Quark - Hadron Duality

↓

At high enough energy

Hadronic Cross Sections averaged over appropriate energy range	=	Perturbative Quark-Gluon Theory

Naturally reflects the Transition from

Strongly Interacting Matter to Perturbative QCD

Duality can guide our understanding/ignorance

Quite general in Nature, e.g.

$e^+ e^-$ ---> Hadrons
Semi-Leptonic Decay of Heavy Quarks
Hadronic τ Decays
Deep Inelastic Scattering (Bloom-Gilman Duality)

But

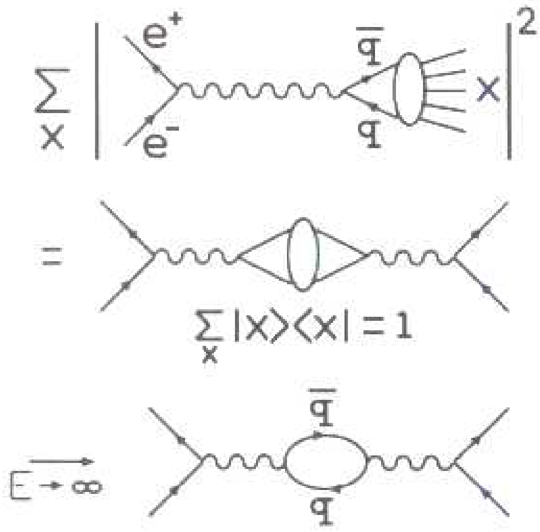
- What energy is high enough?
- What is an appropriate energy range?
- How large are the Duality Violations?

A quantification of Quark-Hadron Duality is still elusive

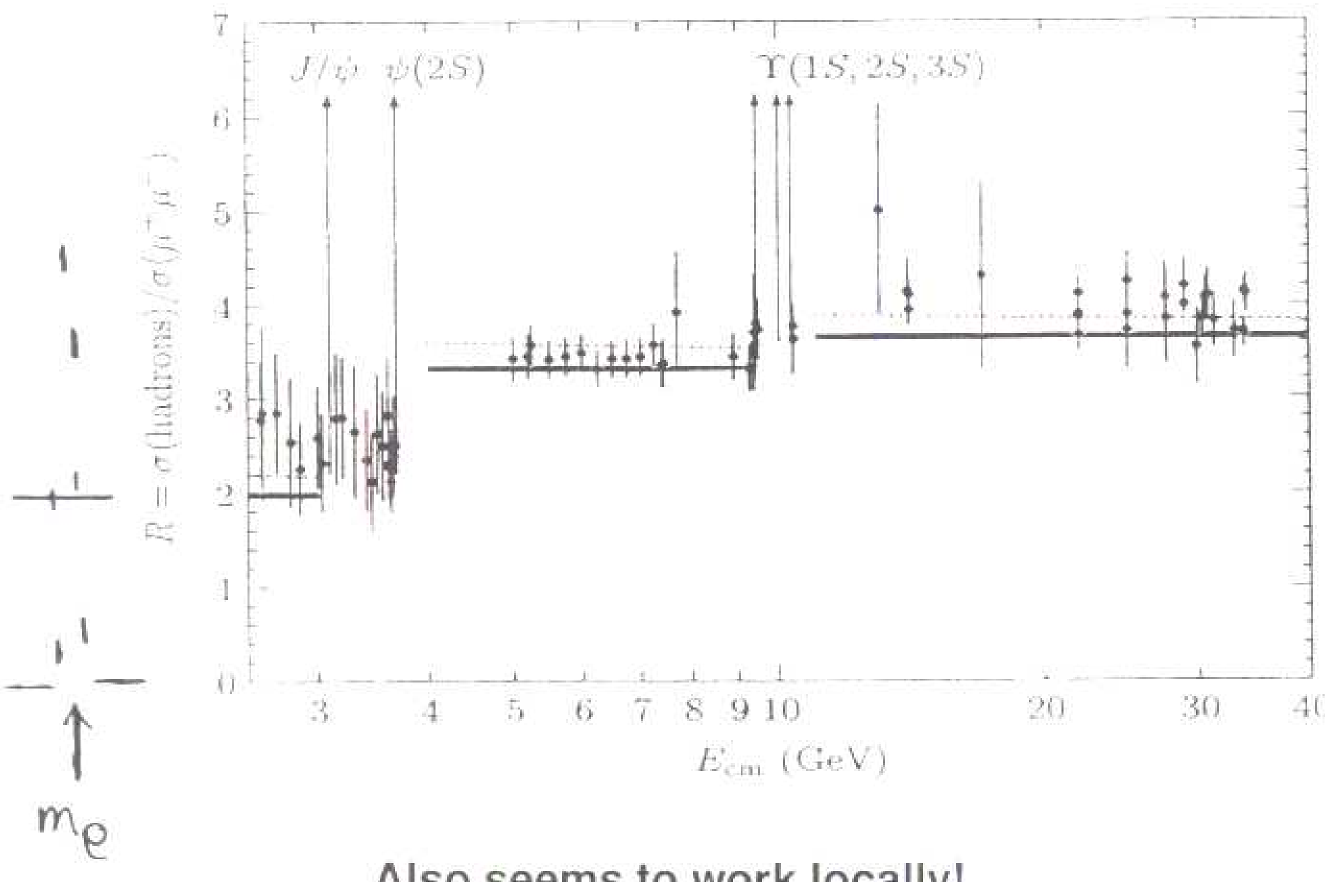
Question is not whether Quark-Hadron Duality works, but why does it work where it works!

