Deep Inelastic Scattering
Part 1

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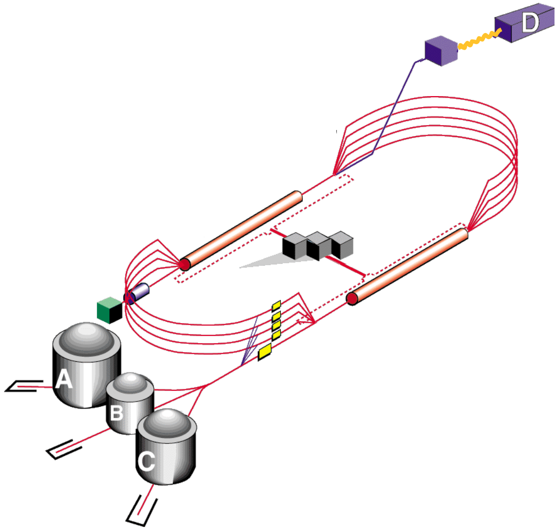


Outline

Day 1:

1. Introduction to DIS and the Quark Parton Model
2. Formalism
   → Unpolarized DIS
   → Polarized DIS
3. Results and examples

Day 2:

1. Nuclear Effects in DIS
2. Beyond inclusive scattering
   → Semi-inclusive reactions (SIDIS)

Disclaimer

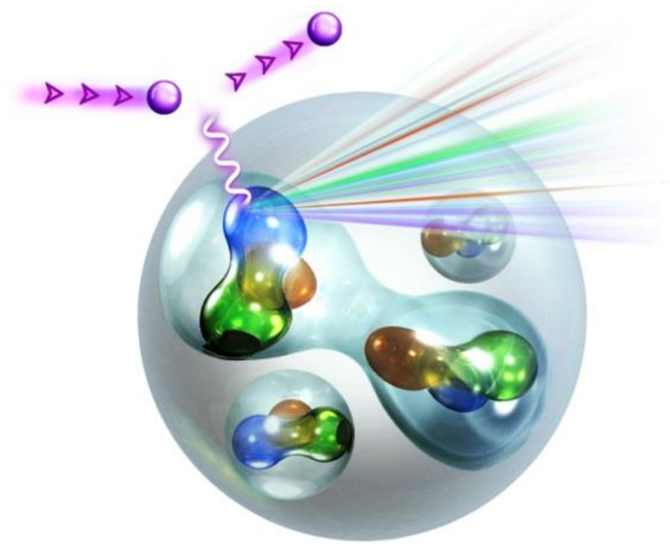
- I am an experimentalist, very interested in nuclear effects
  → Much of what I will say comes from this perspective

- Most of my work has been at Jefferson Lab
  → You will be seeing a lot of examples from JLab

What is Deep Inelastic Scattering?

Some context:

DIS: Using lepton (electron, muon, neutrino) scattering to explore the partonic structure of hadronic matter



Advantages of leptonic (vs. hadronic) probes

→ It's QED: at least ***one*** vertex is well understand
→ No complicated structure of the probe to deal with
→ Small value of α_{QED} = 1/137 means higher order corrections are small*

To access partonic structure (i.e. quarks and gluons) we need "high" energies and large inelasticities → want to avoid the complications from exciting resonances

*Well, usually. Not always true.

What is Deep Inelastic Scattering?

Lepton scattering cross sections have rich, complex structure

→ Elastic scattering
→ Production of excited quark bound states – resonances!

We are primarily interested in the regime in which quarks act like quasi-free, weakly interacting particles

The boundary between these regimes not always so clear cut

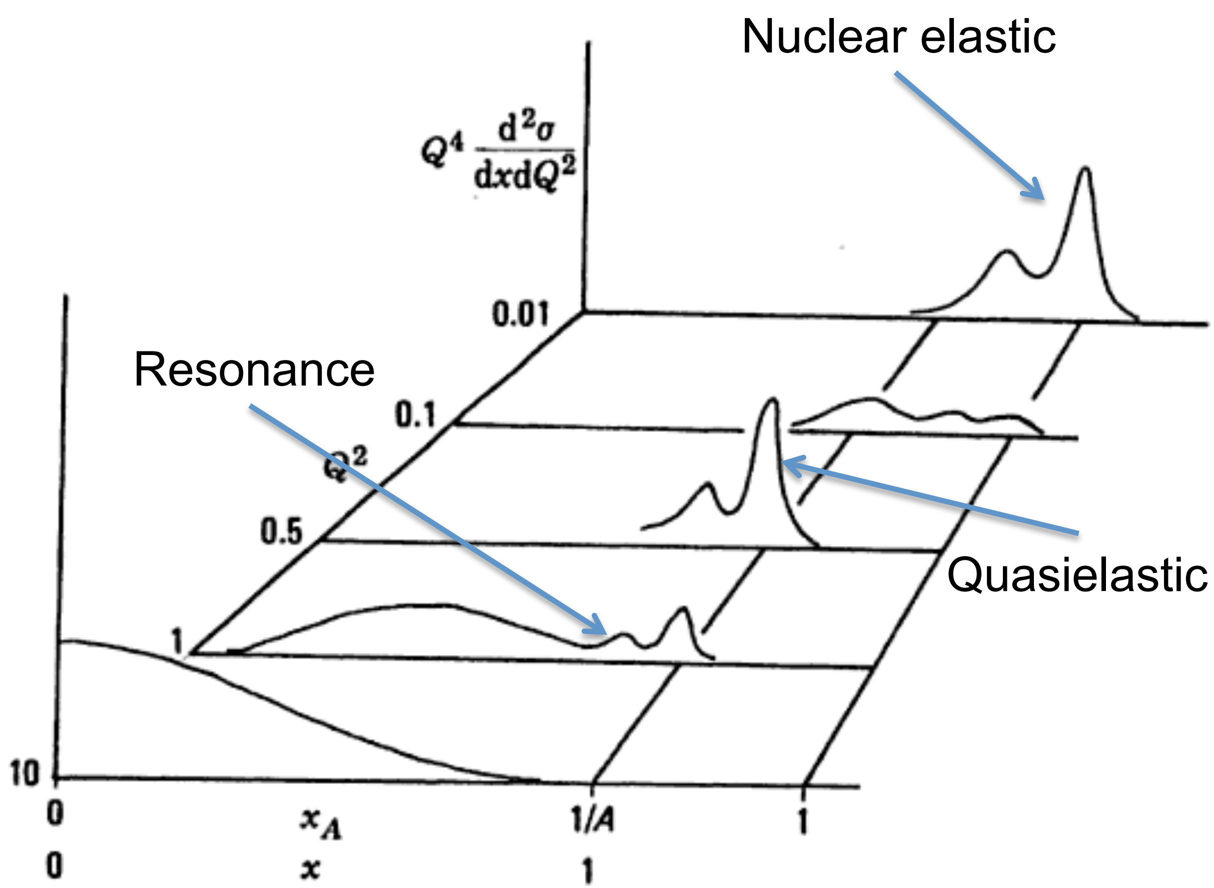


Figure from R.G. Roberts, The Structure of the Proton

DIS Experiments

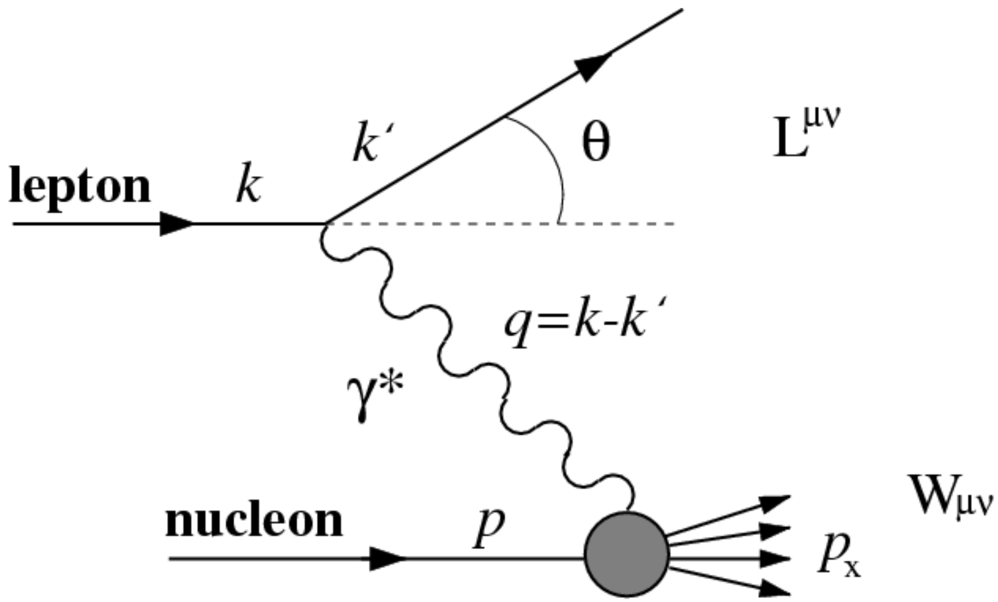
- Plethora of data available from a variety of fixed target experiments
  - SLAC → Electrons at 10's of GeV
  - CERN (EMC/BCDMS/NMC/COMPASS) → Muons at 100's of GeV
  - HERMES → 27 GeV positrons and electrons
  - E665 → Muons at 490 GeV
  - JLab → 6 GeV electrons → 12 GeV
- Only one source of collider DIS data (so far)
  - HERA (Zeus and H1) : 27 GeV positrons (electrons) on 920 GeV protons
- Neutrinos → CCFR, CHORUS, NuTeV, MINER*ν*A
- Important information can also be gleaned from hadron colliders (RHIC, LHC, etc.)

Deep Inelastic Scattering

Kinematics:

Beam: *k= (E, 0,0,p)*
→ Typically ignore electron mass so *E=p*

Scattered electron: *k' = E', θ*
Target: *P = (E$_p$, 0,0,P)*



Useful quantities:

Electron momentum transfer
$$Q^2 = -q^2 = -(k - k')^2$$

Total energy in $\gamma^* p$ center of mass
$$W^2 = (q + P)^2$$

Inelasticity
$$y = \frac{q \cdot P}{k \cdot P}$$

Bjorken scaling variable
$$x = \frac{Q^2}{2p \cdot q}$$

Kinematics: Lab frame

Often DIS kinematics expressed in LAB frame (target at rest)
→ Experiments at HERA (or a future EIC) take place in collider

I tend to think in a fixed-target framework – some useful expressions for working in the lab:

$$x = \frac{Q^2}{2p \cdot q} \rightarrow \frac{Q^2}{2m_p \nu} \qquad \nu = E - E'$$

$$W^2 = (q+P)^2 \rightarrow -Q^2 + m_p^2 + 2m_p\nu$$

$$y = \frac{q \cdot P}{k \cdot P} \rightarrow \frac{\nu}{E}$$

Fraction of electron energy transferred to nucleon

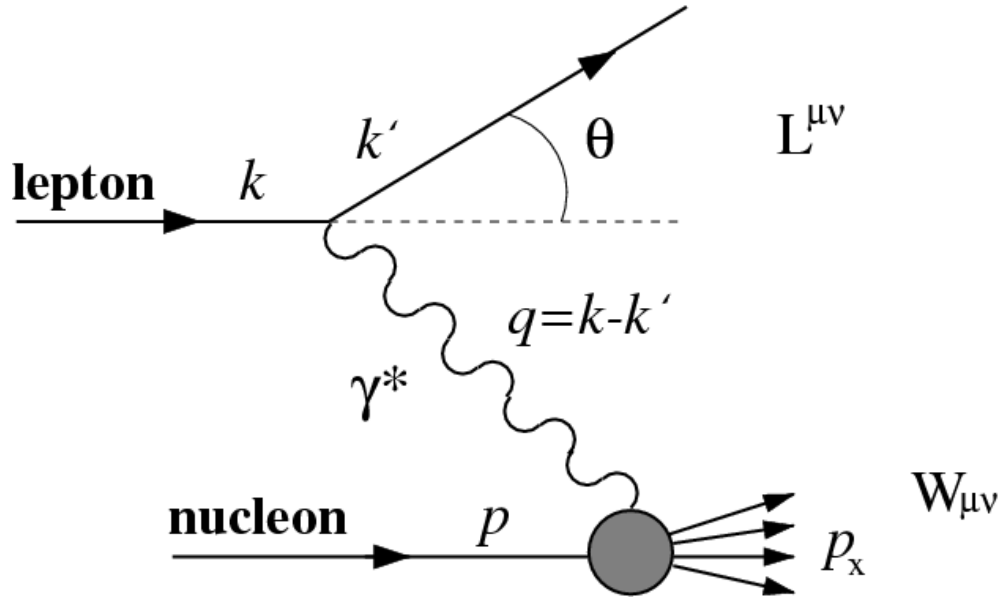
$$\epsilon = \left(1 + \frac{2|\mathbf{q}|^2}{Q^2} \tan\frac{\theta_e}{2}^2\right)^{-1} = \frac{1-y}{1-y+\frac{1}{2}y^2}$$

Ratio of long. to transverse photon flux

DIS Cross Section

Unpolarized cross section:

