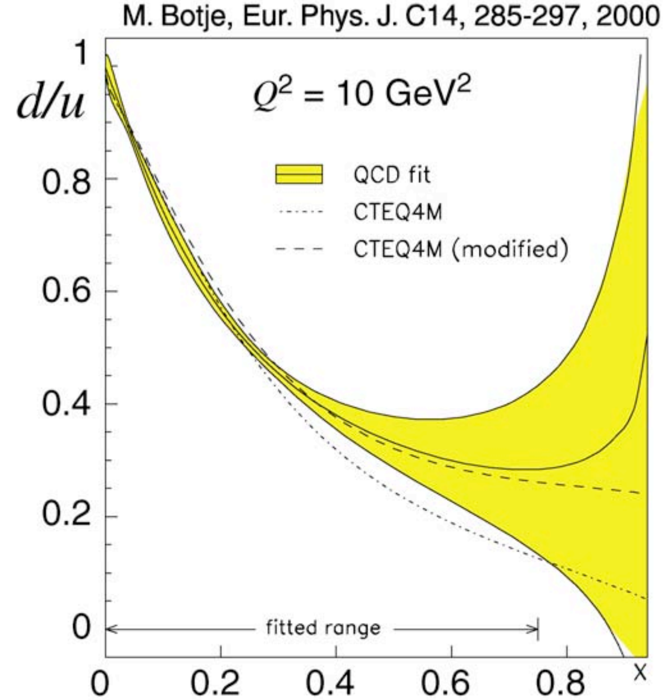
Unpolarized Neutron to Proton ratio

- In the large x region (x>0.5) the ratio F_2^n/F_2^p is not well determined due to the lack of free neutron targets



- Impact:
  - determine valence *d* quark momentum distribution
  - extract helicity dependent quark distributions through inclusive DIS
  - high x and Q^2 background in high energy particle searches.
  - construct moments of structure functions

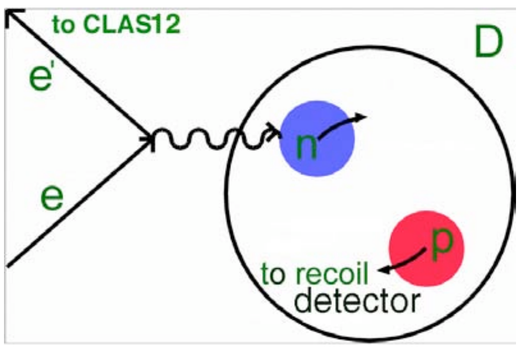
M. Botje, Eur. Phys. J. C14, 285-297, 2000



Unpolarized Neutron to Proton ratio

Spectator tagging

- Nearly free neutron target by tagging low-momentum proton from deuteron at backward angles



- Small p (70-100 MeV/c)
  - Minimize on-shell extrapolation (neutron only 7 MeV off-shell)
- Backward angles (θ_{pq}> 110^o)
  - Minimize final state interactions

DIS from A=3 nuclei

- Mirror symmetry of A=3 nuclei
  - Extract F_2^n/F_2^p from ratio of ^{3}He/^{3}H structure functions

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - \mathcal{R}}$$

  - Super ratio

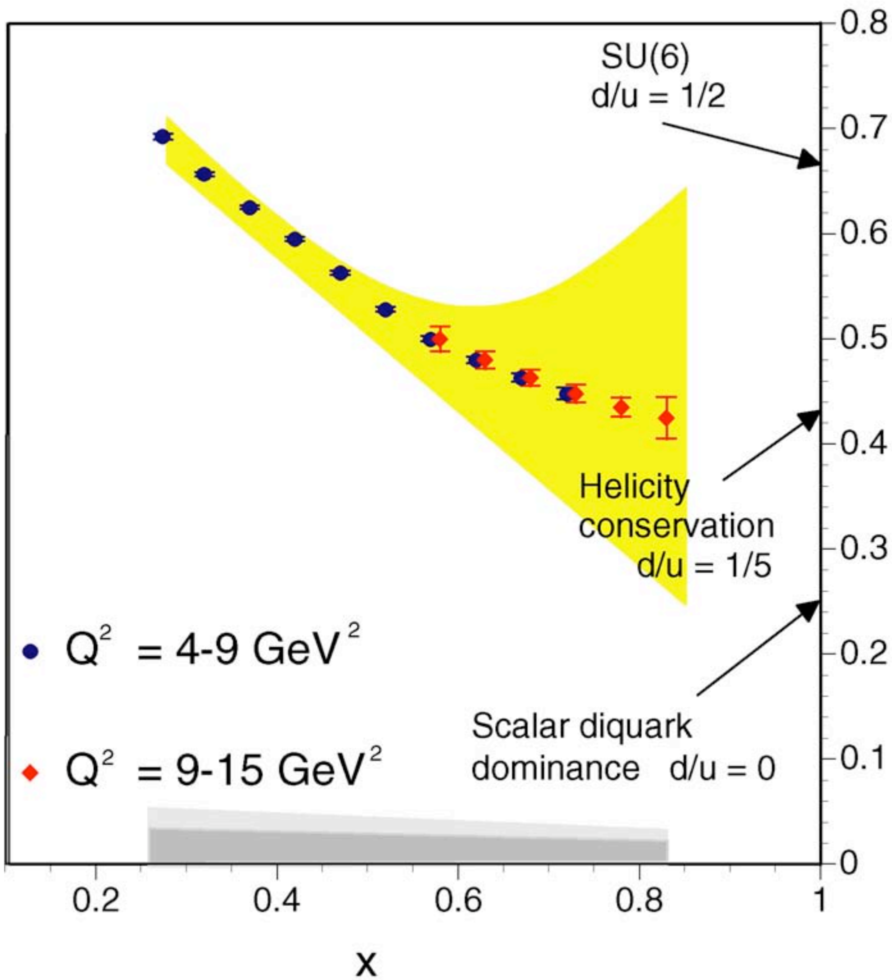
R = ratio of "EMC ratios" for ^{3}He and ^{3}H calculated to within 1%

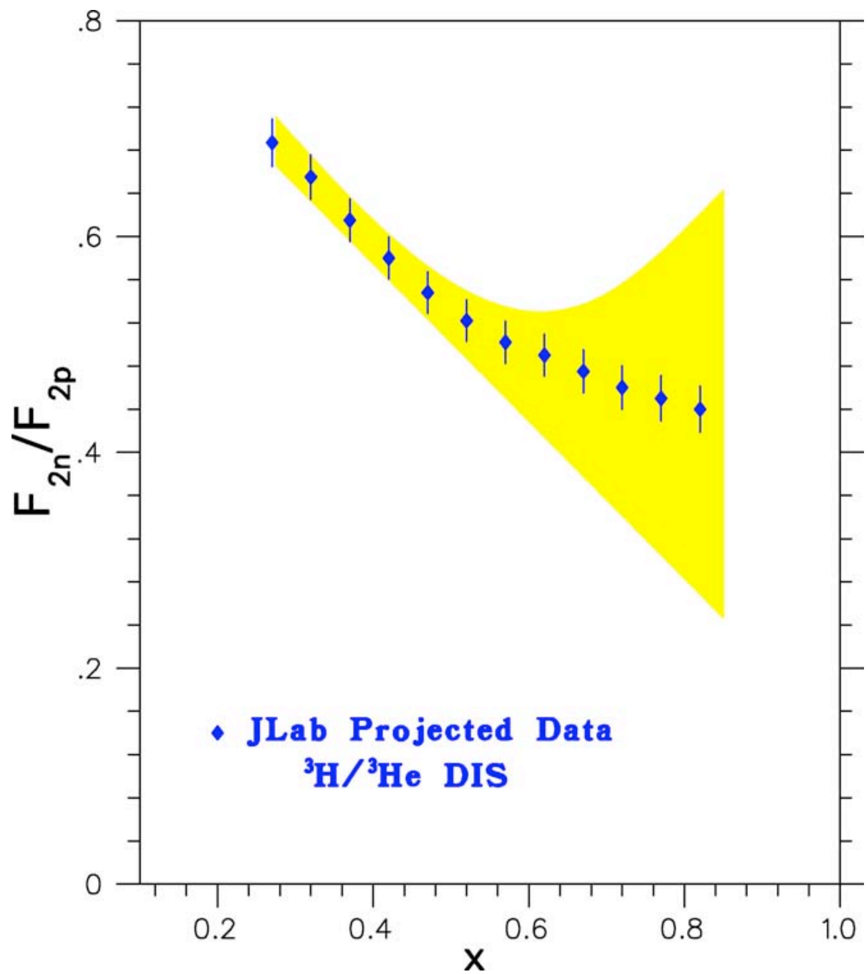
- Most systematic and theoretical uncertainties cancel