$e^+e^- \to$ HADRONS

ROSS SECTION ~



$$\lim_{E\to\infty} \frac{\sigma(e^+e^- \to X)}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_c \sum_q e_q^2$$

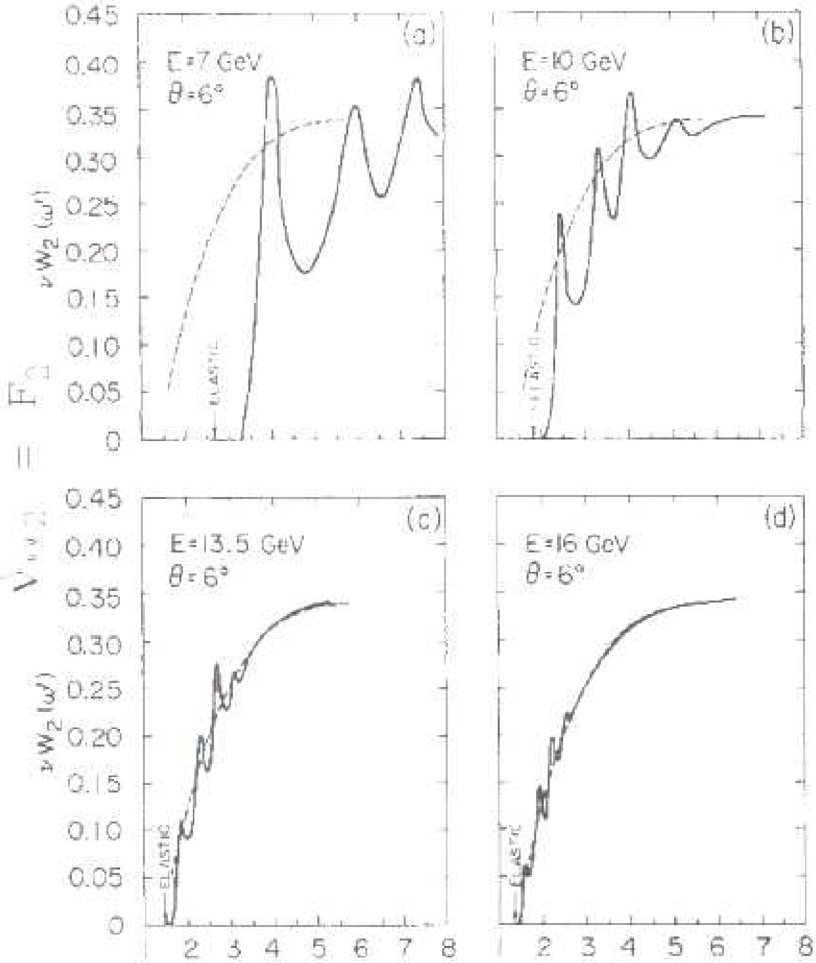


Also seems to work locally!

SCALING, DUALITY, AND THE BEHAVIOR OF RESONANCES IN INELASTIC ELECTRON-PROTON SCATTERING*

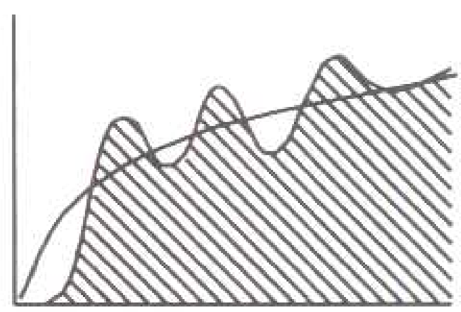
E. D. Bloom and F. J. Gilman
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 25 June 1970)