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



Parity and time invariance → only two structure functions required

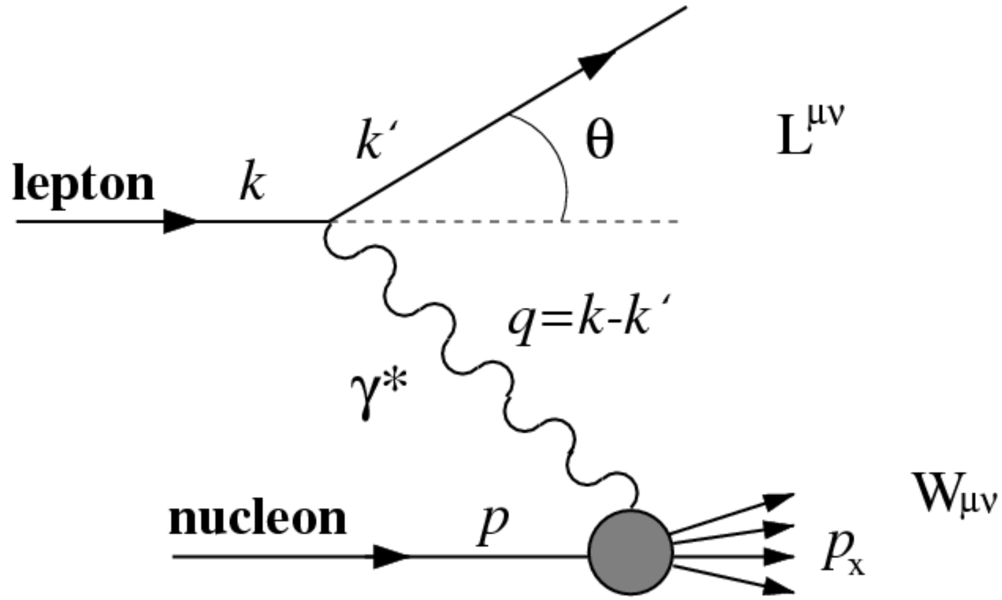
$$\frac{d\sigma}{d\Omega dE^{\prime}} = \frac{4\alpha^2 (E^{\prime})^2}{Q^4}\left[W_2(\nu,Q^2)\cos^2\frac{\theta}{2} + 2W_1(\nu,Q^2)\sin^2\frac{\theta}{2}\right]$$

W_1 and W_2 parameterize the (unknown) structure of the proton

DIS Cross Section

Unpolarized Cross section:

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



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

In the limit of large Q², structure functions scale

$$MW_1(\nu,Q^2) \to F_1(x)$$
$$\nu W_2(\nu,Q^2) \to F_2(x)$$

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

DIS Cross Section

Virtual photon cross section:

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

Transverse photons

Longitudinal photons

$$\epsilon = \left(1 + \frac{2|\mathbf{q}|^2}{Q^2}\tan\frac{\theta_e}{2}^2\right)^{-1}$$

$$\Gamma = \frac{\alpha}{2\pi^2}\frac{E'}{E}\frac{K}{Q^2}\frac{1}{1-\epsilon}$$

$$K = \frac{W^2 - m_p^2}{2m_p}$$

$$W_1 = \frac{K}{4\pi^2\alpha}\sigma_T$$

$$W_2 = \frac{K}{4\pi^2\alpha}\frac{Q^2}{Q^2+\nu^2}(\sigma_L + \sigma_T)$$

Pure transverse

Transverse and longitudinal

DIS Cross Section

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

Replacing W_1 and W_2

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

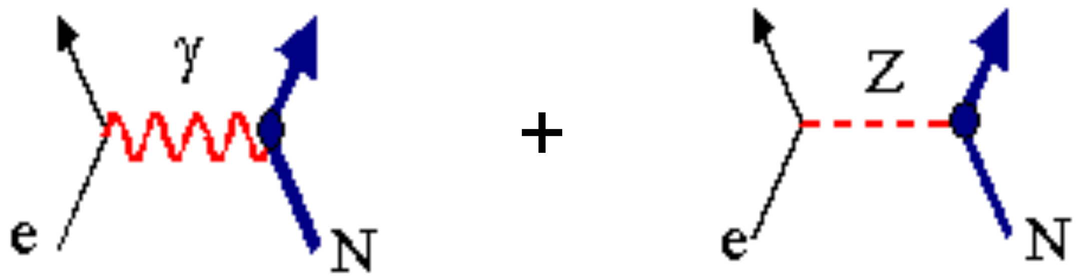
$$\nu W_2(\nu,Q^2) \rightarrow F_2(x,Q^2)$$

And defining:

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

$$\frac{d\sigma}{d\Omega dE'} = \Gamma \frac{4\pi^2\alpha}{x(W^2 - M^2)} \left[2xF_1(x,Q^2) + \epsilon F_L(x,Q^2)\right]$$

Deep Inelastic Scattering



At very high energies (HERA) – contributions from Z exchange can no longer be ignored

$$\frac{d\sigma^{e^\pm}}{dx dQ^2} = \frac{2\pi\alpha^2(1+(1-y)^2)}{Q^4 x}\left[\tilde{F}_2 \mp \frac{1-(1-y)^2}{1+(1-y)^2} x\tilde{F}_3 - \frac{y^2}{1+(1-y)^2}\tilde{F}_L\right]$$

$$\tilde{F}_2 = F_2 - \kappa_Z v_e F_2^{\gamma Z} + \kappa_Z^2 (v_e^2 + a_e^2) F_2^Z$$

$$\tilde{F}_L = F_L - \kappa_Z v_e F_L^{\gamma Z} + \kappa_Z^2 (v_e^2 + a_e^2) F_L^Z$$

$$x\tilde{F}_3 = -\kappa_Z a_e x F_3^{\gamma Z} + \kappa_Z^2 2 v_e a_e x F_3^Z$$

$$\kappa_Z = \frac{Q^2}{Q^2 + M_Z^2}\frac{1}{4\sin\theta_W{}^2\cos\theta_W{}^2}$$

Vector weak coupling $=-1/2+2\sin^2\theta_W$

Axial-vector weak coupling $=-1/2$

Quark Parton Model

DIS can be described as inelastic scattering from non-interacting, point-like constituents in the nucleon

Consequences:

At fixed x, inelastic structure functions scale:

$$MW_1(\nu,Q^2) \rightarrow F_1(x)$$
$$\nu W_2(\nu,Q^2) \rightarrow F_2(x)$$

Large Q^2

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

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

Spin ½: Callan-Gross relation

$$R = \frac{\sigma_L}{\sigma_T} = 0$$

Jefferson Lab

Quark Parton Model

DIS can be described as inelastic scattering from non-interacting, point-like constituents in the nucleon

$$F_2(x) = \sum_q e_q^2 x(q(x) + \bar{q}(x))$$

$$g_V^q = \pm\frac{1}{2} - 2e_q \sin\theta_W{}^2$$

u=+, d=-

$$g_A^q = \pm\frac{1}{2}$$

$$F_2^{\gamma Z}(x) = \sum_q 2e_q g_V^q x(q(x) + \bar{q}(x))$$

$$F_2^{Z}(x) = \sum_q [(g_V^q)^2 + (g_A^q)^2] x(q(x) + \bar{q}(x))$$

$$F_3^{\gamma Z}(x) = \sum_q 2e_q g_A^q (q(x) - \bar{q}(x))$$

$$F_3^{Z}(x) = \sum_q [(g_V^q)^2 + (g_A^q)^2] (q(x) - \bar{q}(x))$$

Scaling – SLAC-MIT result from 1970

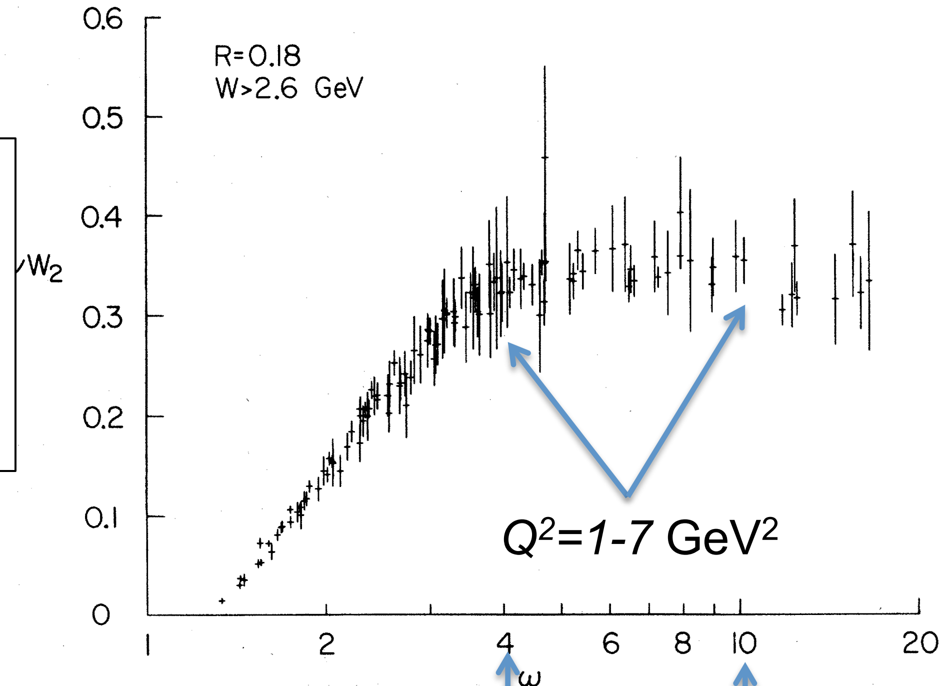
A series of experiments at SLAC (performed by SLAC-MIT collaboration) gave first hints that the partonic hypothesis was valid

→ Cross sections at large angles (momentum transfers) larger than if proton was an amorphous blob-like object

→ Analogous to Rutherford's alpha scattering experiments

We observe the excitation of several nucleon resonances[4-7] whose cross sections fall rapidly with increasing q^2. The region beyond $W \approx 2$ GeV exhibits a surprisingly weak q^2 dependence. This Letter describes the experimental procedure and reports cross sections for $W \geq 2$ GeV. Discussion of the results and a detailed description of the resonance region will follow.[8]

Phys.Rev.Lett. 23 (1969) 930-934



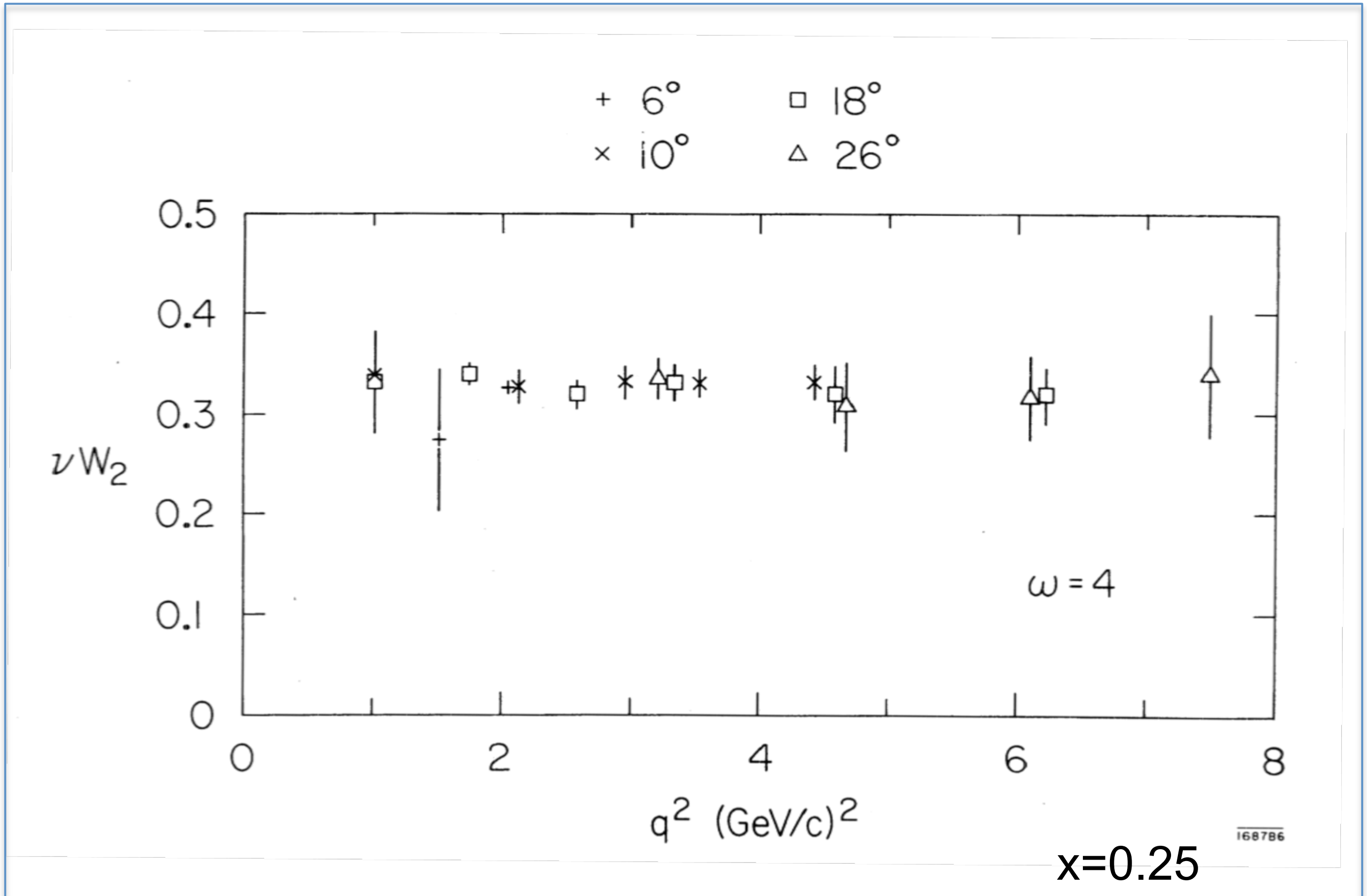
Beam energy up to ~ 20 GeV

Phys.Rev. D5 (1972) 528

x=0.25 x=0.1

Scaling – SLAC-MIT result from 1970

A series of experiments at SLAC (performed by SLAC-MIT collaboration) gave first hints that the partonic hypothesis was valid