Unpolarized Neutron to Proton Ratio

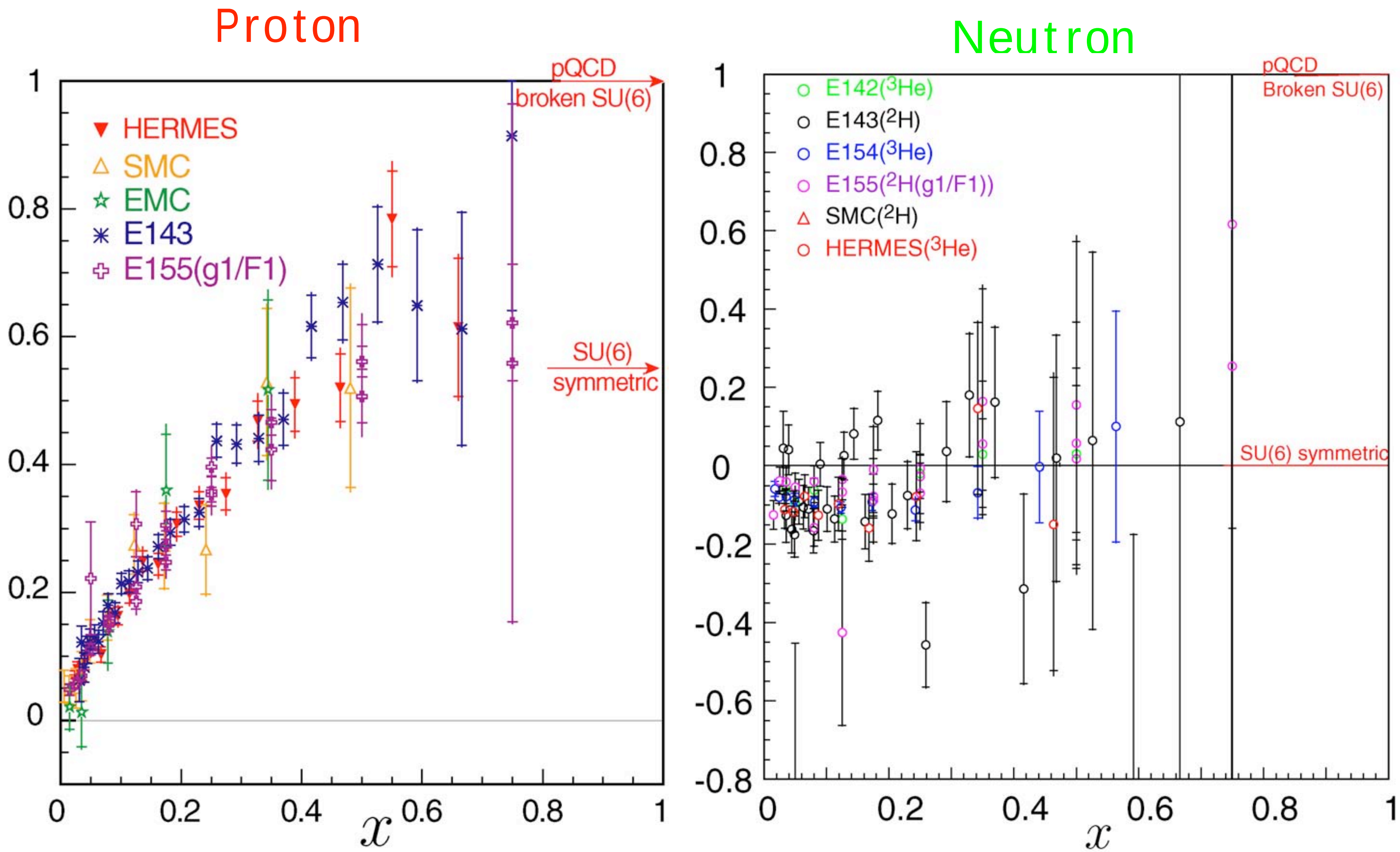
HallB 11 GeV with CLAS12

Hall C 11 GeV with HMS

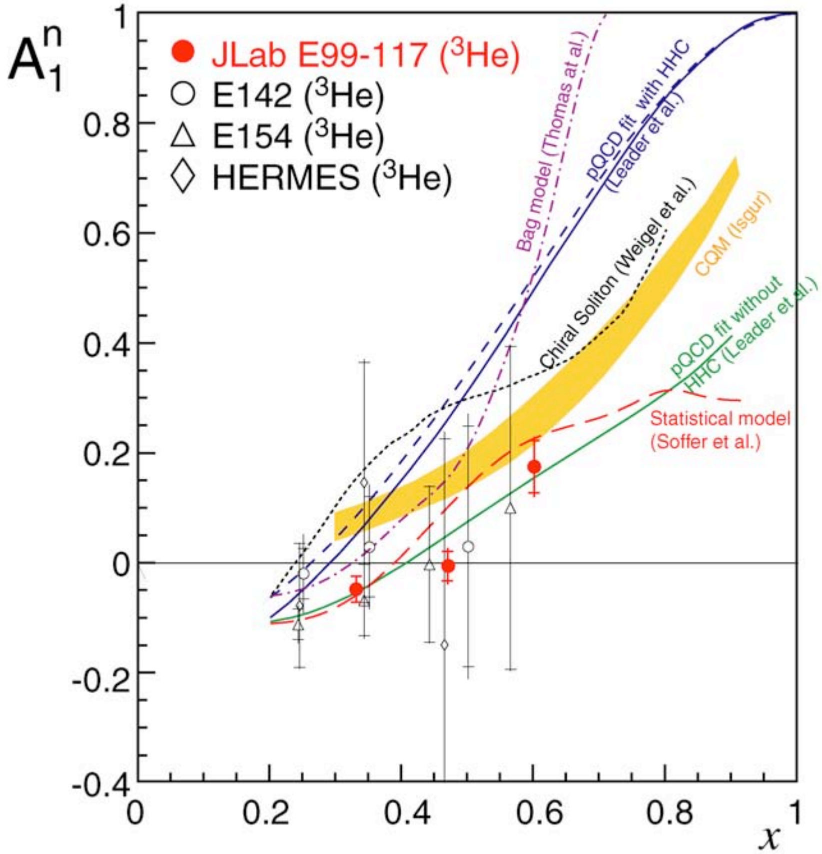


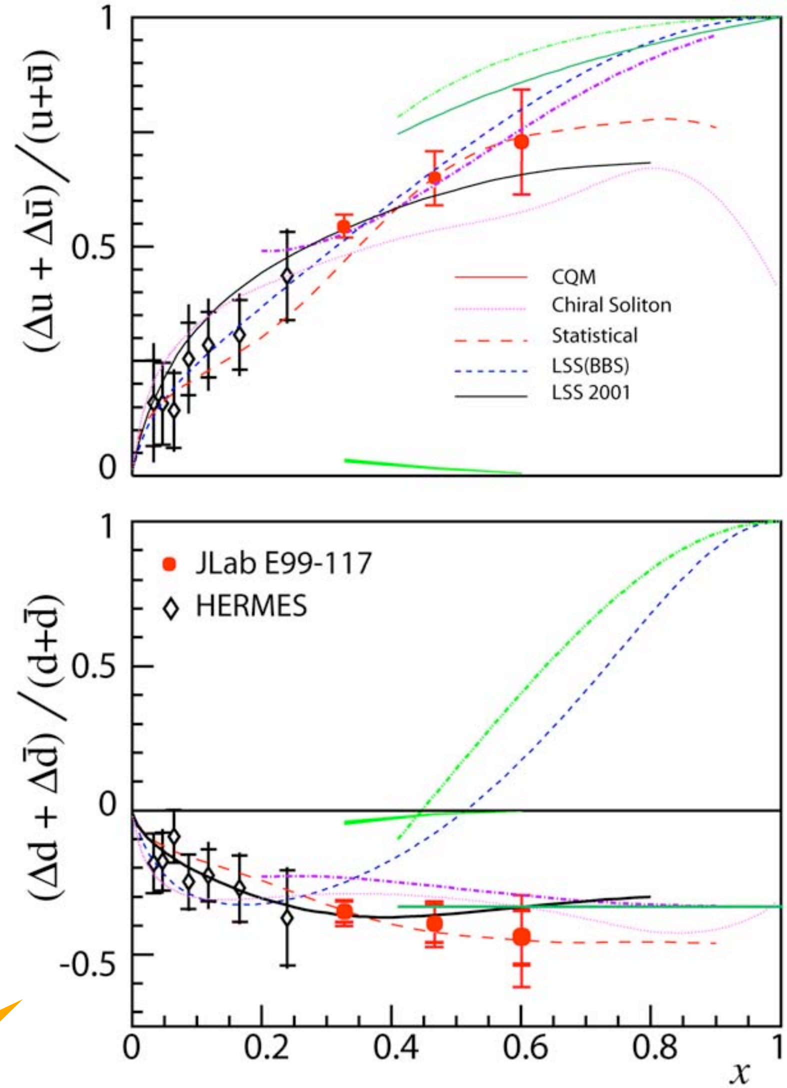


World data for A_1



A_1^n and Helicity-Flavor Decomposition





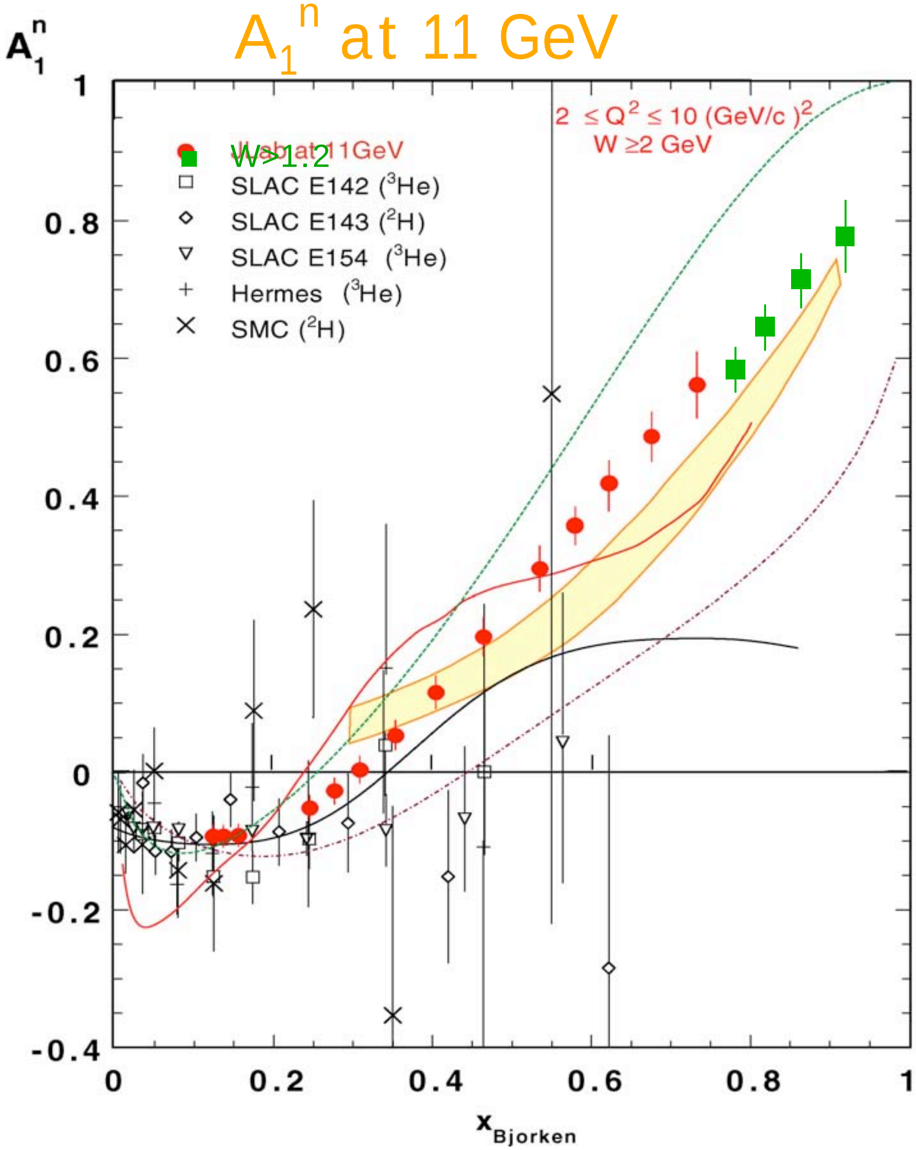
$$\frac{\Delta u + \Delta \bar{u}}{u} = \frac{4}{15}\frac{g_1^p}{F_1^p}(4 + R^{du}) - \frac{1}{15}\frac{g_1^n}{F_1^n}(1 + 4R^{du})$$