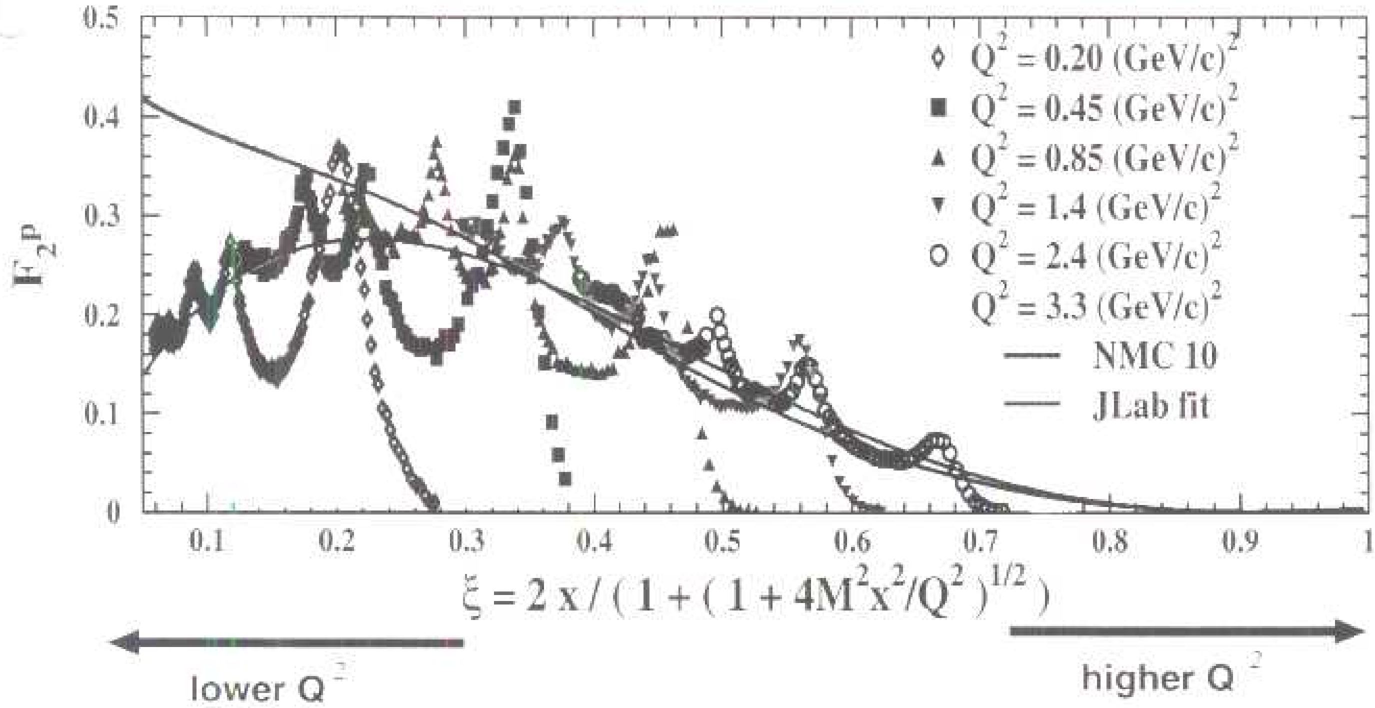
$$\omega' = 1 + \frac{W^2}{Q^2}$$

$$\frac{2M}{q^2}\int_0^{\nu_m} d\nu\, \nu W_2(\nu, q^2) = \int_1^{(2M\nu_m + m^2)/q^2} d\omega'\, \nu W_2(\omega')$$

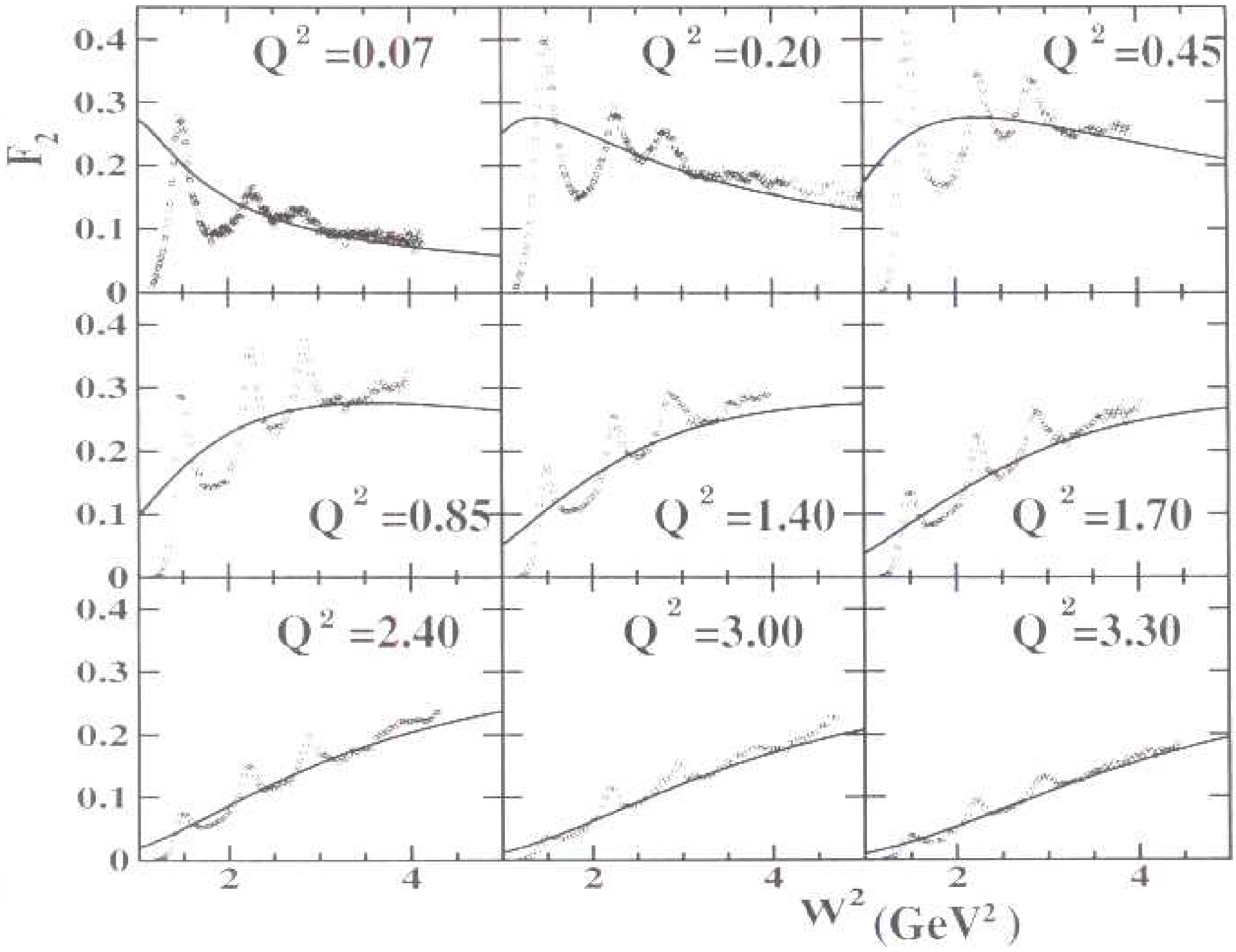


We therefore propose that the resonances are not a separate entity but are an intrinsic part of the scaling behavior of νW_2, and that a substantial part of the observed scaling behavior of inelastic electron-proton scattering is nondiffractive in nature.