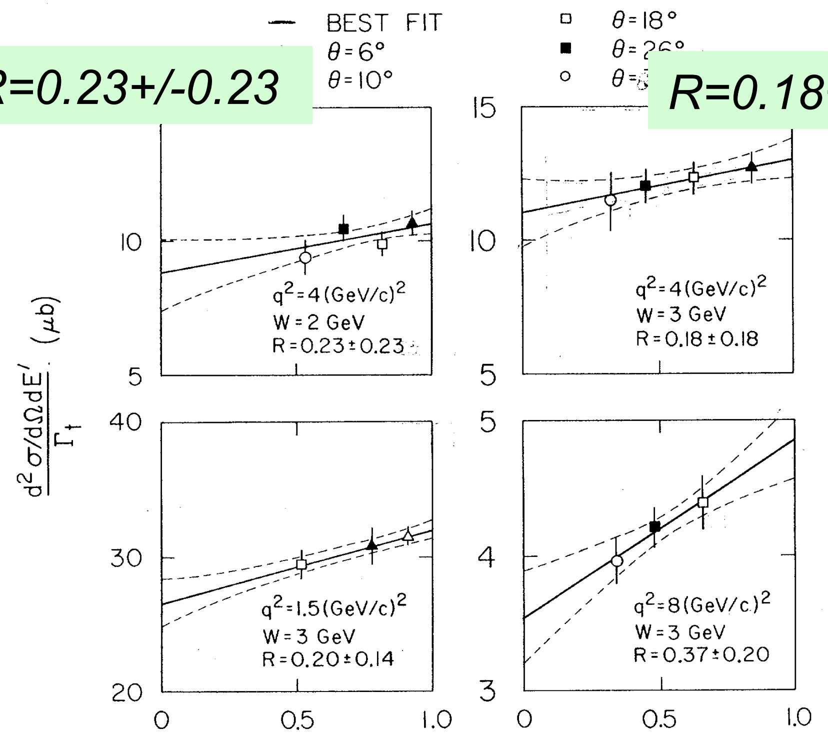
SLAC-PUB 796 (1970)

$R=\sigma_L/\sigma_T$

SLAC-MIT also performed initial L-T separations, suggesting *R* was not large
→ L-T separations experimentally challenging – precise extractions came later

R=0.23+/-0.23

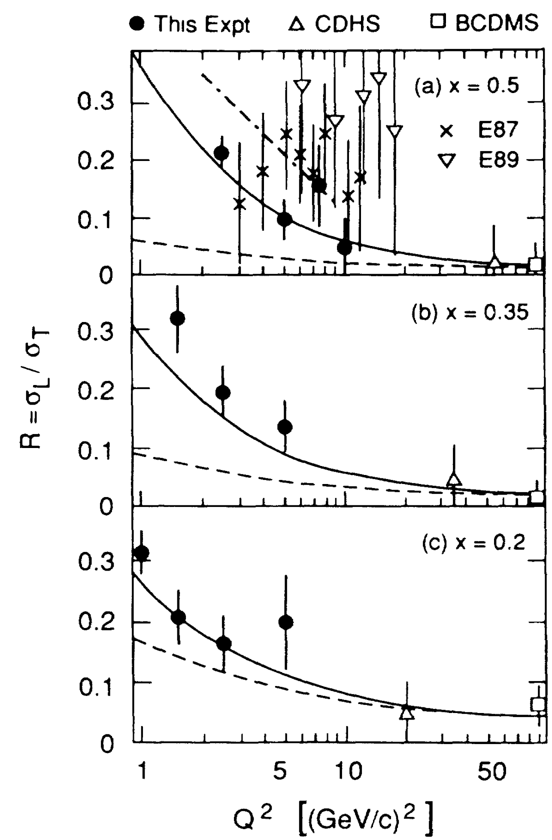
R=0.18+/-0.18



R=0.20+/-0.14

R=0.32+/-0.2

Phys.Rev. D5 (1972) 528



Phys.Rev.Lett. 61 (1988) 1061

QPM and QCD

The quark parton model is the asymptotic limit of the real theory of strong interactions → QCD

- In reality – structure functions (and parton distributions) are not Q^2 independent – even for large values of Q^2
- Struck quark radiates hard gluons – leads to logarithmic Q^2 dependence

Q^2 evolution can be described by DGLAP equations:

Non singlet quark distributions: $q^{NS} = q - \bar{q}$

Splitting function – probability for quark to radiate gluon

$$\frac{dq^{NS}(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y} q^{NS}(y,Q^2) P_{qq}(\frac{x}{y})$$

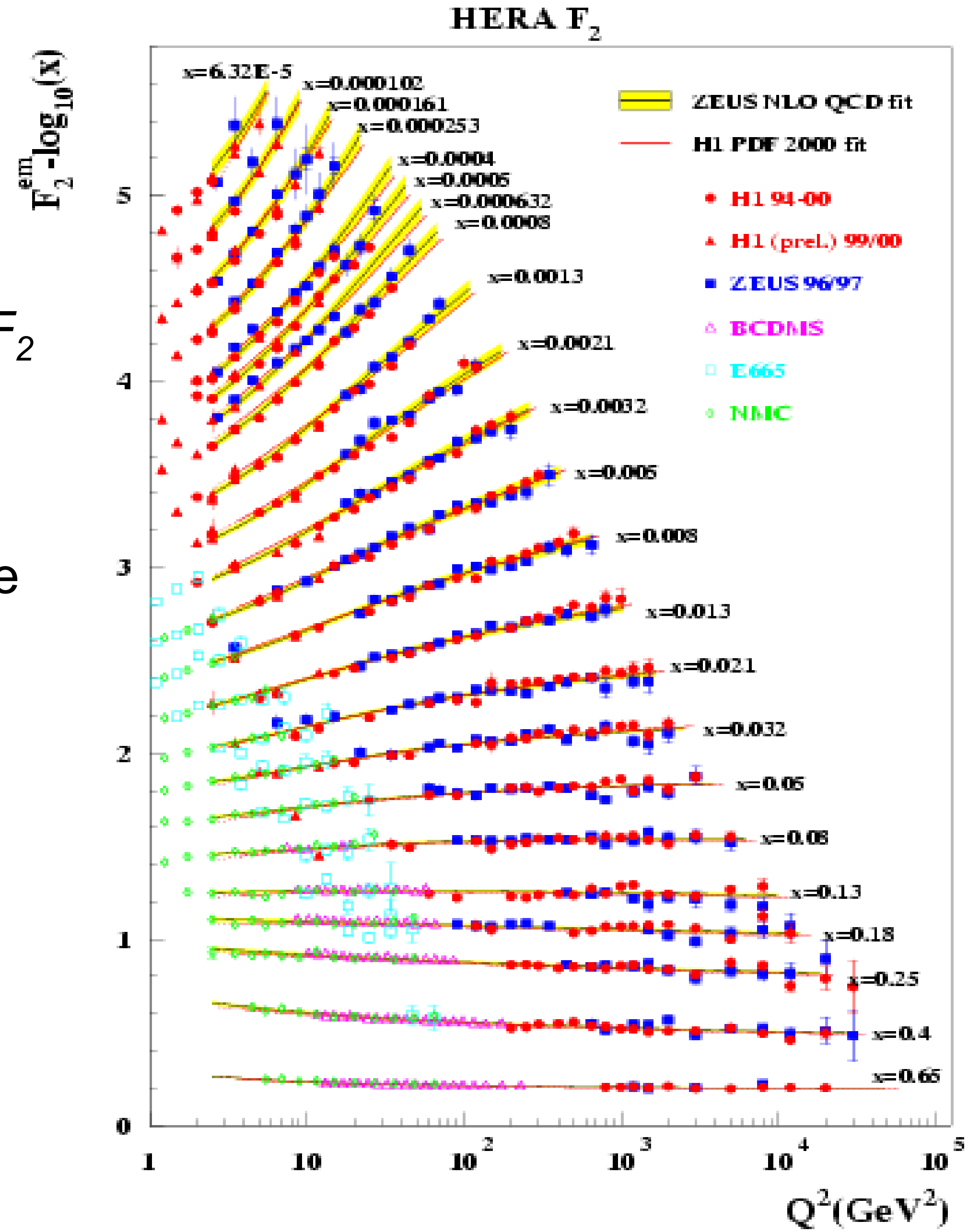
Gluon quark singlet distributions: $q^S = \sum_i q_i + \bar{q}_i$

$$\frac{d}{d\ln Q^2}\begin{pmatrix} q^S(x,Q^2) \\ G(x,Q^2) \end{pmatrix} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z}\begin{pmatrix} P_{qq}(z) & N_f P_{qG}(z) \\ P_{Gq}(z) & P_{GG}(z) \end{pmatrix}\begin{pmatrix} q^S(\frac{x}{z},Q^2) \\ G(\frac{x}{z},Q^2) \end{pmatrix}$$

DGLAP =Dokshitzer–Gribov–Lipatov–Altarelli–Parisi

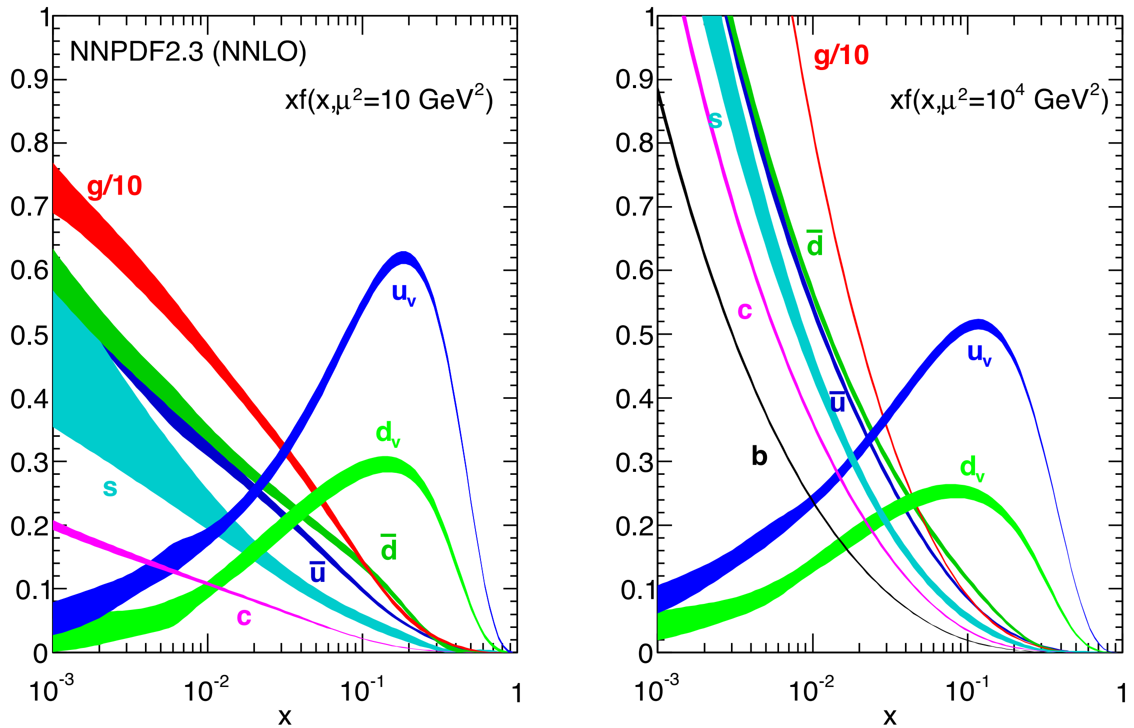
Q^2 Dependence of F_2

- Overall, Q^2 dependence of F_2 well-described by NLO DGLAP evolution
- Note that near *x=0.1-0.2*, the Q^2 dependence is rather small → early SLAC measurements
- At small *x*, Q^2 dependence becomes quite large



Q^2 Dependence of PDFs

10 GeV^2



10,000 GeV^2

K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014).

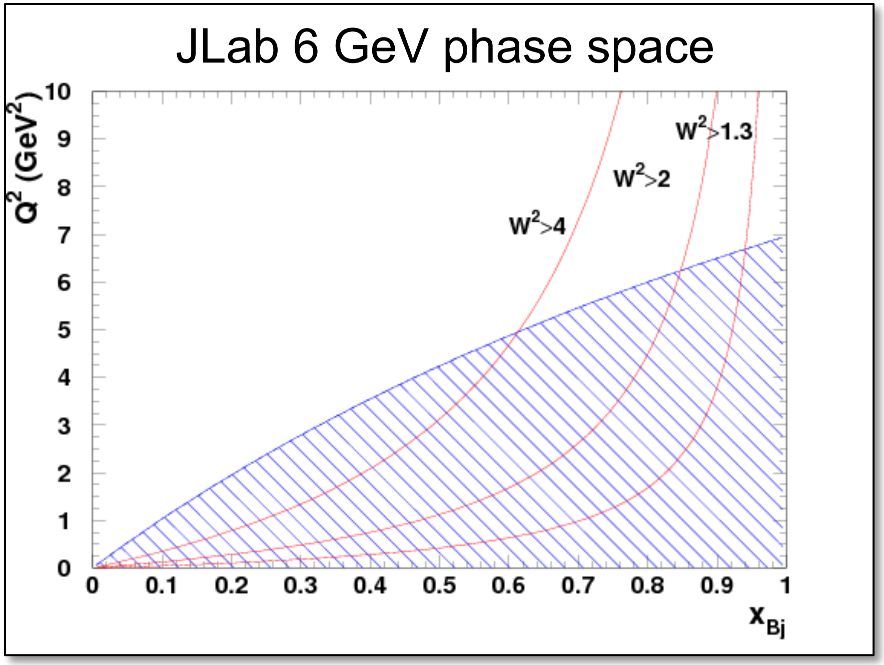
DGLAP evolution allows us to use measurements at an arbitrary scale and evolve them to another → PDFs not scale independent