$$\frac{\Delta d + \Delta \bar{d}}{d} = \frac{4}{15}\frac{g_1^n}{F_1^n}\left(4 + \frac{1}{R^{du}}\right) - \frac{1}{15}\frac{g_1^p}{F_1^p}\left(1 + 4\frac{1}{R^{du}}\right)$$

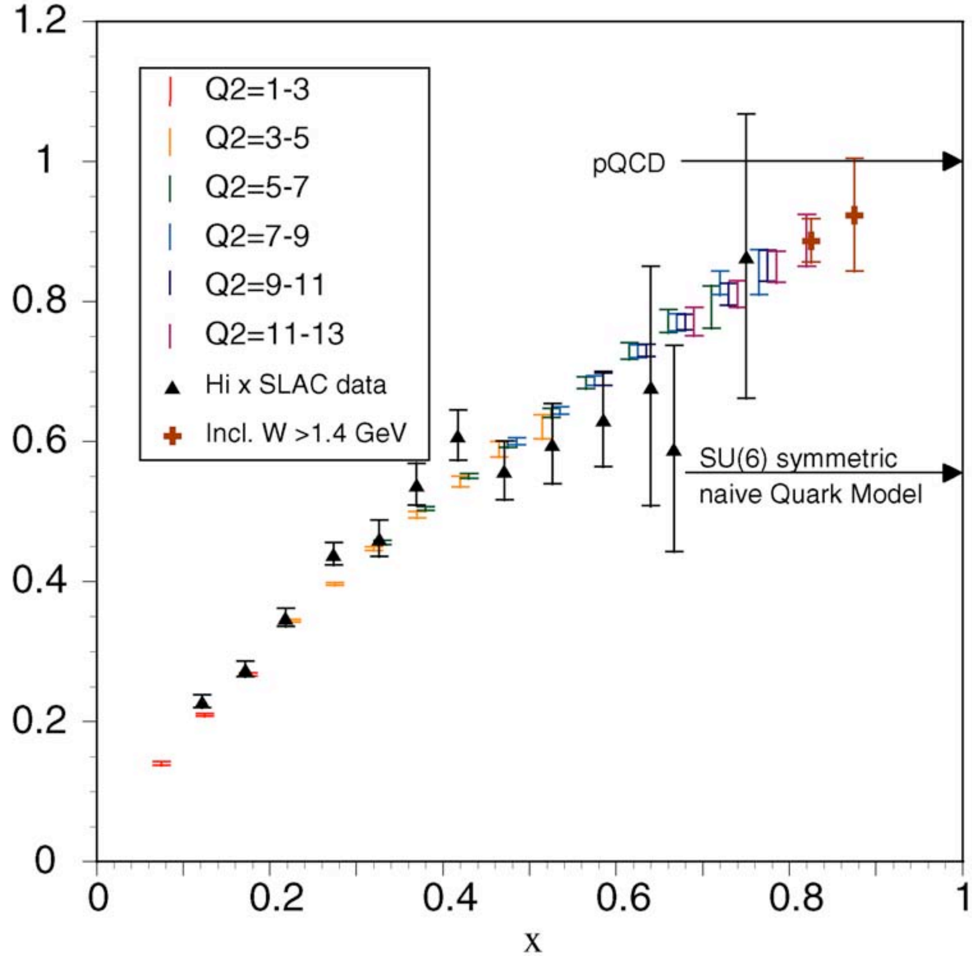
$$R^{du} = \frac{d + \bar{d}}{u + \bar{u}}$$

Inclusive measurements of asymmetries

A_1^n at 11 GeV



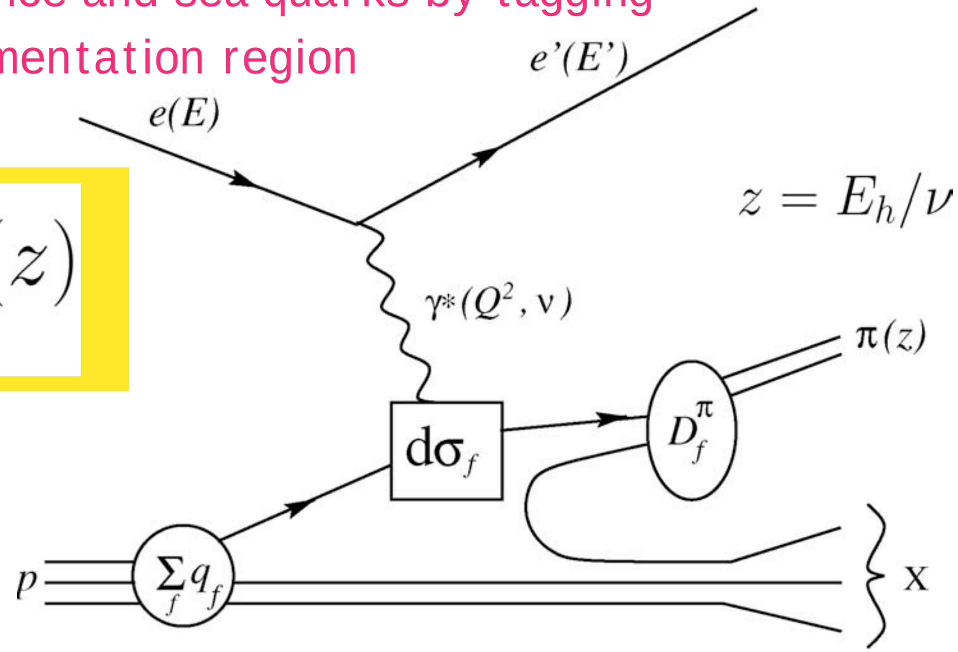
A_1^p at 11 GeV



Semi-inclusive DIS

- Spin-flavor decomposition of valence and sea quarks by tagging hadron (e.g. π, K) in current fragmentation region