Parton-Hadron Duality Studies at Jefferson Lab



- Inclusive data from a range of (Q^2,W^2) values average to the same smooth curve.
- At higher Q^2, this curve is equivalent to the deep inelastic scaling curve (Bloom-Gilman duality).
- Results from quantitative tests show that duality works to <10% in the range $0.5 < Q^2 < 5\ GeV/c^2$.
- In the accepted QCD explanation of duality, this indicates that higher twist effects are small- even at low Q^2.
- The JLab duality - averaged curve has a valence-like shape, and is in qualitative agreement with neutrino xF_3 data.



- SAME duality-averaged curve as obtained on previous figure, now plotted as a function of W.
- The Q^2-dependence of the resonances is apparently governed by the range they cover of this single smooth curve.
- Additionally, the Q^2-dependence of the elastic form factor has been found to agree with this curve to within 20%.
- The resonance region produces a smooth scaling behavior.
- If understood, can use duality as tool to reach large x regime.

Ioana Niculescu, May 2000

Duality in QCD

[redacted] is [redacted] around the Twist-2 curve

Moments of the Structure Function

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

If n = 2, this is the duality integral!!

Operator Product Expansion

$$M_n(Q^2) = \sum_{k=1}^{\infty} \left(\frac{n M_0^2}{Q^2} \right)^{k-1} B_{nk}(Q^2)$$

with B_{nk} having logarithmic dependence

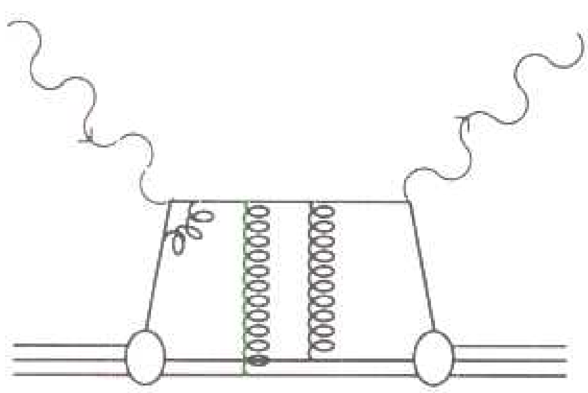
DeRujula, Georgi, Politzer (1977)

$$M_n(Q^2) = \sum_{k=0}^{\infty} E_{nk} \left(\frac{Q^2}{\mu^2} \right) M_{nk}(\mu^2) \left(\frac{1}{Q^2} \right)^k$$

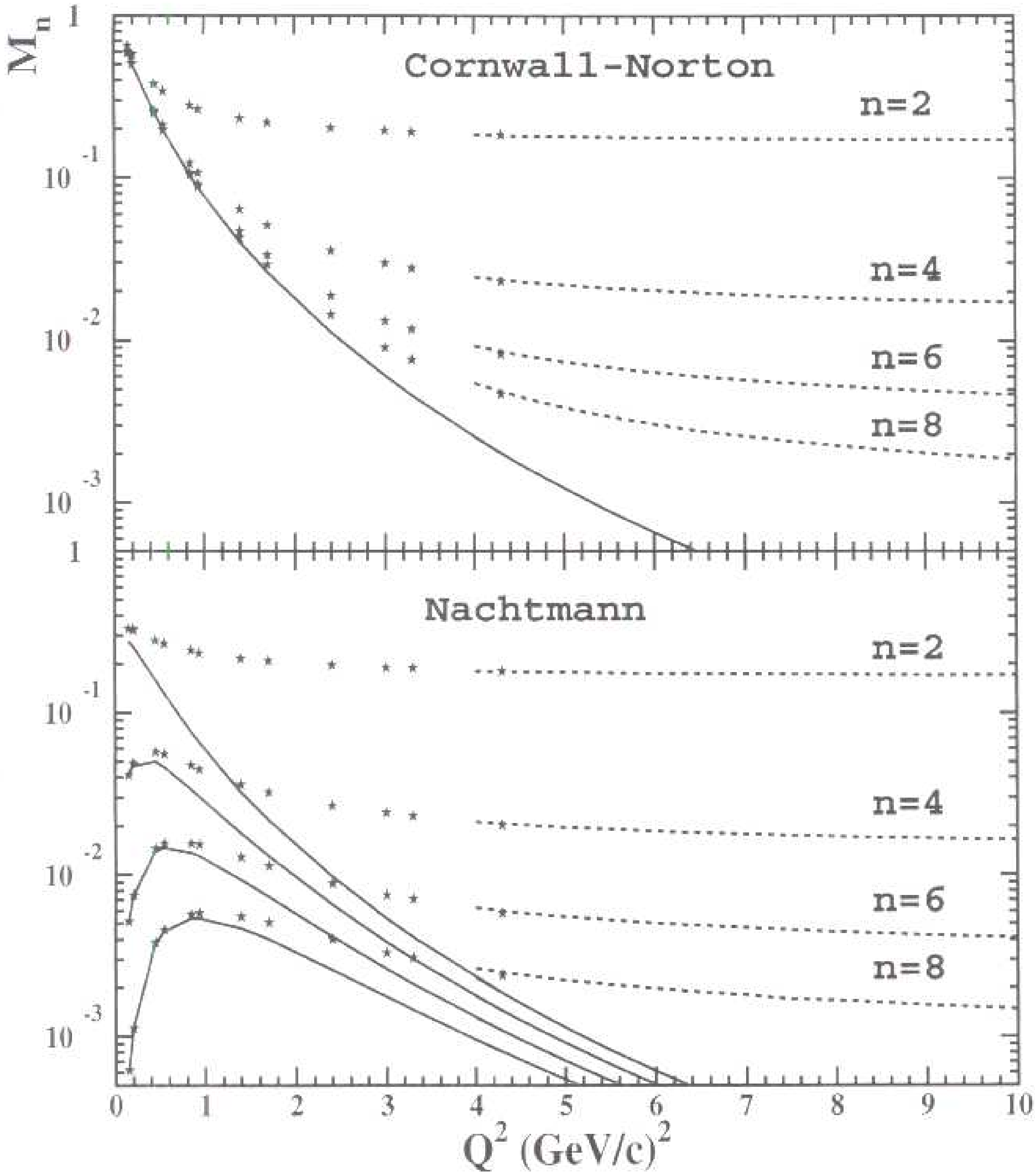
where E_{nk} are dimensionless coefficients, calculated perturbatively