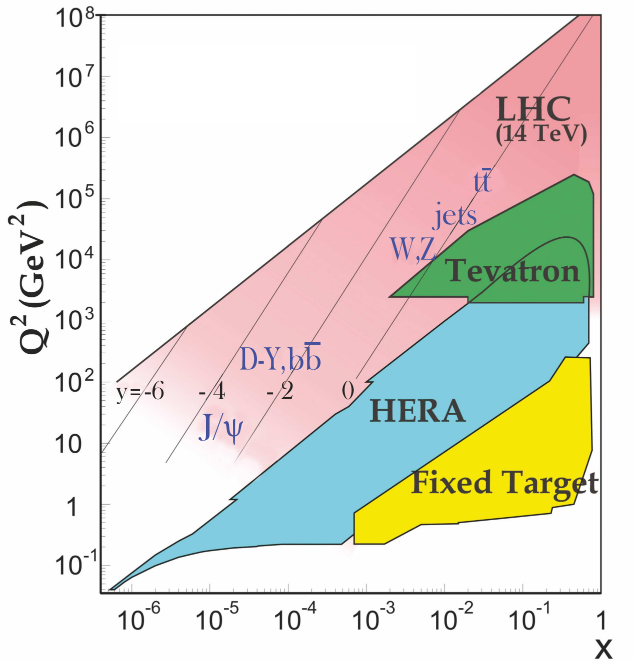
Experimental Challenges - Kinematics

Large x typically pursued at fixed target machines

→ Can reach large Q^2, but need large luminosities

→ Large energies required to avoid resonance region at largest x





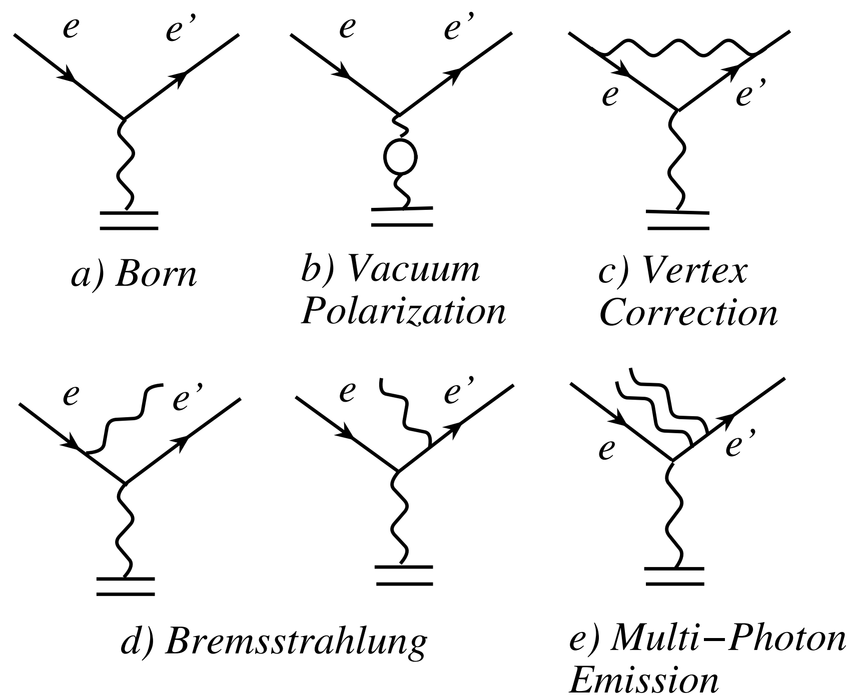
Colliders excellent for accessing smallest values of x

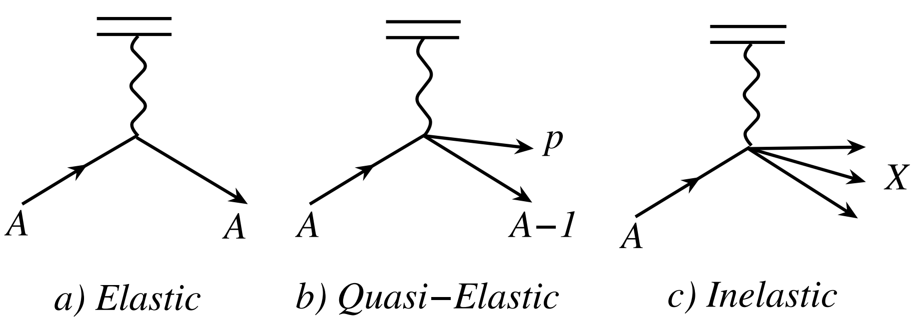
→ As x shrinks, ever increasing energies needed to achieve even modest Q^2 range

Experimental Challenges - Radiative Corrections

Radiative corrections pose additional experimental challenge for the analysis of DIS data

→ Reliable RC requires knowledge of the process of interest over a wide kinematics region since events can “radiate in” to the acceptance





Other processes (elastic scattering) can also contribute to experimental yield

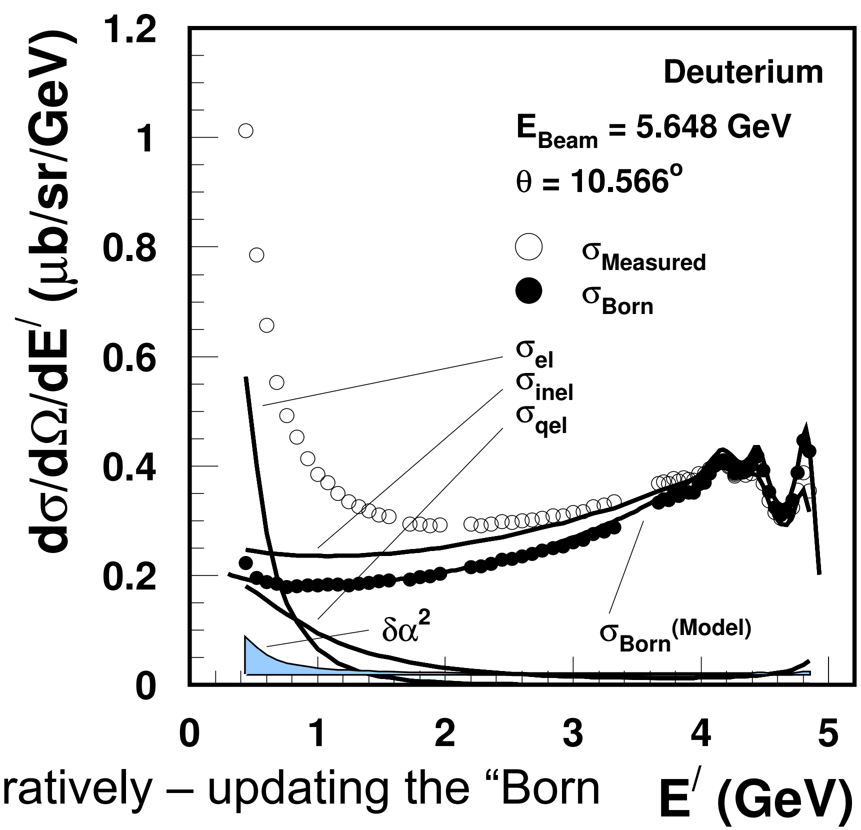
Figures from V. Tvaskis (PhD Thesis)

Radiative Corrections

Radiative effects can be broken into 2 contributions:

1. Radiation in field of nucleus from which electron scatters → Internal
2. Radiation if field of other nuclei → External

External typically only an issue for fixed target experiments



Cross sections must be extracted iteratively – updating the “Born model” at every iteration

→ In the end, the need to avoid large radiative corrections can limit kinematic reach

Typical requirement: y<0.85

Figures from V. Tvaskis (PhD Thesis)

Polarized DIS

In addition to unpolarized structure functions, polarized targets and beams are sensitive to polarized structure functions: $g_1(x)$ and $g_2(x)$

Longitudinally polarized target, longitudinally polarized beam:

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

Transversely polarized target, longitudinally polarized beam:

$$\frac{d\sigma}{d\Omega dE'}(\downarrow\rightarrow - \uparrow\rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1(x,Q^2) + 2Eg_2(x,Q^2)\right]$$

g_1 in Quark Parton Model

In QPM, g_1 is weighted sum of polarized quark distributions

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 q_i(x) \qquad g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$$

Unpolarized

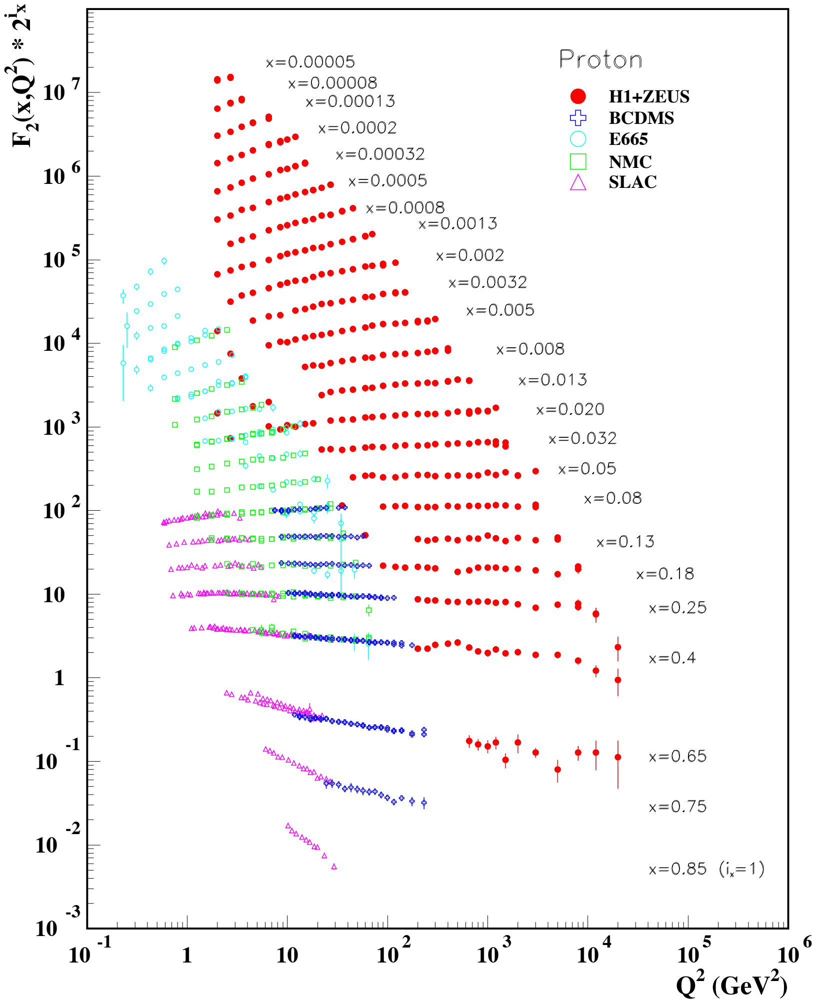
Polarized

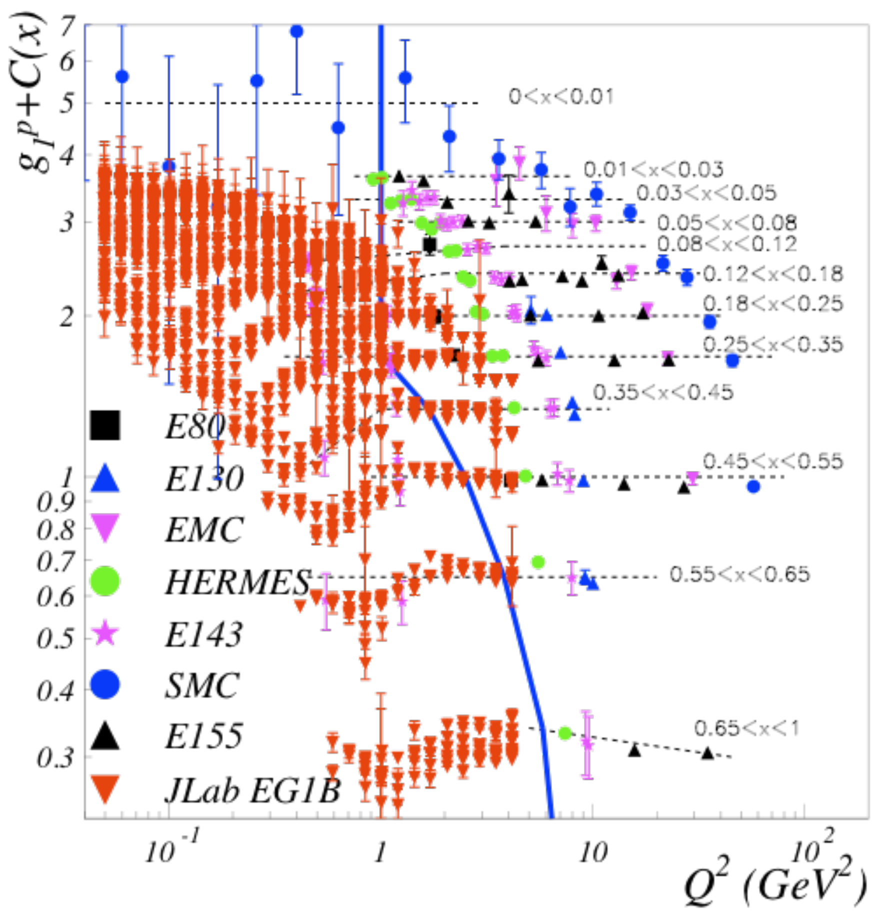
$$\Delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$$

parallel to target spin

antiparallel

World data* on F_2 and g_1





Great increase in amount of data on g_1 in recent years – sill not even close to F_2

*COMPASS data on g_1 missing

Quark contribution to spin of the nucleon

Using quark parton model, g_1 of proton and neutron, can extract quark contribution to nucleon spin