$$d\sigma = \sum_f e_f^2 q_f(x) D_f^h(z)$$



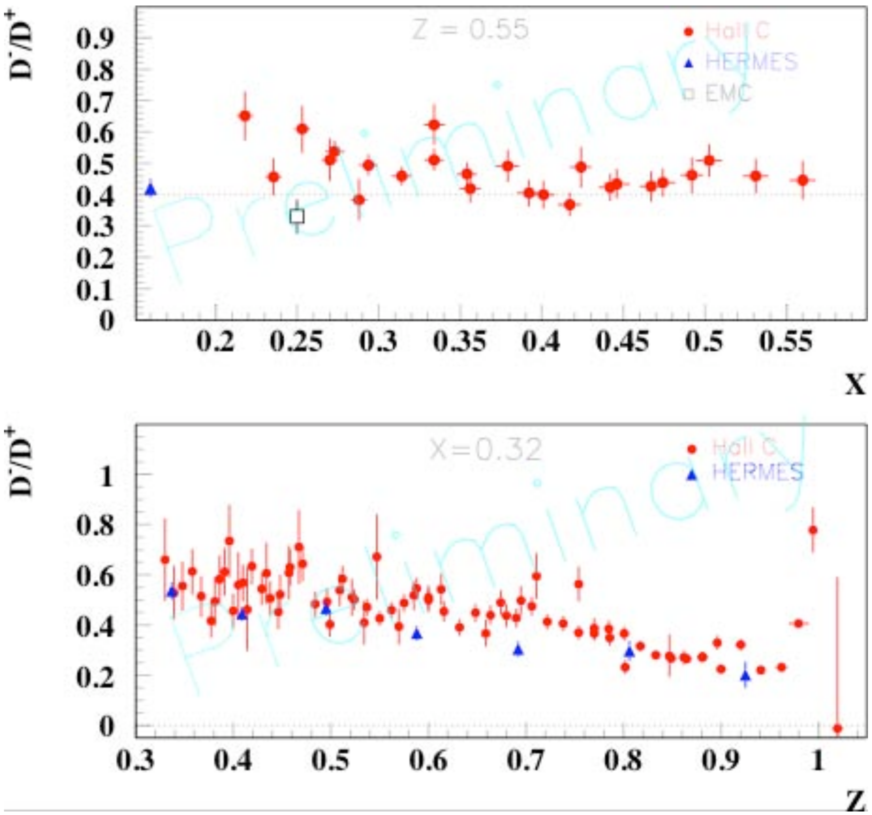
D(z) quark--> hadron fragmentation function

- unpolarized or polarized beam and target
- mass of unobserved X system, W_X > 2 GeV

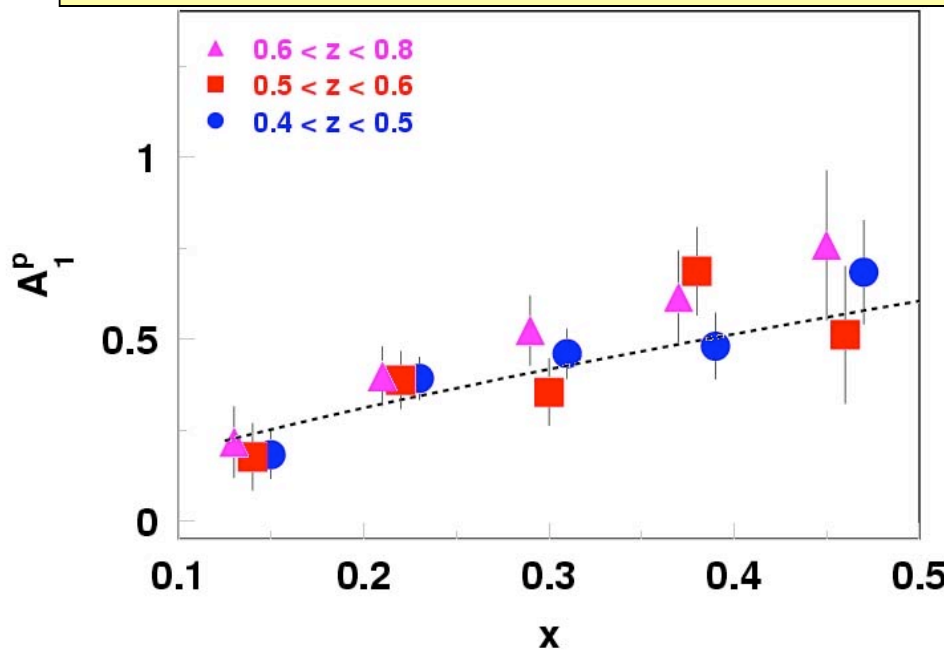
Semi-inclusive DIS (Factorization!)

Factorization of current and target fragmentation

- Berger criterion $\Delta\eta>2$ to avoid contamination from target fragmentation ($z > 0.4$)

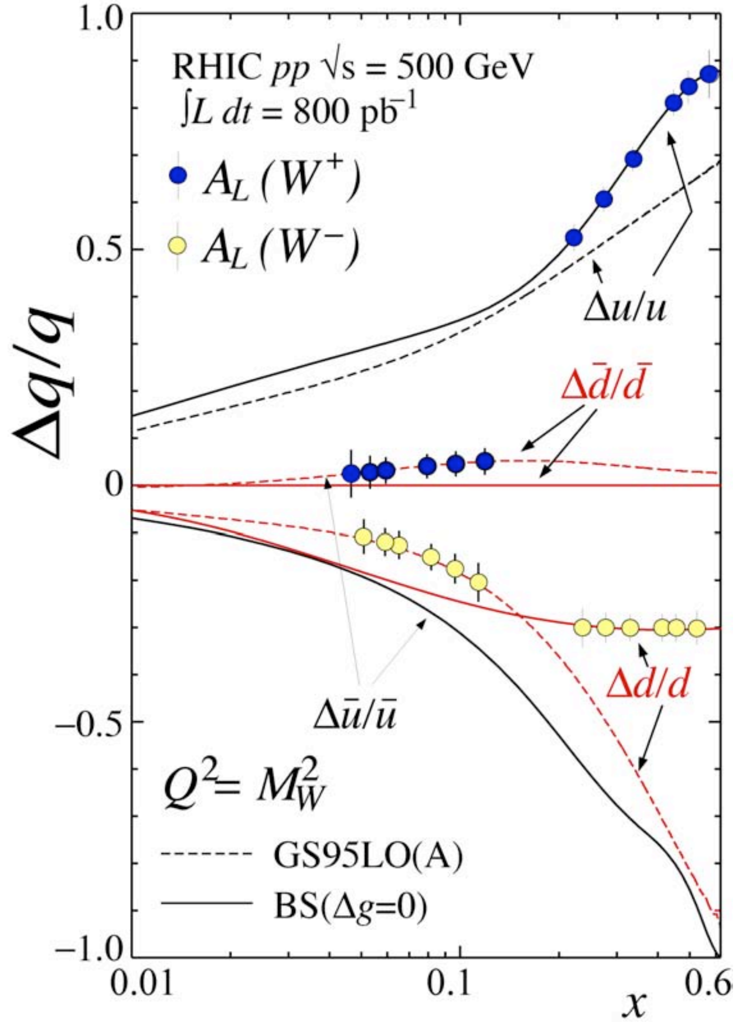


ep -> e’ π^+ X (E_e =5.7 GeV, $M_X > 1.1$)