Ji, Unrau (1995)

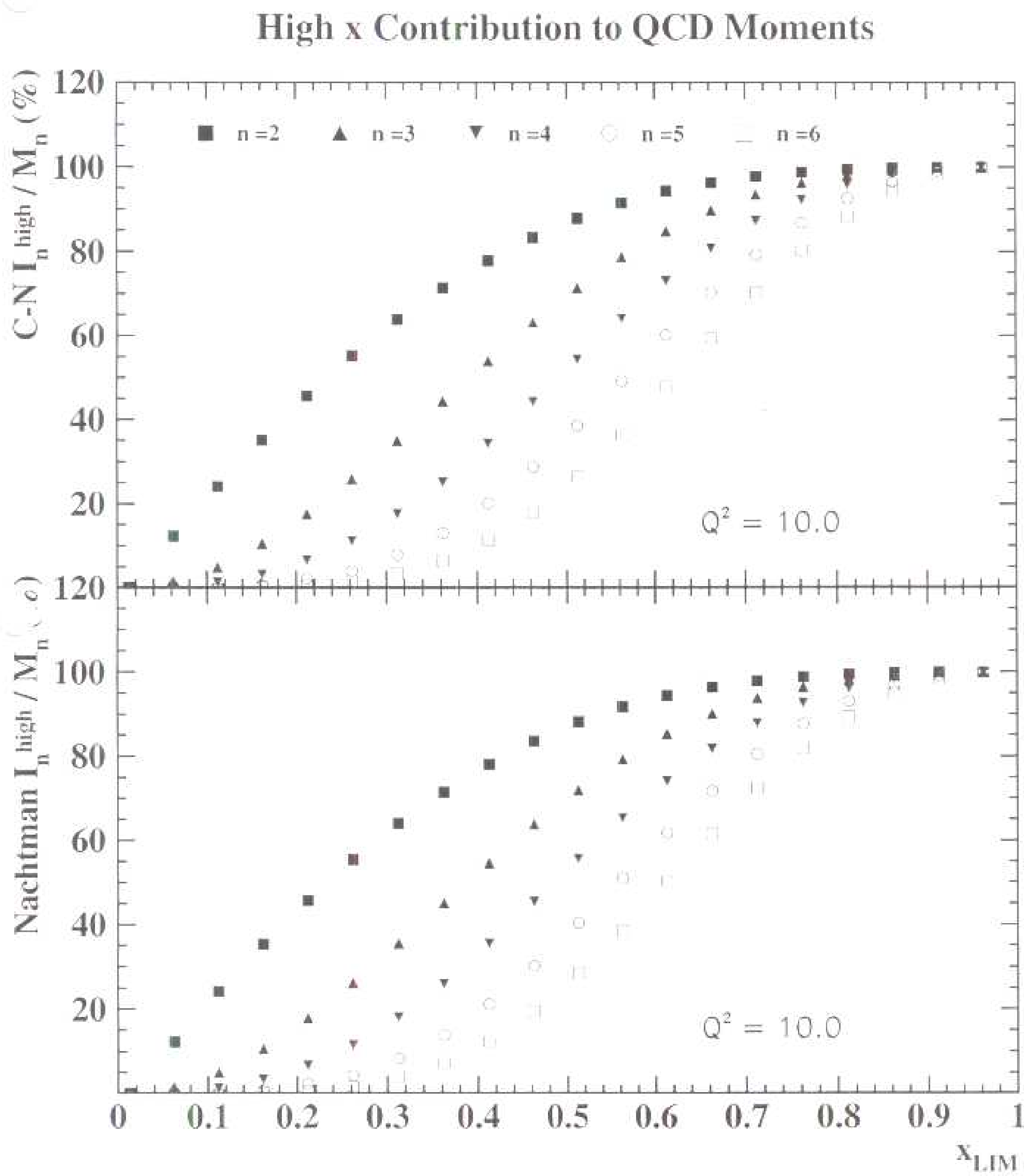
The $O(\frac{1}{Q^2})$ power dependence is due to initial and final state interactions between the struck quark and target remnants