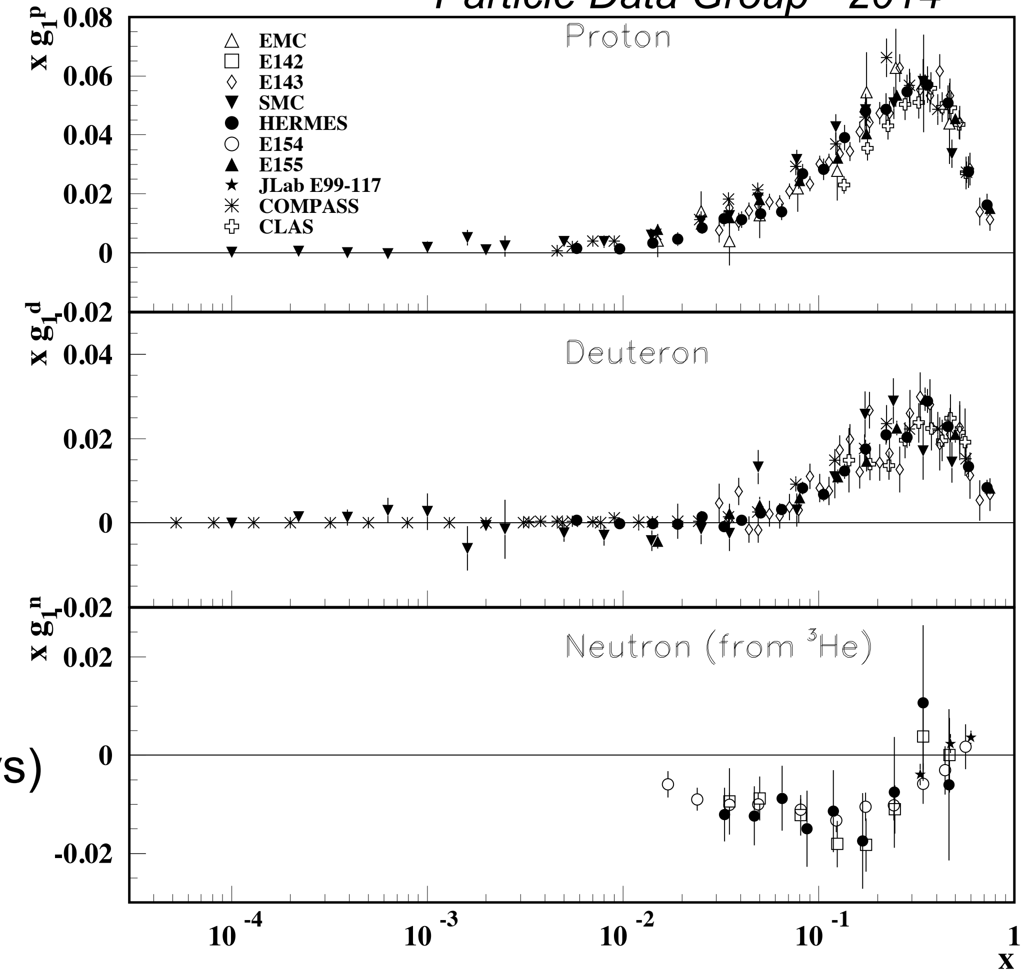
$$\Delta q = \int_0^1 dx \Delta q(x)$$

EMC (*Phys. Lett. B* **206** (2): 364) estimated quark contribution to spin of proton to be (assuming $\Delta s = 0$)

$\Delta\Sigma = 0.14 \pm 0.09$ (stat) +/- 0.21 (sys)

Spin Crisis!

Particle Data Group - 2014



More recent HERMES result (Phys. Rev. D 75 (2007) 012007)

$\Delta\Sigma = 0.330 \pm 0.011(\text{theo.}) \pm 0.025(\text{exp.}) \pm 0.028(\text{evol.})$

g_2 Polarized Structure Function

g_2 does not have a simple interpretation in the Quark Parton Model

→ Can be written as a sum of 2 terms

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

Twist-2 term (Wandzura and Wilczek)

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

Twist-3 + Twist-2

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

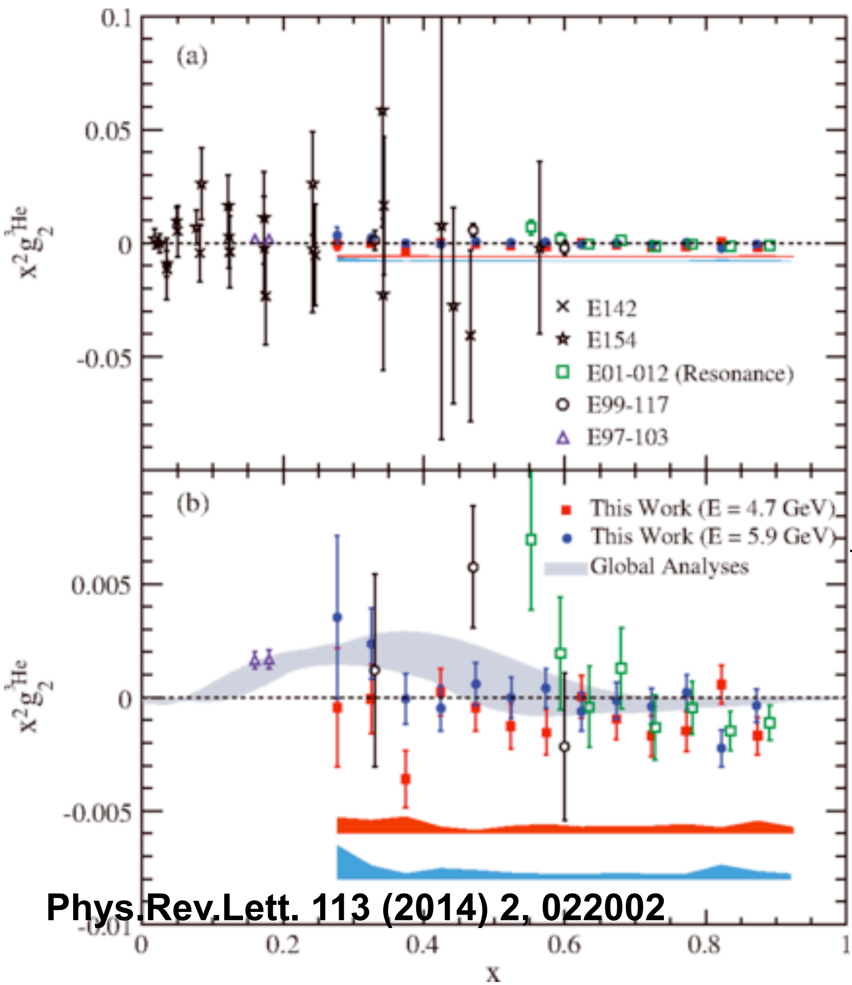
Quark gluon correlations

g_2 Spin Structure Function

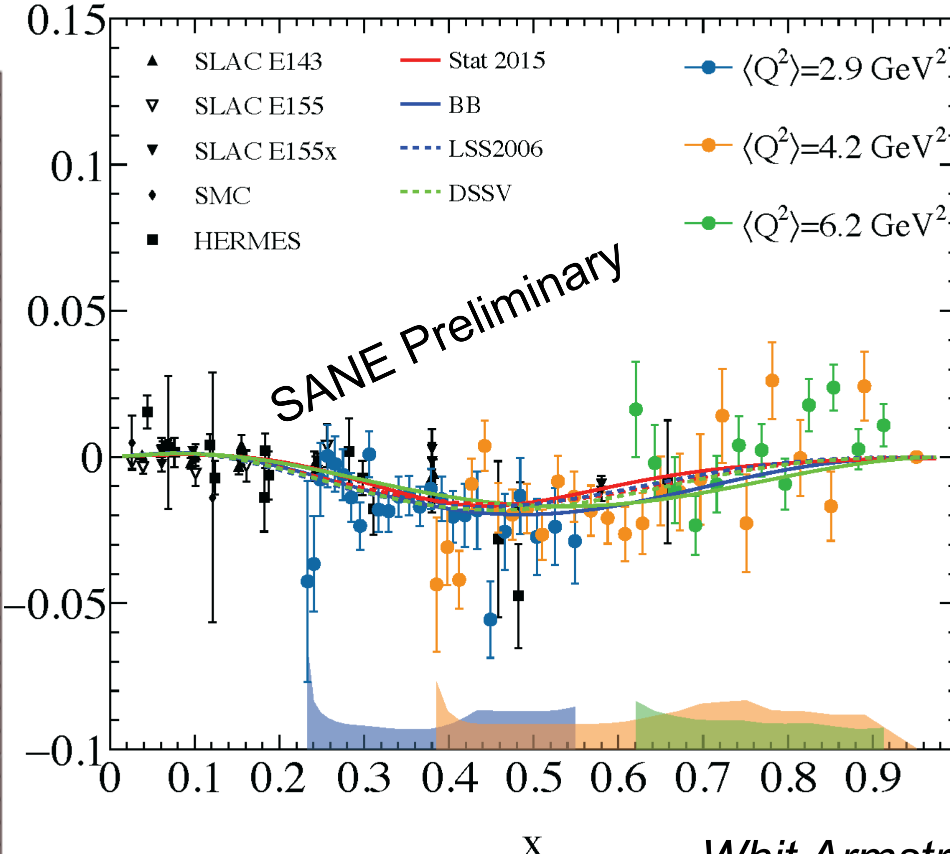
New measurements from JLAB

$x^2 g_2^p$ Proton – Hall C

^{3}He (neutron) – Hall A



Phys.Rev.Lett. 113 (2014) 2, 022002



Whit Armstrong

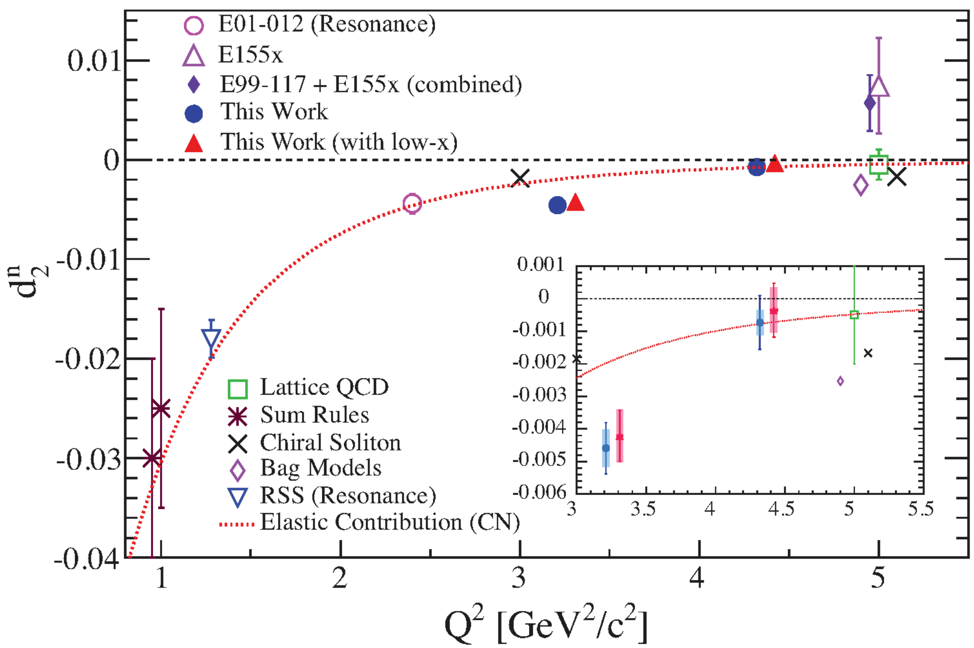
Solid curves = g_2^{WW}

Second moment of $\overline{g}_2$

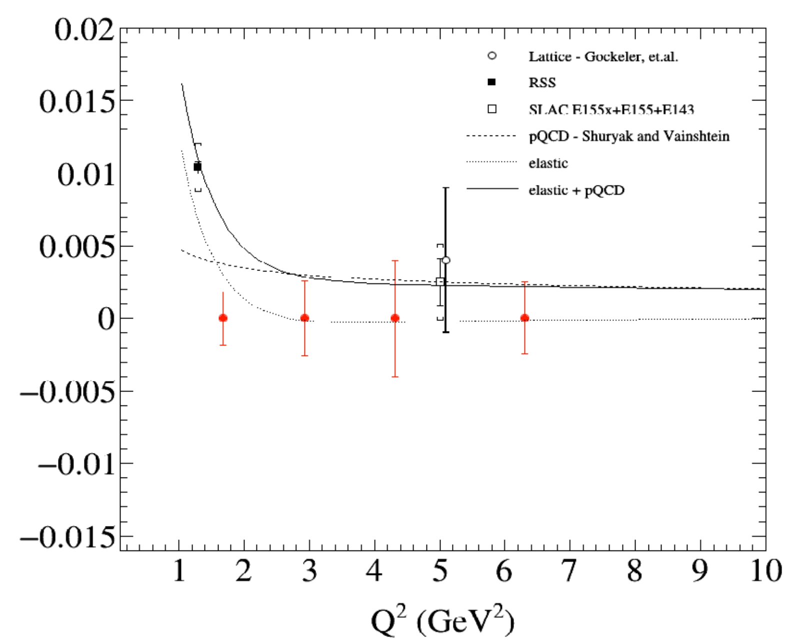
d_2 moment directly sensitive to “interesting” part of g_2

$$d_2 = \int_0^1 dx x^2 [3g_2(x) + 2g_1(x)] = 3\int_0^1 dx x^2 \bar{g}_2(x)$$

Neutron



Proton – projected uncertainties



DIS at Large x

- At large x, cross sections are small → low rates
  - High luminosity required – historically the purview of fixed-target facilities
- Moderate energies available at high luminosity, fixed target accelerators implies moderate Q^2 measurements at sometimes rather low W
  - In this kinematic regime, so-called target mass corrections can be important
- Additional complication comes about in extraction of neutron cross sections and structure functions
  - Nuclear effects