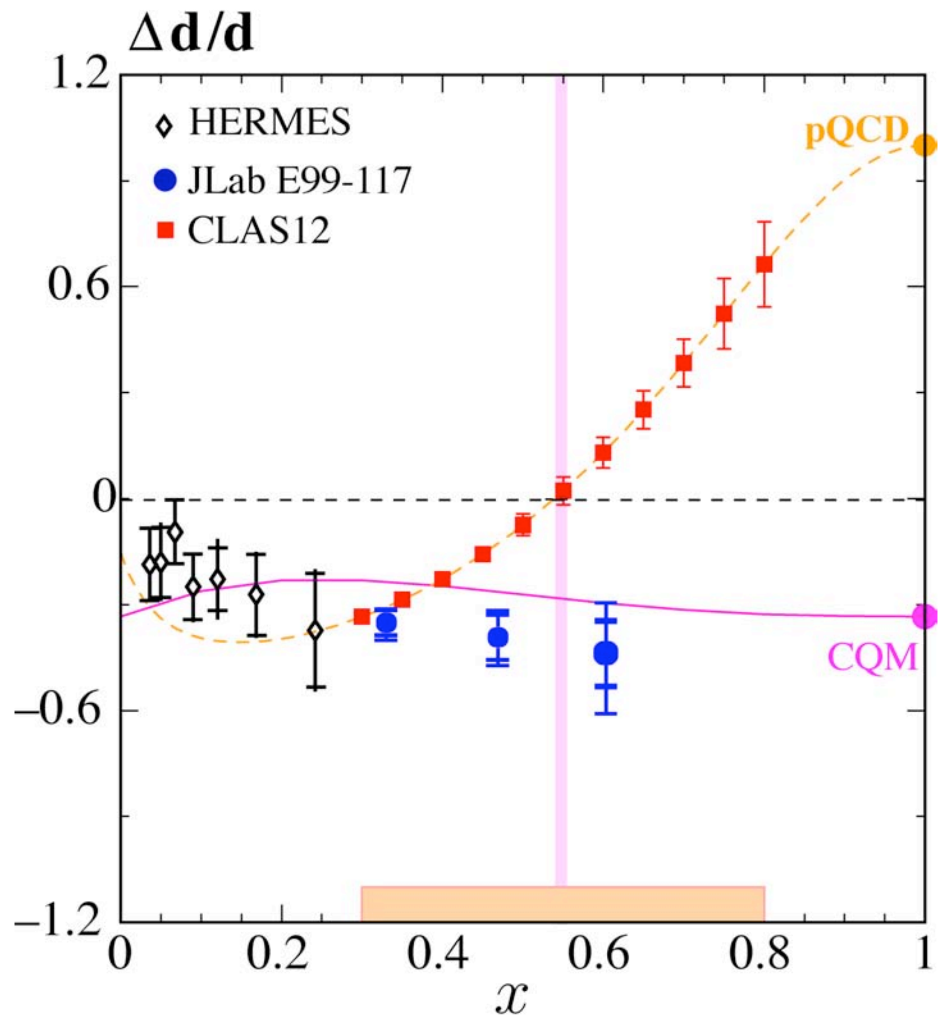


Flavor decomposition (2)

At RHIC with W production



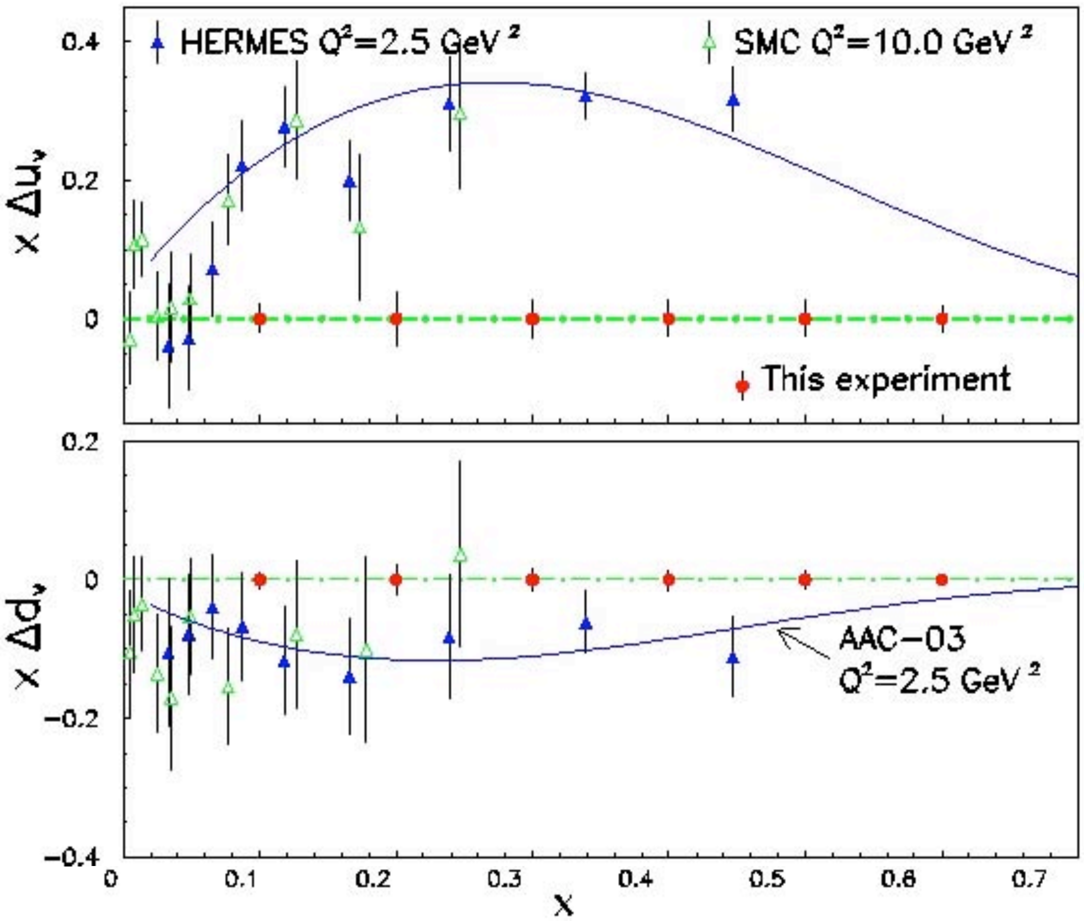
At JLab 12 GeV with SIDIS



Flavor decomposition (2)

E_e =11 GeV NH_3 and ^3He

- Asymmetry measurements with different hadrons (π+, π–) and targets (p,n) allow flavor separation



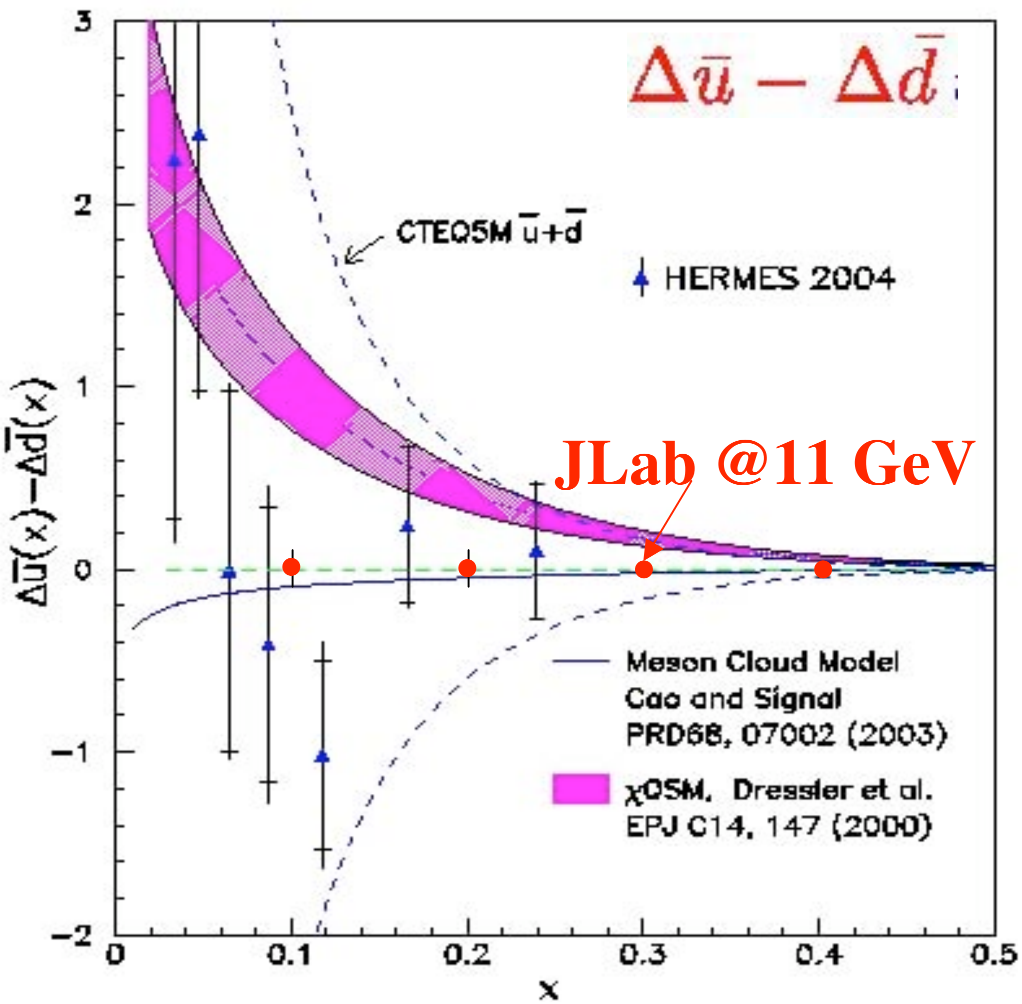
Flavor decomposition: polarized sea

- Predictions:
  - Instantons (χQSM):

$$\Delta\bar{u} \approx -\Delta\bar{d}$$

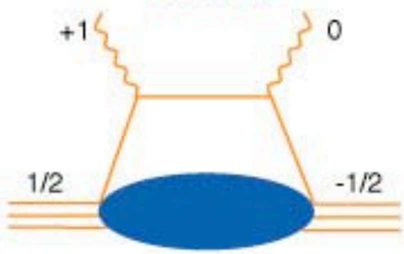
- First data from HERMES

$$\Delta\bar{u} - \Delta\bar{d} \approx 0$$



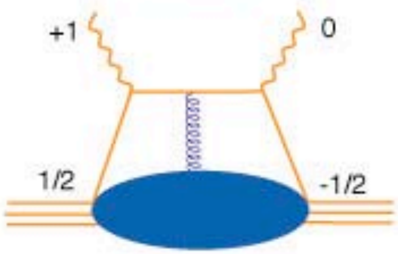
Quark-gluon correlations and g_2

twist-2



Carry one unit of orbital angular momentum

twist-3



Couple to a gluon

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$$

- a twist-2 term (Wandzura & Wilczek, 1977):