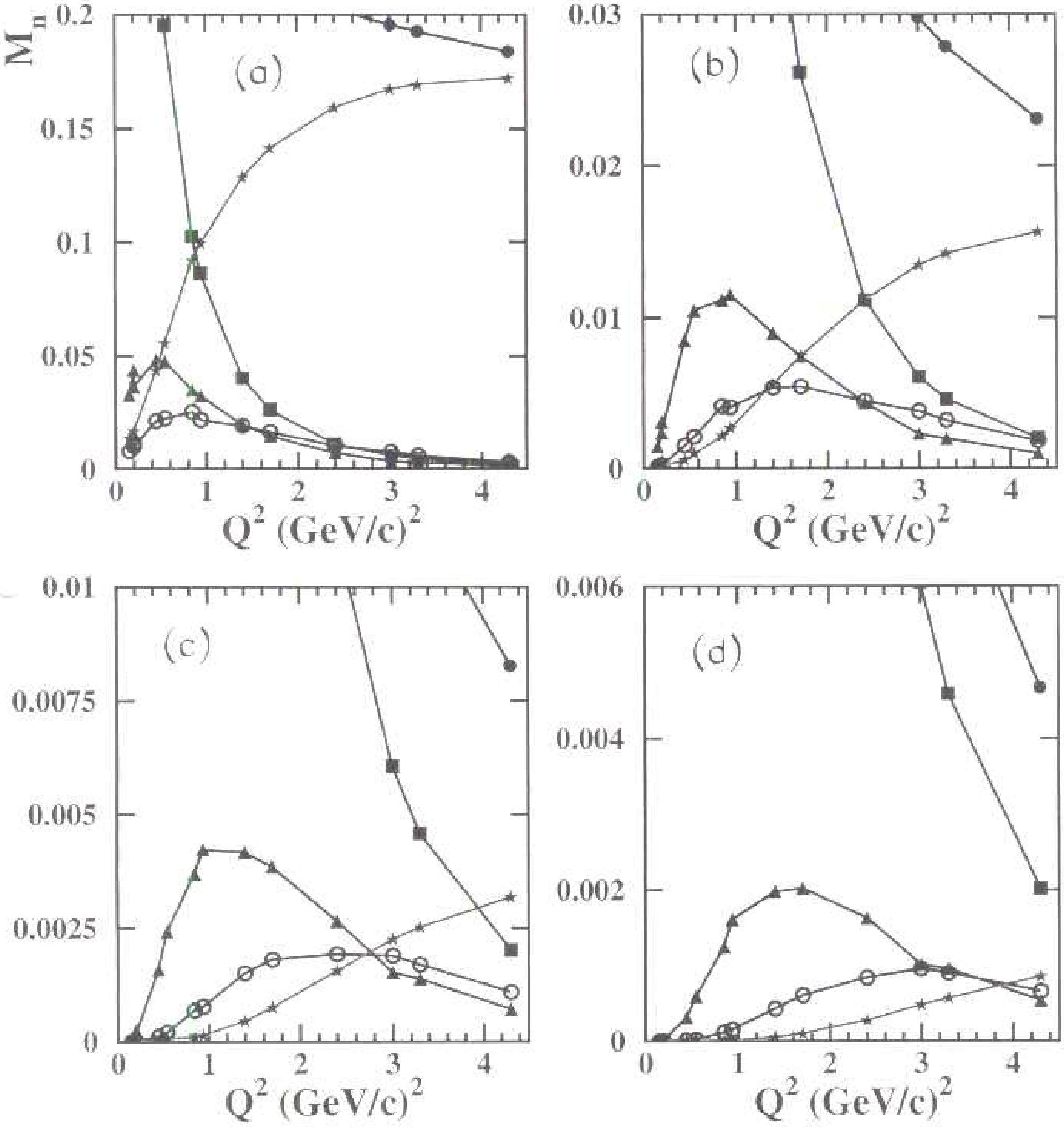
"Higher Twist"