Target Mass Corrections

$$x = \frac{Q^2}{2p \cdot q}$$

For massless quarks and targets (or $Q^2 \rightarrow \infty$) Bjorken scaling variable is the light-cone momentum fraction of target carried by parton

Finite Q^2, light-cone momentum fraction given by Nachtmann variable

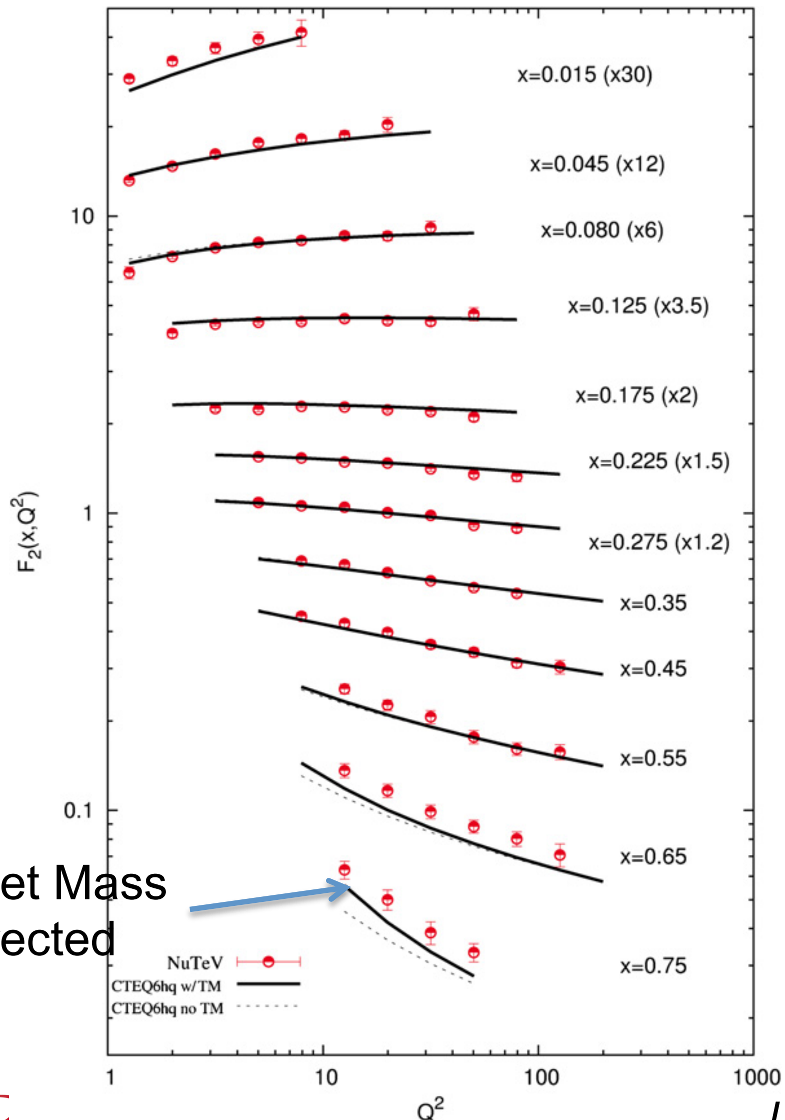
$$\xi = \frac{2x}{1 + \sqrt{1 + 4x^2 M^2 / Q^2}}$$

A prescription for target mass corrections can be derived in terms of the Operator Product Expansion and moments of the structure functions
→ Result is "master equation"

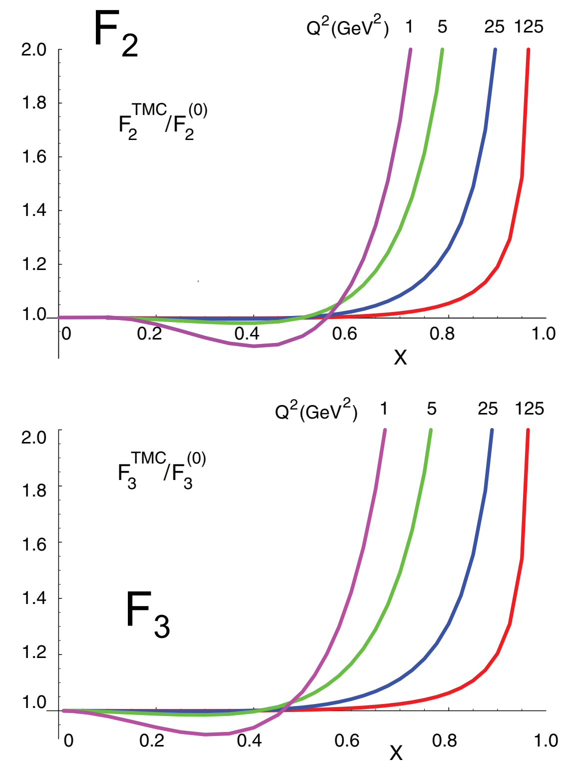
$$\boxed{F_2^{TMC}}(x, Q^2) = \frac{x^2}{\xi^2 r^3} \boxed{F_2^{(0)}}(\xi, Q^2) + \frac{6M^2 x^3}{Q^2 r^4} h_2(\xi, Q^2) + \frac{12 M^4 x^4}{Q^4 r^5} g_2(\xi, Q^2)$$

Weighted integrals over $F_2^{(0)}$

Target Mass Corrections



Target Mass Corrected



Effects of target mass corrections can be quite large – highly Q^2 dependent

J. Phys. G: Nucl. Part. Phys. ***35*** *(2008) 053101*

Neutron Structure Functions

- Structure function information from the neutron is crucial for understanding the quark structure of nucleons

$$\frac{F_2^n}{F_2^p} = \frac{1 + 4d_v(x)/u_v(x)}{4 + d_v(x)/u_v(x)}$$

- No free neutron targets – typically deuterium targets are used and the very simple approximation is used:

$$F_2^D = F_2^p + F_2^n$$

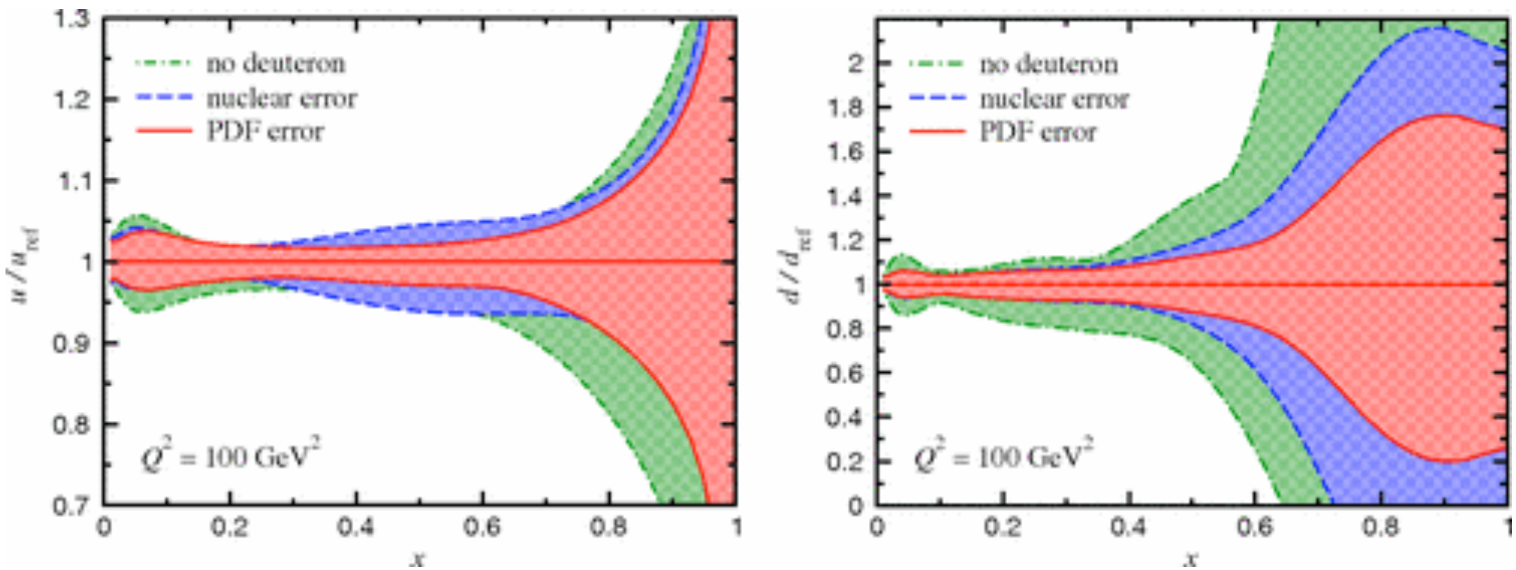
- At low x (x<0.3), nuclear effects are small – this approximation introduces minimal error
- At larger x, this assumption becomes increasingly incorrect

CJ12 PDFs

Nuclear effects in deuteron lead to significant uncertainties in quark PDFs at large *x*

→ This has been studied in some depth by the CTEQ-JLAB collaboration

up



down

J. F. Owens, A. Accardi and W. Melnitchouk, Phys. Rev. D 87, 094012 (2013)

Extraction of Neutron Structure Functions

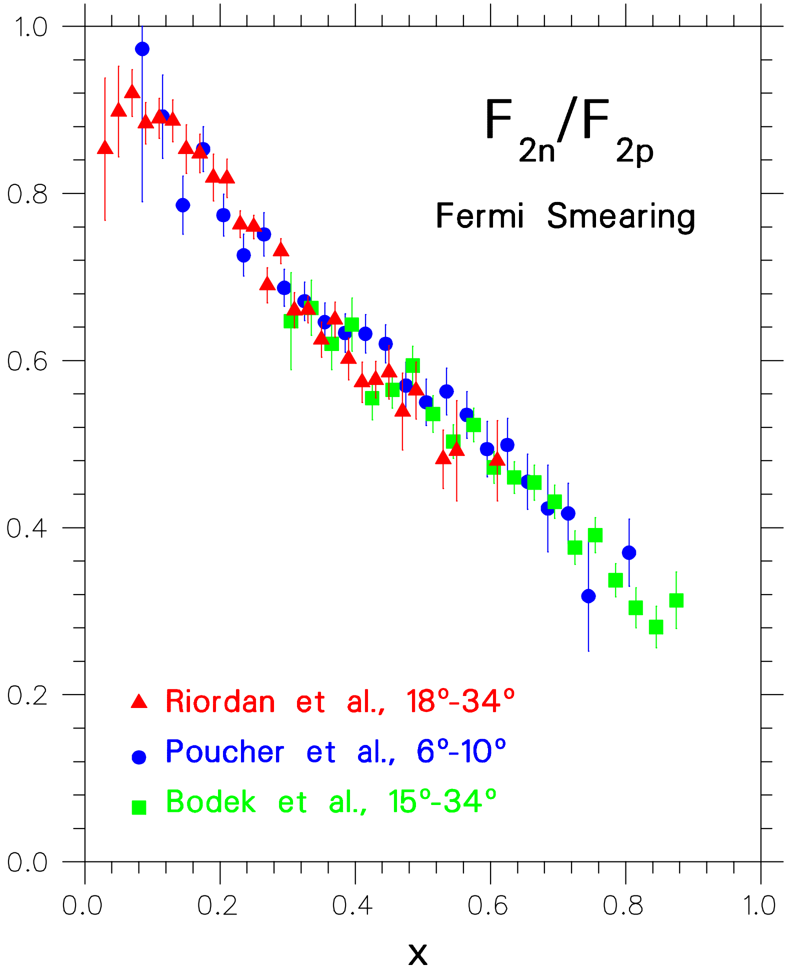


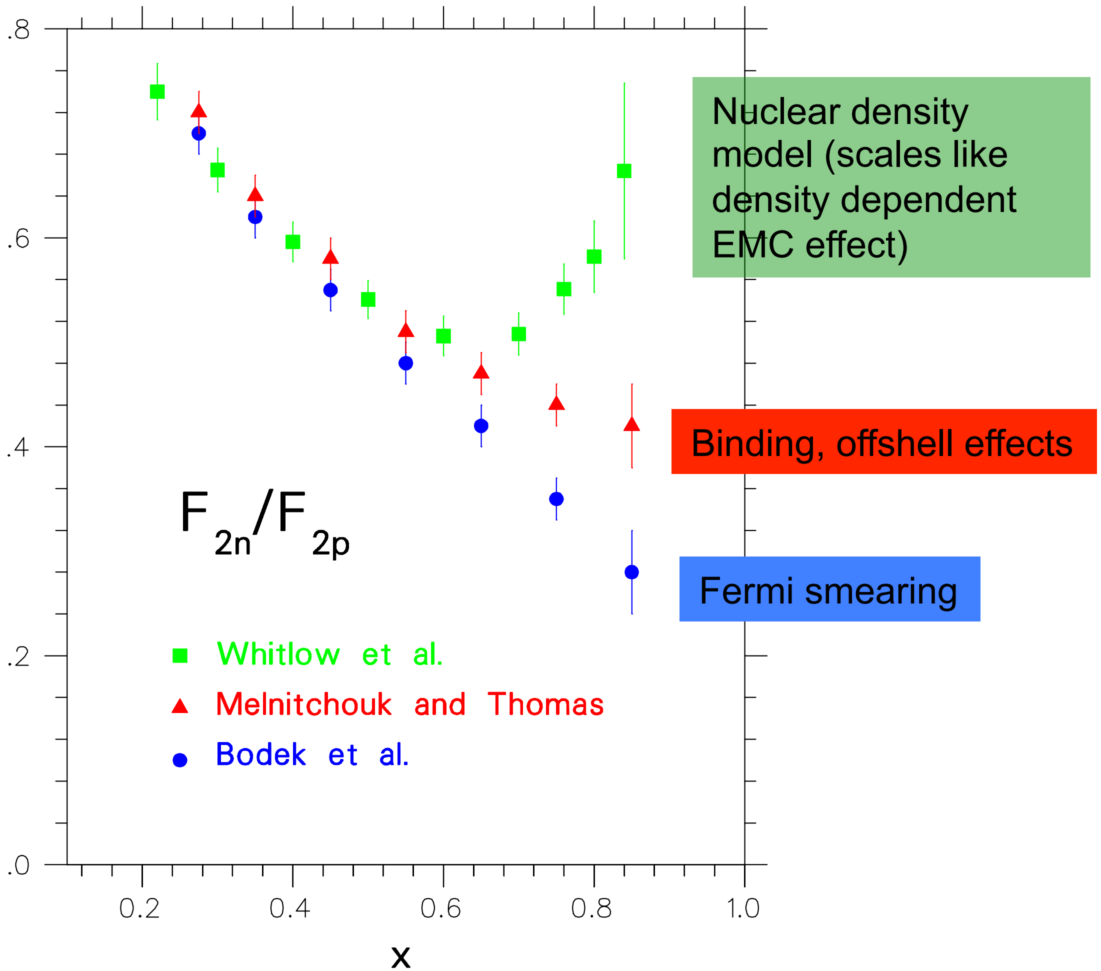
Figure from JLab proposal E12-10-103

Early extraction of the *n/p* ratio tried to incorporate a model including corrections for Fermi smearing

For example, see:
Phys.Rev. D20 (1979) 1471-1552

Bodek et al., Phys. Rev. Lett. 30, 1087 (1973)
E. M. Riordan et al., Phys. Rev. Lett. 33, 561 (1974)
J. S. Poucher et al., Phys. Rev. Lett. 32, 118 (1974).