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(y,Q^2)\frac{dy}{y}$$

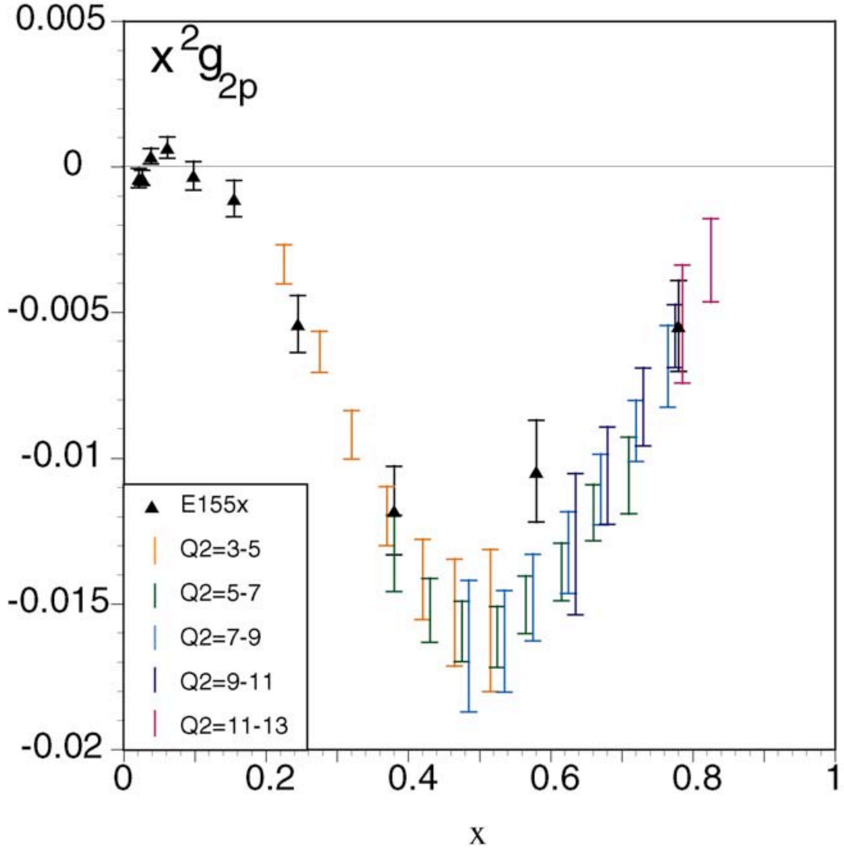
- a twist-3 term with a suppressed twist-2 piece (Cortes, Pire & Ralston, 92):

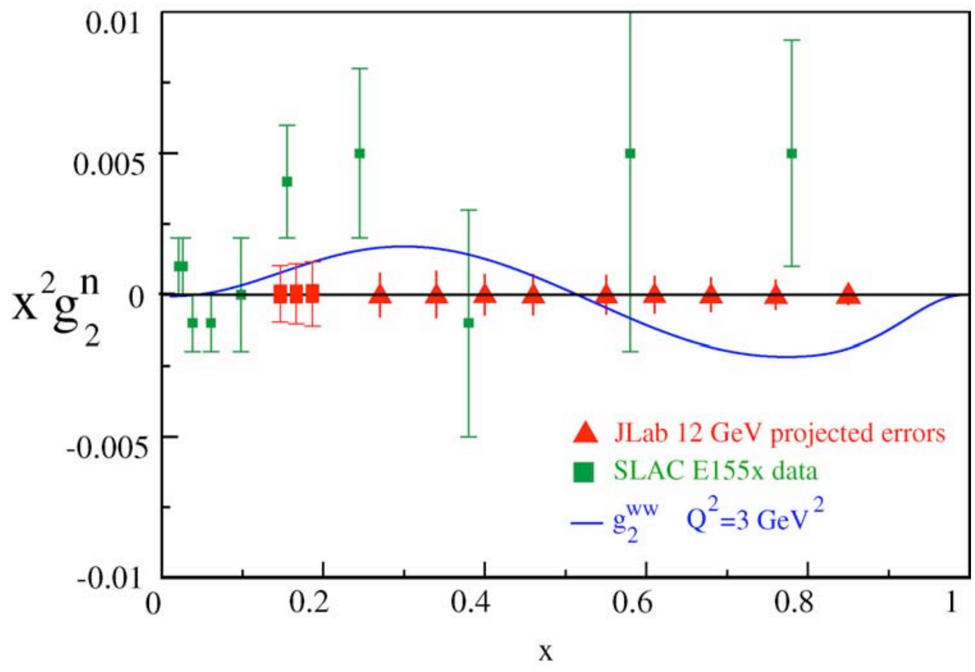
$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left(\frac{m_q}{M}h_T(y,Q^2) + \xi(y,Q^2)\right)\frac{dy}{y}$$

transversity → h_T

quark-gluon correlation → ξ

g_2 at JLab with 11 GeV





Color "Polarizabilities"

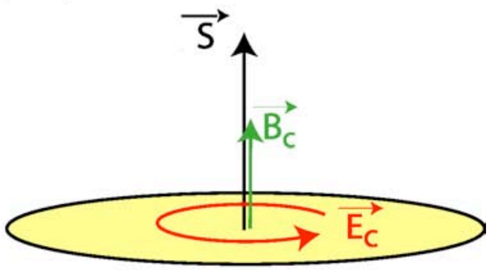
How does the gluon field respond when a nucleon is polarized ?

Define color magnetic and electric polarizabilities (in nucleon rest frame):

$$\chi_{B,E} 2M^2 \vec{S} = \langle PS | \vec{O}_{B,E} | PS \rangle$$

where $\vec{O}_B = \psi^\dagger g \vec{\boldsymbol{B}} \psi$

$$\vec{O}_E = \psi^\dagger \vec{\alpha} \times g \vec{\boldsymbol{E}} \psi$$



$$d_2 = (\chi_E + 2\chi_B)/8$$

$$f_2 = (\chi_E - \chi_B)/2$$

d_2 and f_2 represent the response of the color $\vec{B}$ & $\vec{E}$ fields to the nucleon polarization

Moments of Structure Functions

$$\Gamma_1(Q^2) \equiv \int_0^1 \mathrm{d}x\, g_1(x,Q^2)$$

$$= \Gamma_1^{\mathrm{twist}-2}(Q^2) + \frac{M_N^2}{9\,Q^2}\left[a_2(Q^2) + 4\,d_2(Q^2) + 4\,f_2(Q^2)\right] + \mathcal{O}\left(\frac{M_N^4}{Q^4}\right)$$

$$a_2(Q^2) \equiv 2\int_0^1 \mathrm{d}x\, x^2\, g_1^{\mathrm{twist}-2}(x,Q^2)$$ → target mass correction term

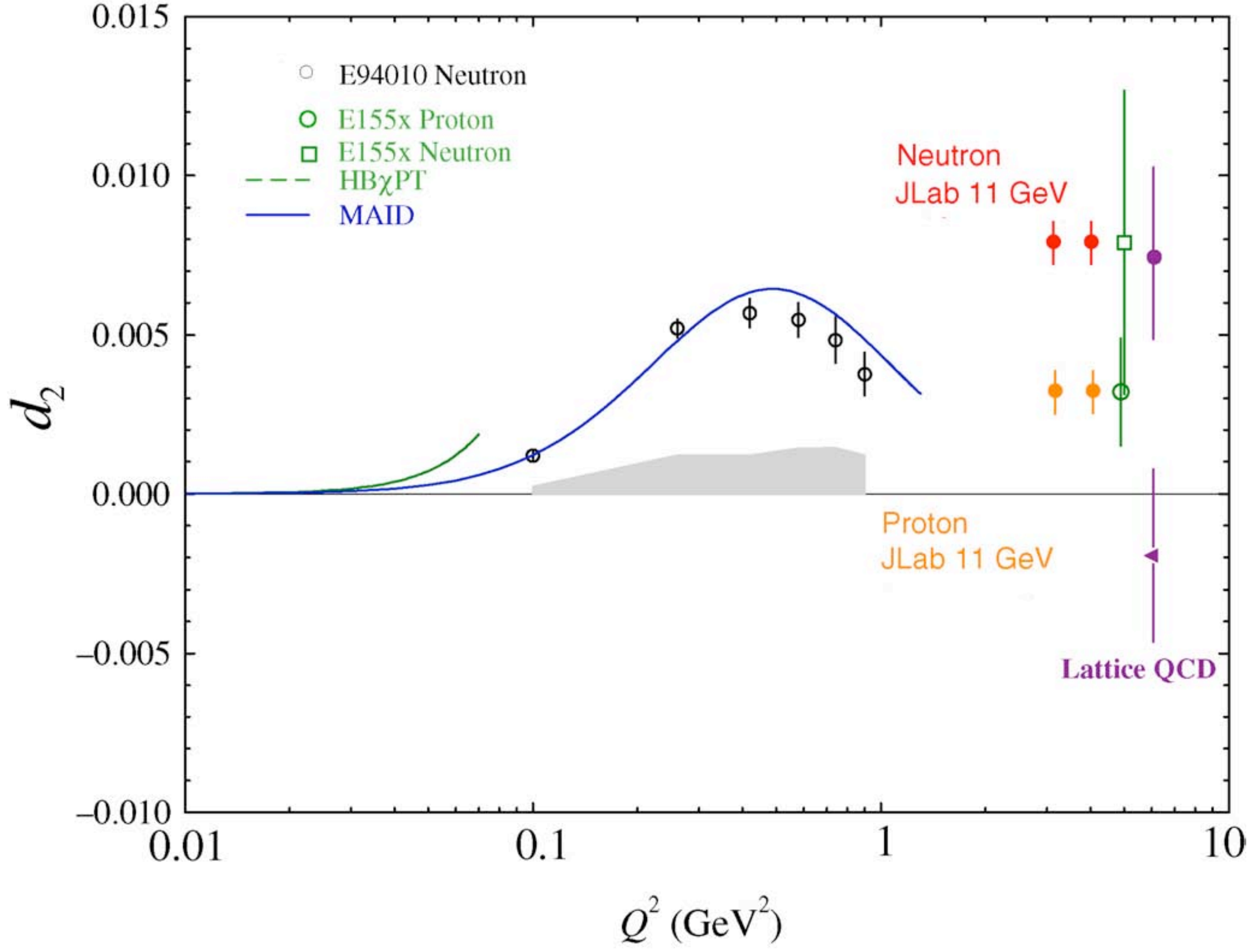
$d_2(Q^2)$ → dynamical twist-3 matrix element