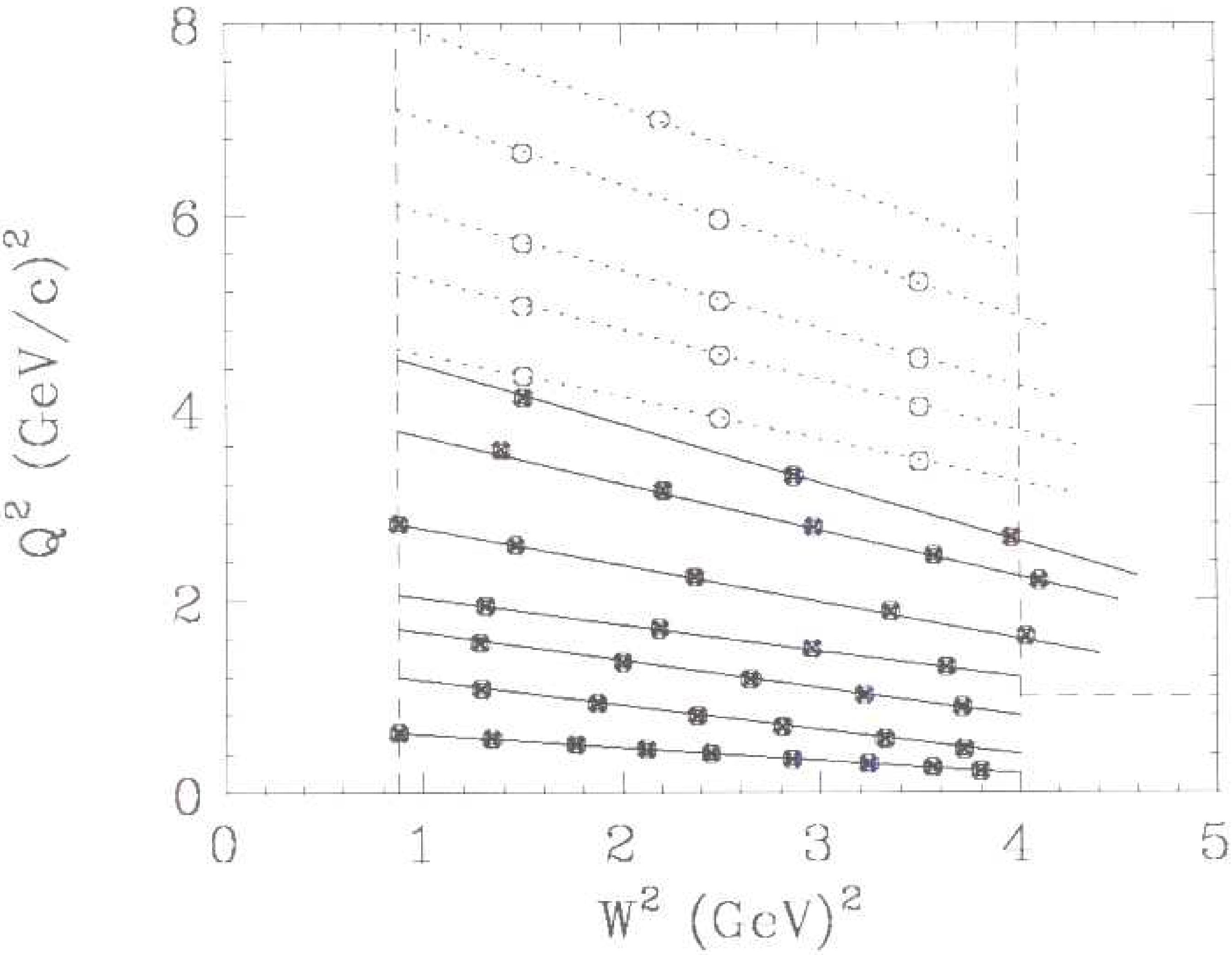
Cornwall-Norton
Nachtmann
n=2
n=4
n=6
n=8
M_n
1
10^{-1}
10^{-2}
10^{-3}
0
1
2
3
4
5
6
7
8
9
10
Q^2 (GeV/c)^2



High x Contribution to QCD Moments
C-N I_n^{high} / M_n (%)
n =2
n =3
n =4
n =5
n =6
Q^2 = 10.0
Nachtman I_n^{high} / M_n (%)
Q^2 = 10.0
x_{LIM}



M_n
(a)
(b)
(c)
(d)
0.2
0.15
0.1
0.05
0
0.03
0.02
0.01
0.0075
0.005
0.0025
0.006
0.004
0.002
0
1
2
3
4
Q^2 (GeV/c)^2



8
6
4
2
0
0
1
2
3
4
5
Q^2 $(GeV/c)^2$
W^2 $(GeV)^2$

E00-116

Proposal E97-010 ~~Update~~:

Measurement of Hydrogen and Deuterium Inclusive Resonance Cross Sections at Intermediate Q^2 for Parton-Hadron Duality Studies

Submitted by

K. Assamagan, S. Avery, O.K. Baker, H. Bitao, E. Christy, A. Gasparian, P. Gueye, C.E. Keppel (spokesperson), Y. Liang, V. Nazaryan, L. Tang