Extraction of Neutron Structure Functions



Later extractions attempted to include nuclear effects

→ Large variation in n/p ratio as *x*→ *1*!

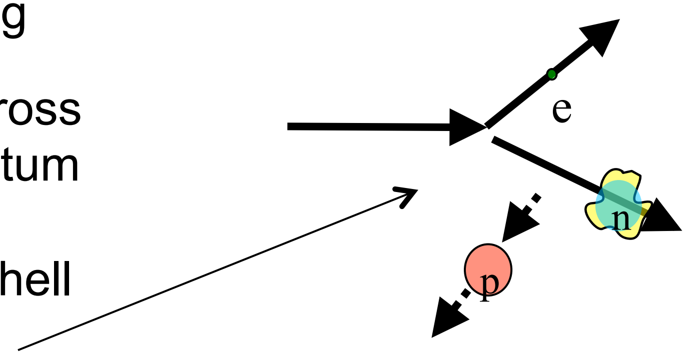
Figure from JLab proposal E12-10-103

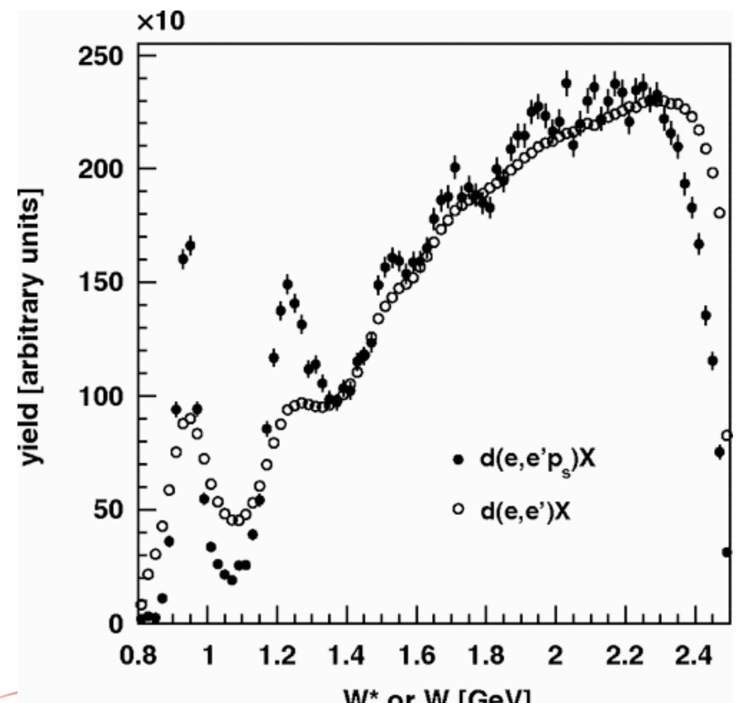
Bodek et al., Phys. Rev. Lett. 30, 1087 (1973)
E. M. Riordan et al., Phys. Rev. Lett. 33, 561 (1974)
J. S. Poucher et al., Phys. Rev. Lett. 32, 118 (1974).

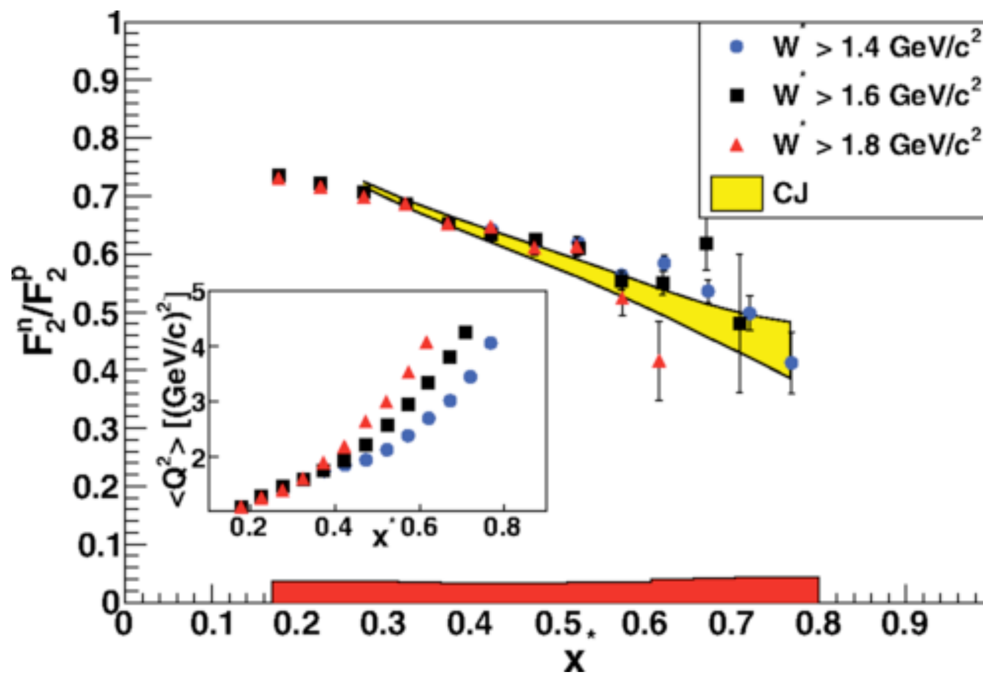
BONUS – d/u via Spectator Tagging

BONUS = Barely Offshell Neutron Scattering

Minimize nuclear effects by measuring DIS cross section from neutrons with low Fermi momentum
→ Tag low momentum "spectator" protons at backward angles; struck neutron almost on-shell

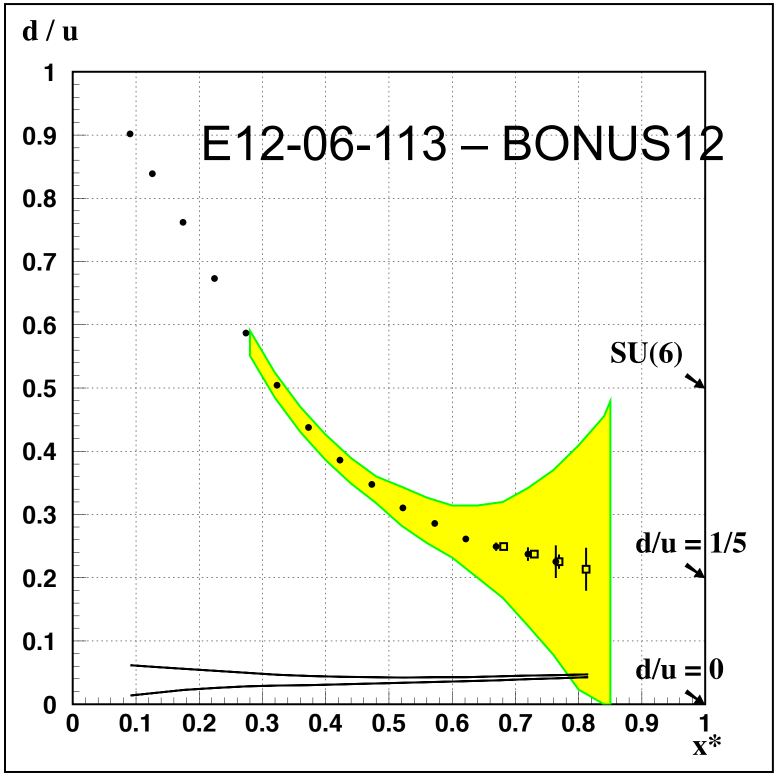


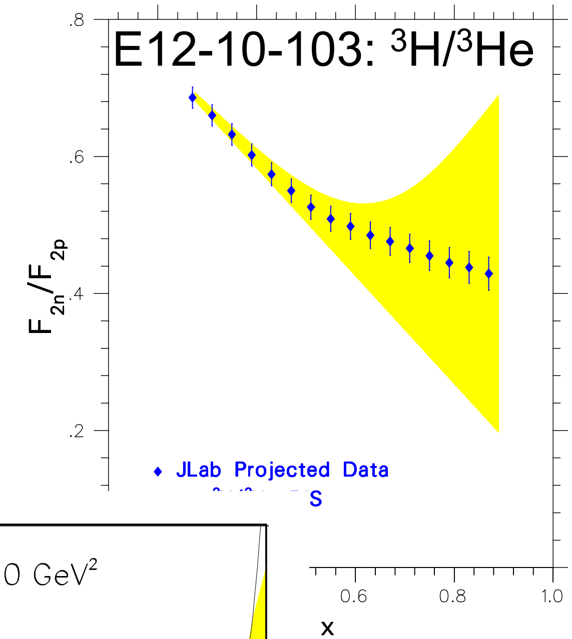


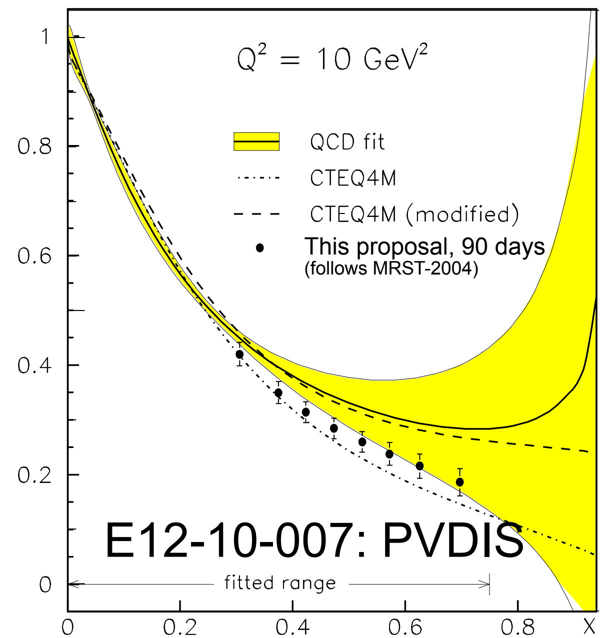


Phys.Rev. C89 (2014) 045206,

Future Measurements of d/u







JLAB-12 GeV will allow extraction of d/u using a variety of techniques

1. Spectator tagging (BONUS)
2. PVDIS
3. Mirror nuclei ^{3}H/^{3}He

Jefferson Lab

Transition to the perturbative regime

- DIS often viewed as simply a “tool” to gain access to parton distributions in the perturbative regime
- Understanding the transition to this regime is also of key interest, and one of the reasons JLab was built

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.

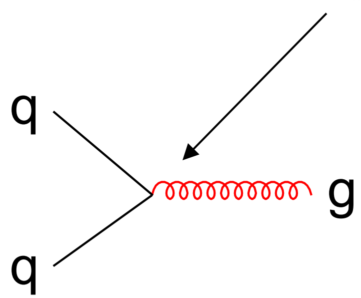
The Strong Force at Long and Short Distances

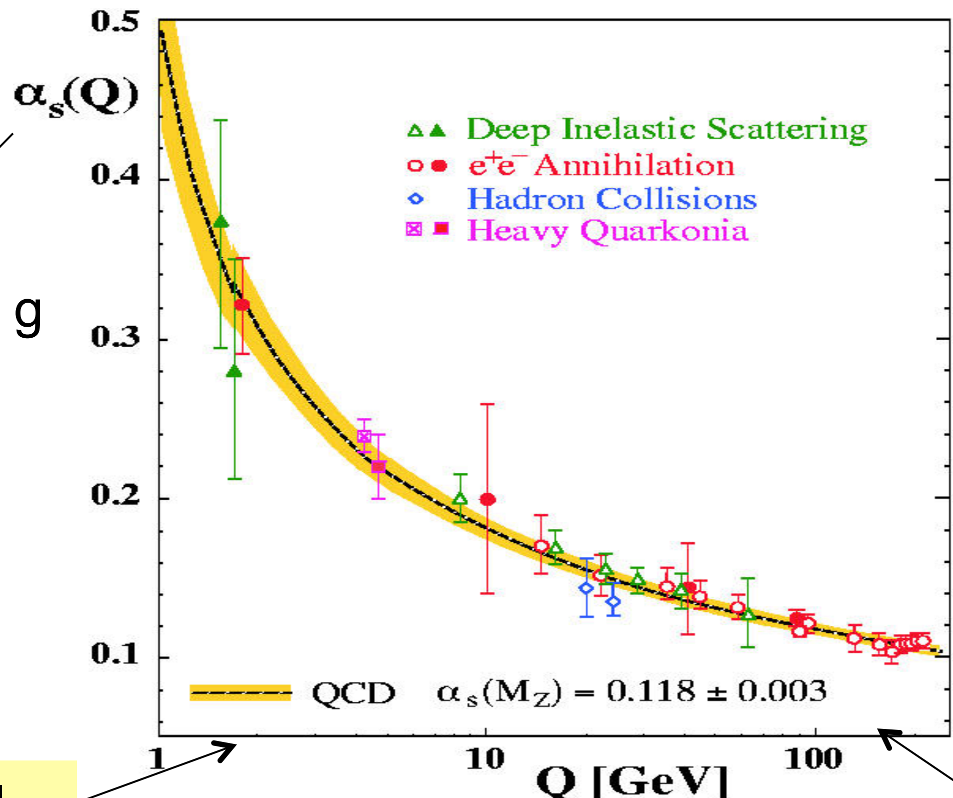
<u>Confinement</u>
Protons & Neutrons
$Q < \Lambda$
$\alpha_s(Q) > 1$

Constituent Quarks

$Q > \Lambda$
$\alpha(Q)$ large

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





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

"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

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

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

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.