$$d_2(Q^2) \equiv \int_0^1 \mathrm{d}x\, x^2\, \left\{3\,g_2(x,Q^2) + 2\,g_1(x,Q^2)\right\}$$

$f_2(Q^2)$ → dynamical twist-4 matrix element

- Both d_2 and f_2 are required to determine the color polarizabilities
- To extract f_2, d_2 needs to be determined first.

d_2 with 11 GeV at JLab

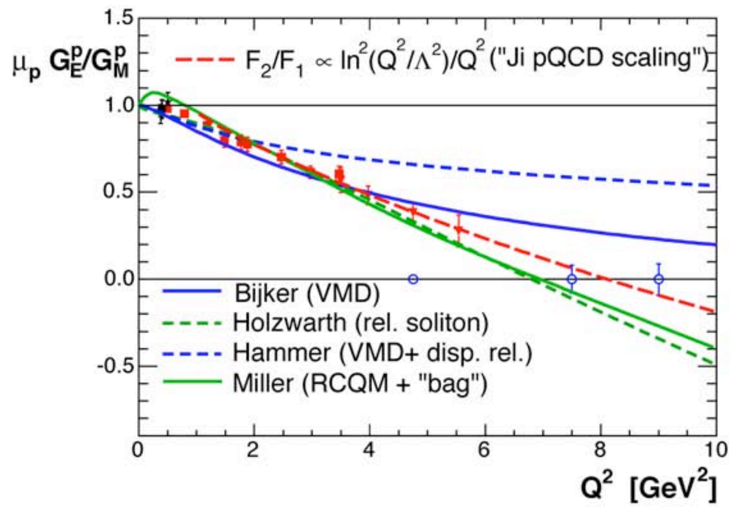


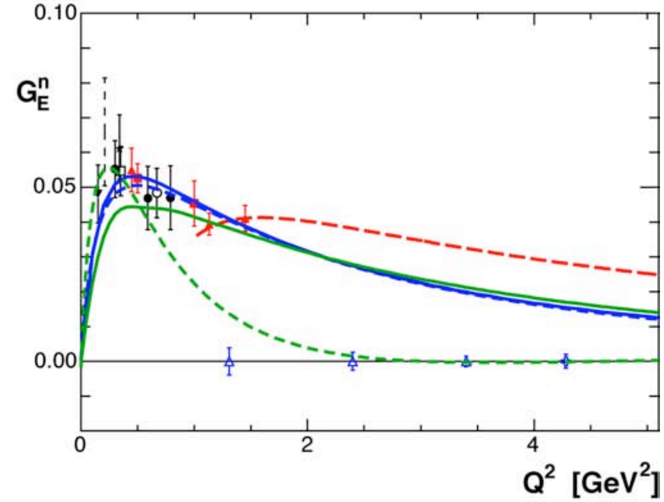
Nucleon Form Factors

proton

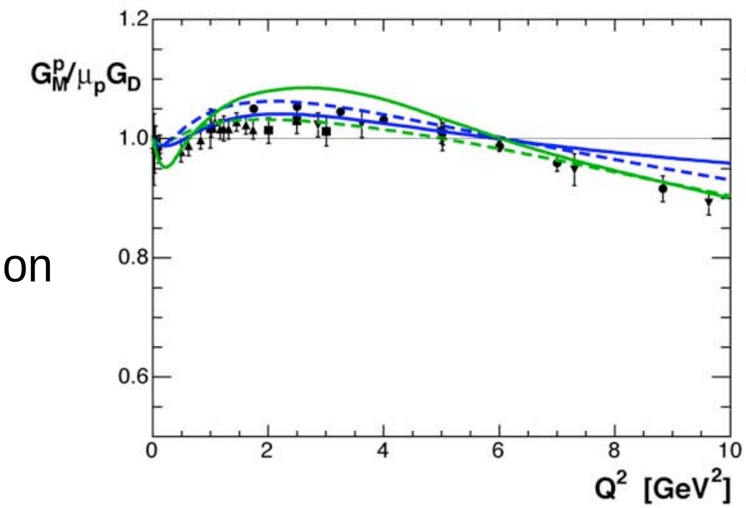
neutron

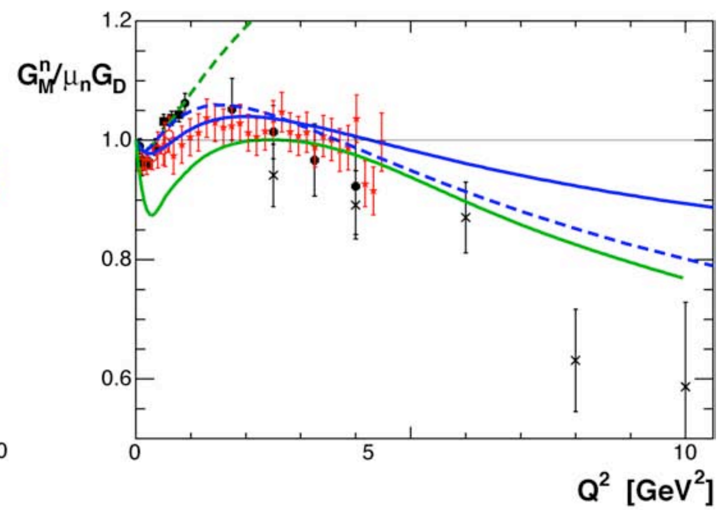
charge





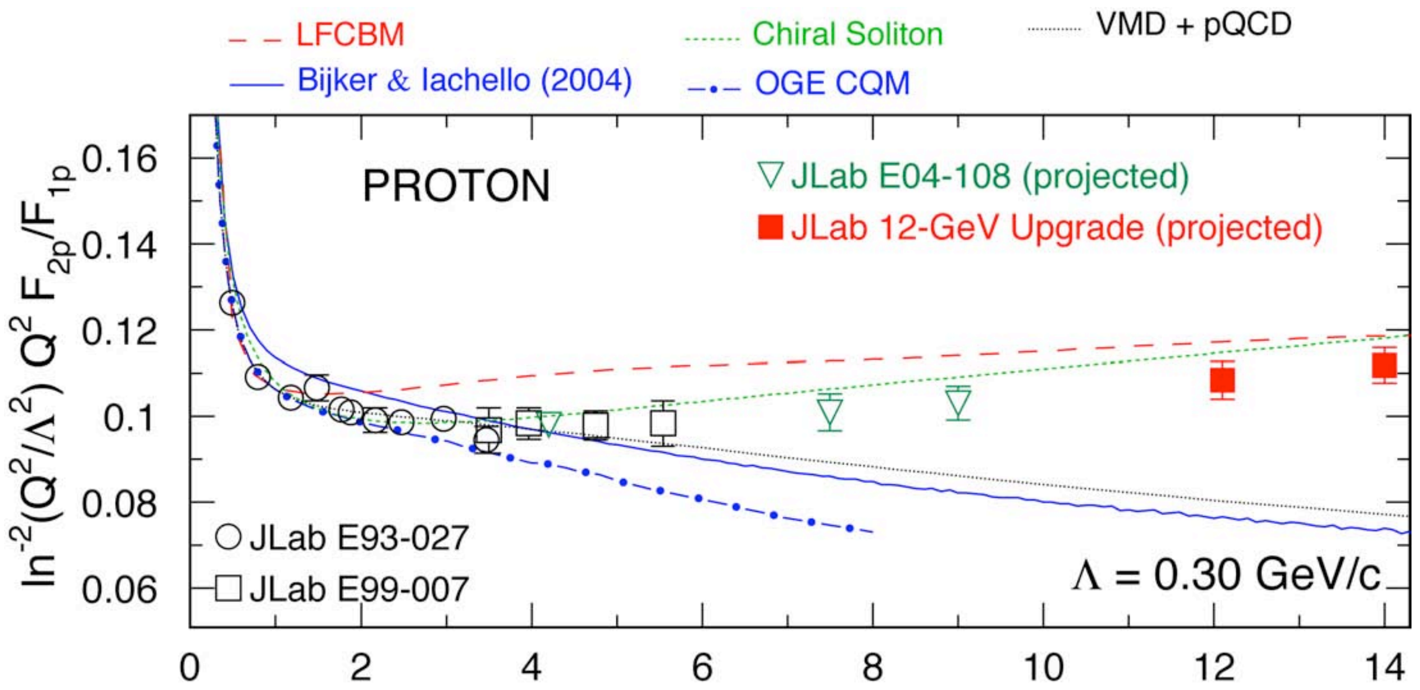
magnetization





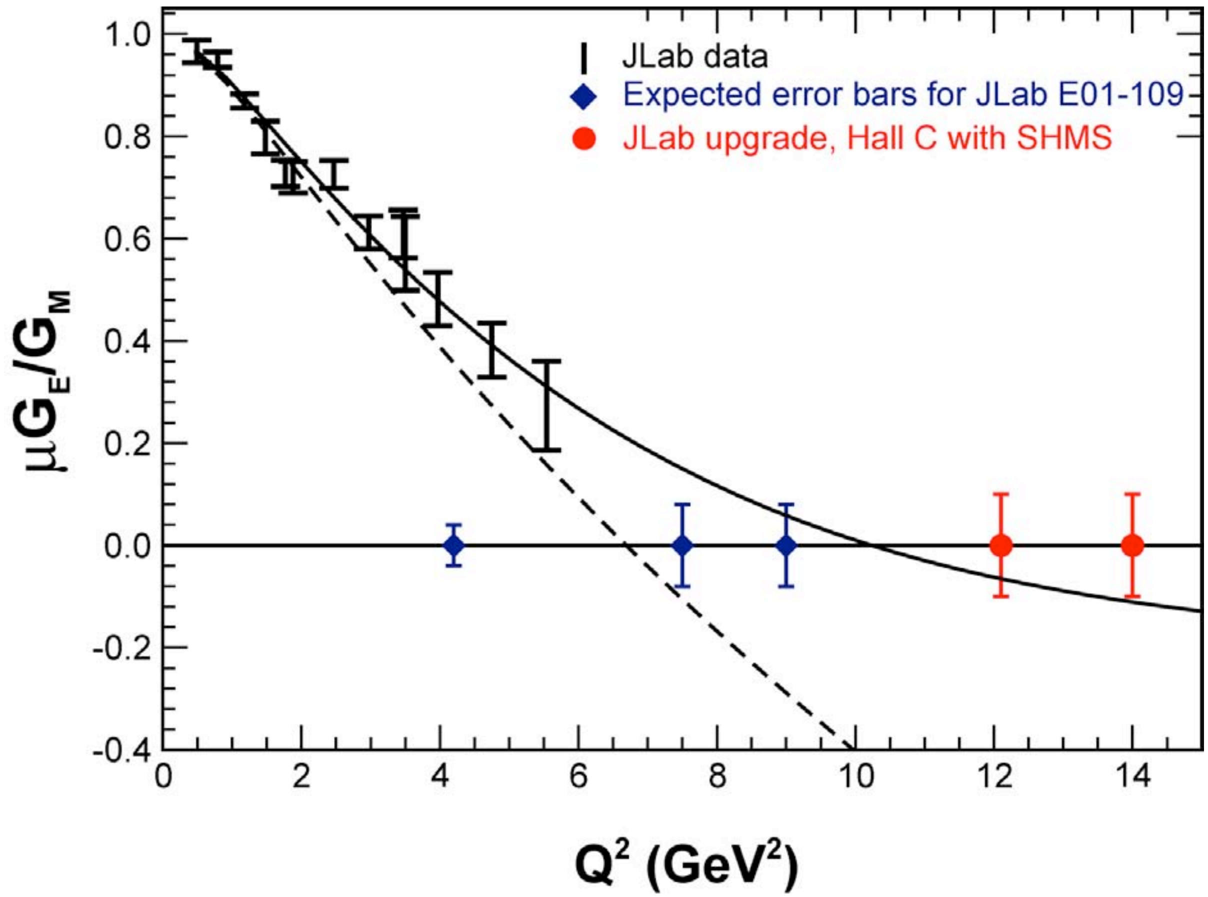
Proton Charge Form Factor @ 12GeV

Here shown as ratio of Pauli & Dirac Form Factors F_2 and F_1



Transverse quark momentum allows for a spin-flip amplitude, thus orbital momentum plays a role and $\ln^{-2}(Q^2/\Lambda^2)Q^2F_2/F_1 \rightarrow$ constant (Ji)

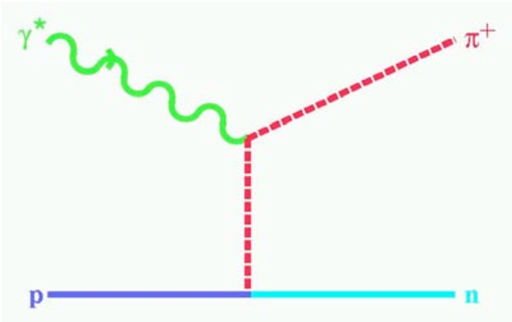
G_E^p with the 12 GeV upgrade

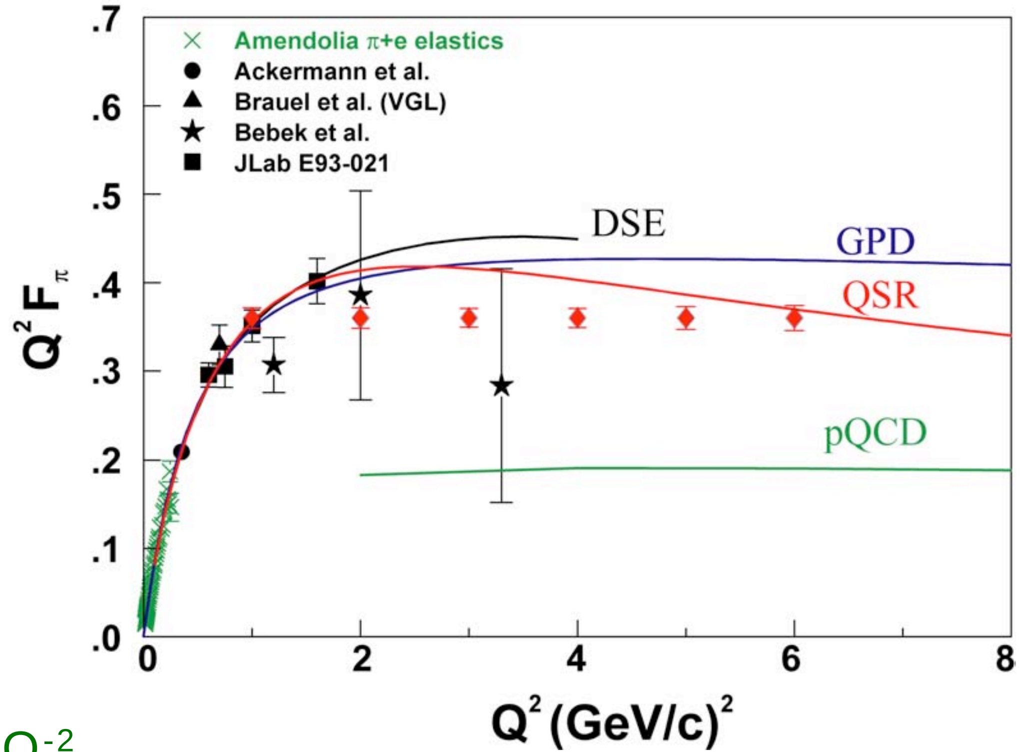


Charged Pion Electromagnetic Form Factor

Where does the dynamics of the q-q interaction make a transition from the strong QCD (confinement) to the pQCD regime?

- It will occur earliest in the simplest systems
  - ➥the pion form factor $F_\pi(Q^2)$ provides a good starting system to determine the relevant distance scale experimentally





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

HMS+SHMS (11 GeV) projection

Conclusion

- JLab at 12 GeV is a unique facility to determine the nucleon large x quark distributions.
- Semi-inclusive DIS will allow an unprecedented flavor decomposition for valence quarks at large x
- First quantitative insights into the effect of the color E and B fields in the nucleon structure by the measurement of d_2 and f_2.
- Proton charge/magnetic (coherent) response will be explored at very short distances.
- Charged Pion (coherent) response will be investigated to link our understanding to the pQCD regime.

This program will have a clear and comprehensive impact on our understanding of QCD within the first 5 years