Quarks Hadron Duality

At high enough energy:

Hadronic Cross Sections averaged over appropriate energy range

Perturbative Quark-Gluon Theory

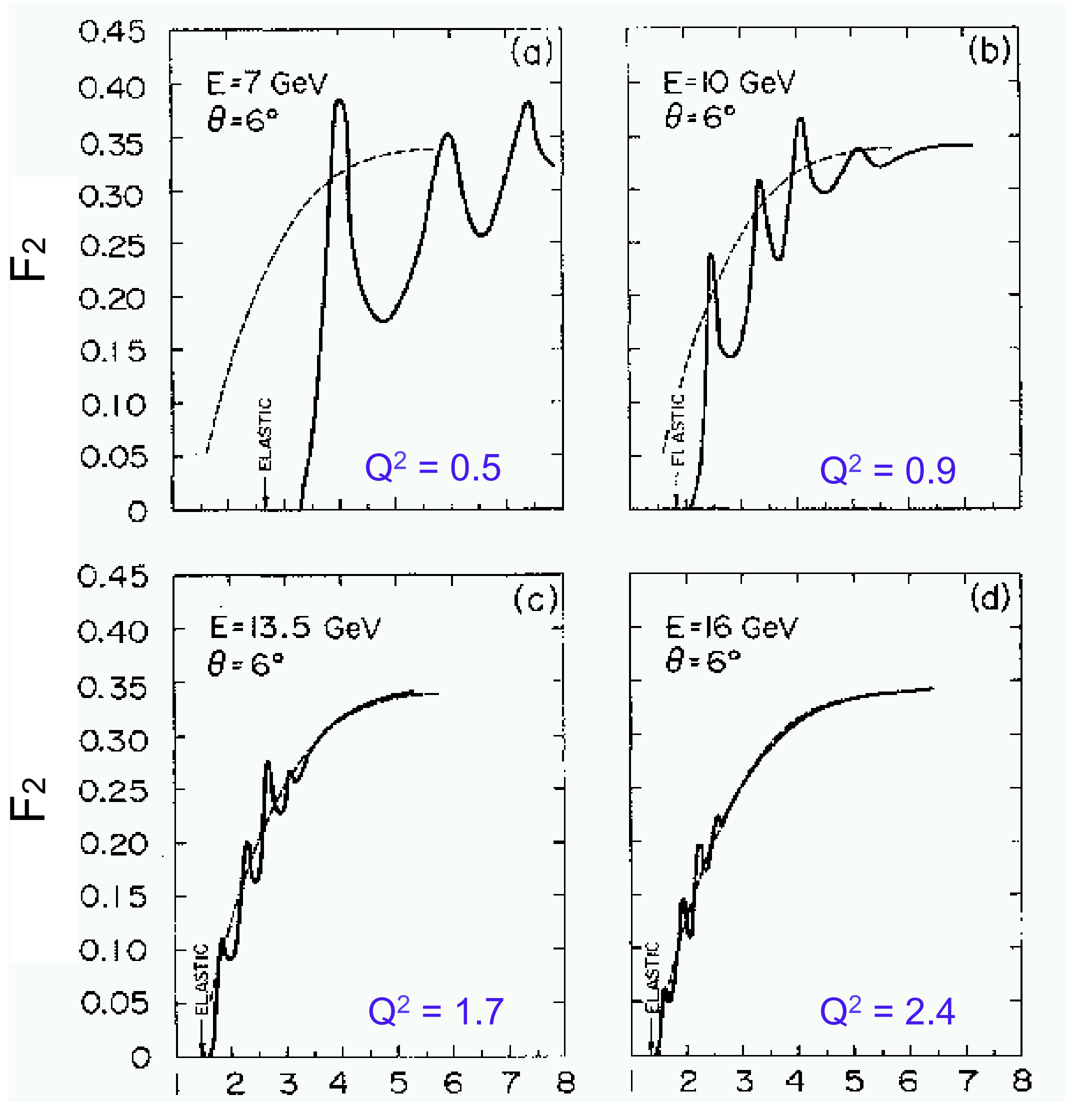
$$\sum_{hadrons} = \sum_{quarks+gluons}$$

Can use either set of complete basis states to describe physical phenomena

In different energy regimes one description is more "economical" than the other: how can we understand the transition between these 2 regimes?

Duality in the F_2 Structure Function

- ***First observed ~1970 by Bloom and Gilman at SLAC by comparing resonance production data with deep inelastic scattering data***
- ***Integrated F_2 strength in Nucleon Resonance region equals strength under scaling curve. Integrated strength (over all ω') is called Bloom-Gilman integral***



$\omega' = 1+W^2/Q^2$

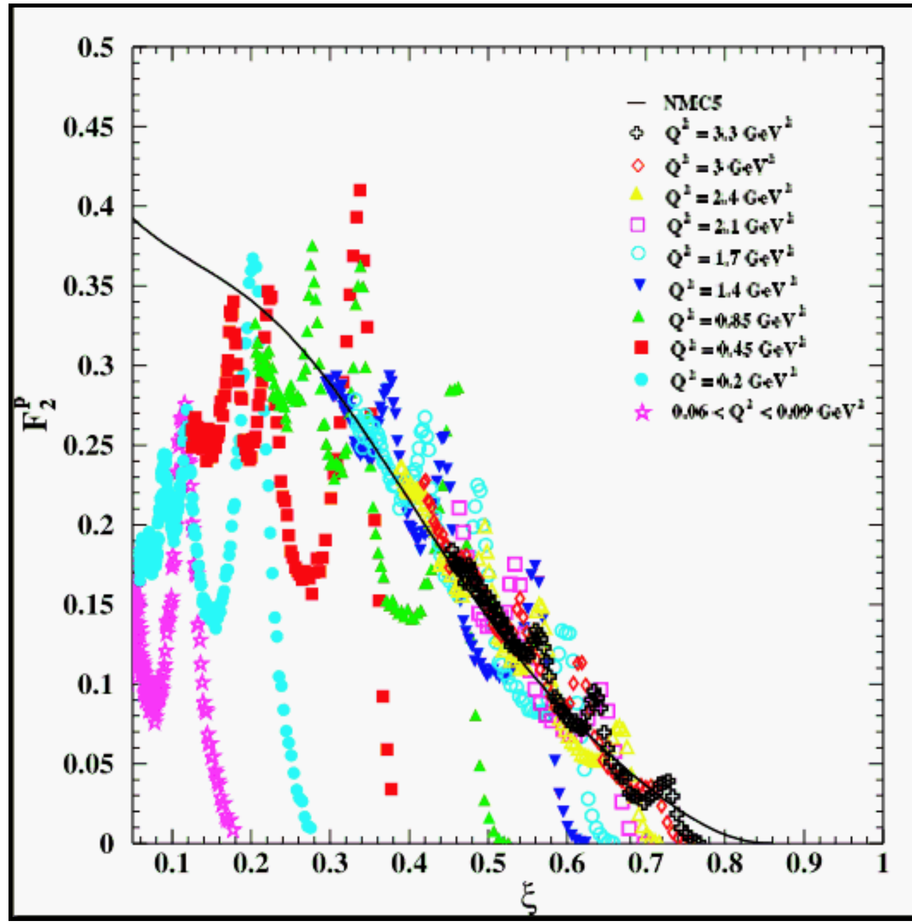
Shortcomings:

- Only a single scaling curve and no Q^2 evolution (Theory inadequate in pre-QCD era)
- No σ_L/σ_T separation → F_2 data depend on assumption of $R = \sigma_L/\sigma_T$
- Only moderate statistics

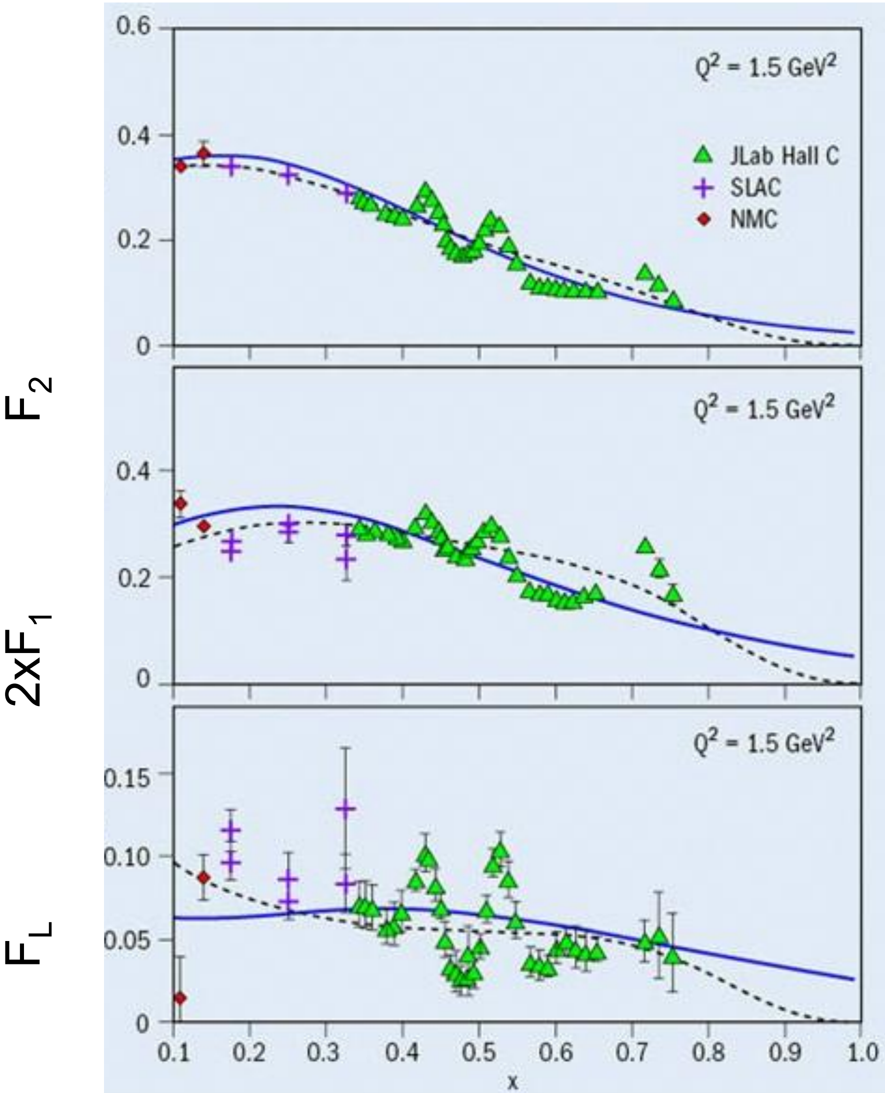
Quark-Hadron Duality

I. Niculescu et al., PRL85:1182 (2000)

- In the late 90s, a large body of data in the resonance region was acquired at JLab
- High statistics, large phase space allowed the examination of duality with high precision
- Most interesting – duality was observed to hold even when looking at individual resonances above Q^2=*1-2* GeV^2!



Duality in Separated Structure Functions



JLab, Hall C: E94-110

The resonance region is, on average, well described by NNLO QCD fits for separated structure functions as well.

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)*.

Duality Summary

- In addition to unpolarized proton structure functions, duality has been observed to manifest for:
  - Neutron structure functions
  - Asymmetries (A^p_1 and A^n_1)
  - Semi-inclusive DIS (SIDIS)
- Other duality-like manifestations
  - Approach to scaling of charged pion form-factor
  - Scaling of deep-exclusive reactions
- The dual nature of these reactions (globally) is not so surprising – its ***required***
- But why does it work so well *locally*?
  - Experimentally, we may have done as much as we can – need new theoretical insight to understand the detailed behavior

Summary – Part 1

- Deep Inelastic Scattering is a powerful tool for probing the quark-gluon structure of nucleons
- DIS gave us first evidence that the partonic picture of the nucleon was accurate
- Since then, unpolarized and polarized DIS has provided a huge body of data that has constrained PDFs
  - Polarized data not yet achieved same kinematic reach and coverage as unpolarized
- While DIS itself is useful – understanding the transition from the non-perturbative to the perturbative regime is a key issue
- What about the 3D structure of nucleons?

EXTRA

Quark Flavor Dependent Effects on Proton

- Measurement of d(x)/u(x) ratio for the proton at high x

$$a_1^p(x) \sim \frac{u(x) + 0.912d(x)}{u(x) + 0.25d(x)}$$

- A clean measurement free from any nuclear corrections
- Uncertainties of set of PVDIS measurements are shown in the plot (red dots)
  - Provides high precision measurements in range of x