Hampton University, Hampton, VA

J. Arrington

Argonne National Laboratory, Argonne, IL

I. Niculescu

George Washington University, Washington, DC

R. Ent, K. Garrow, J. Gomez, D. Mack, D. Meekins, J.H. Mitchell, W.F. Vulcan, S.A. Wood

Jefferson Laboratory, Newport News, Virginia, VA

J. Dunne

Mississippi State University, Mississippi State, MS

D. Gaskell

Oregon State University, Corvallis, OR

J. Napolitano, P. Stoler

Rensselaer Polytechnic Institute, Troy, NY

T. Averett

College of William and Mary, Williamsburg, VA

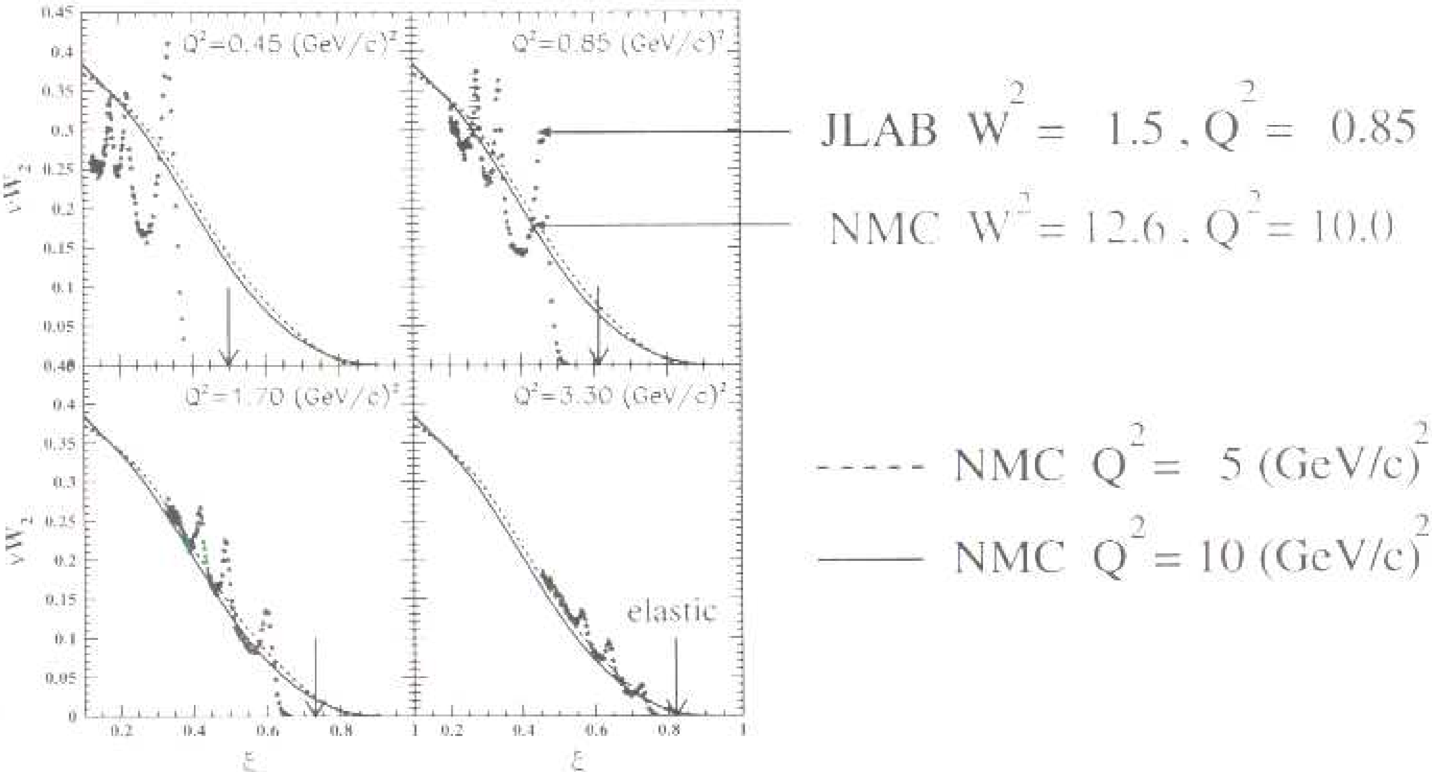
3 DAYS - a bargain!

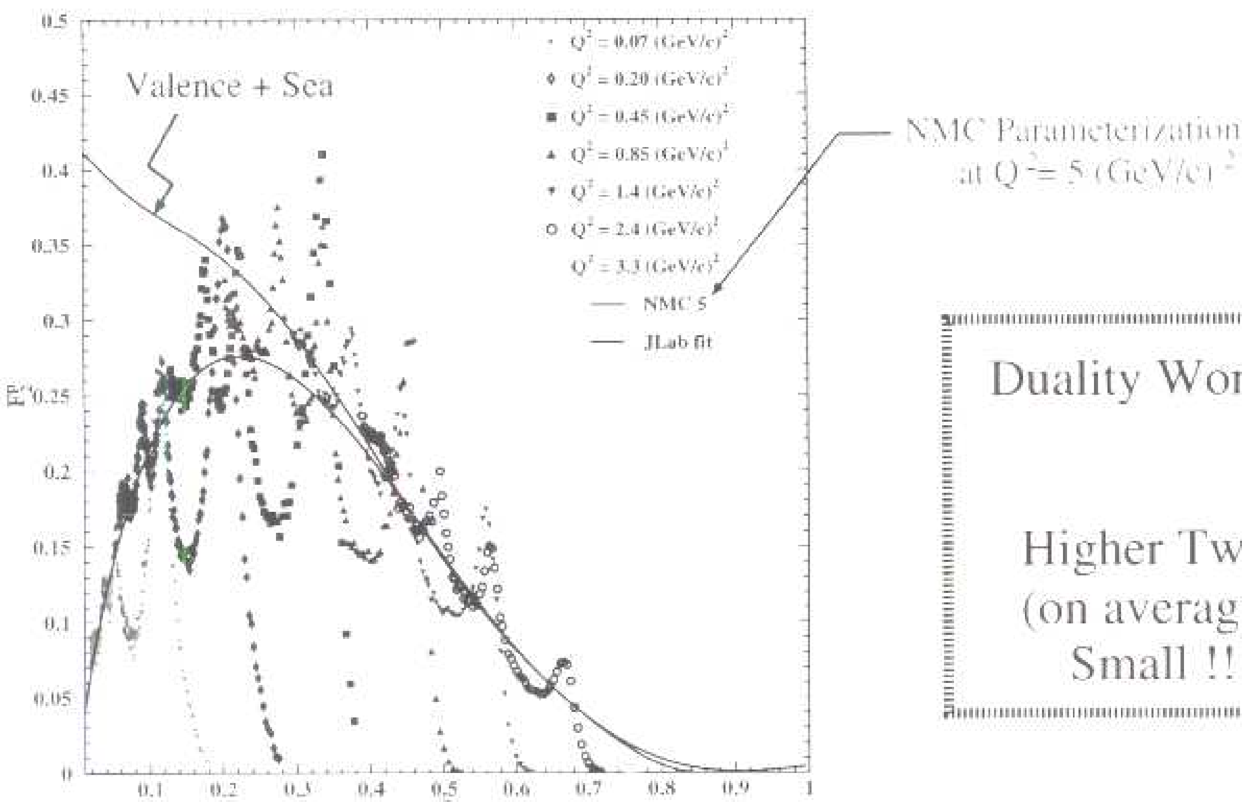
^1H, ^2H

Simultaneous single arm

Bloom-Gilman Duality : Recent Results

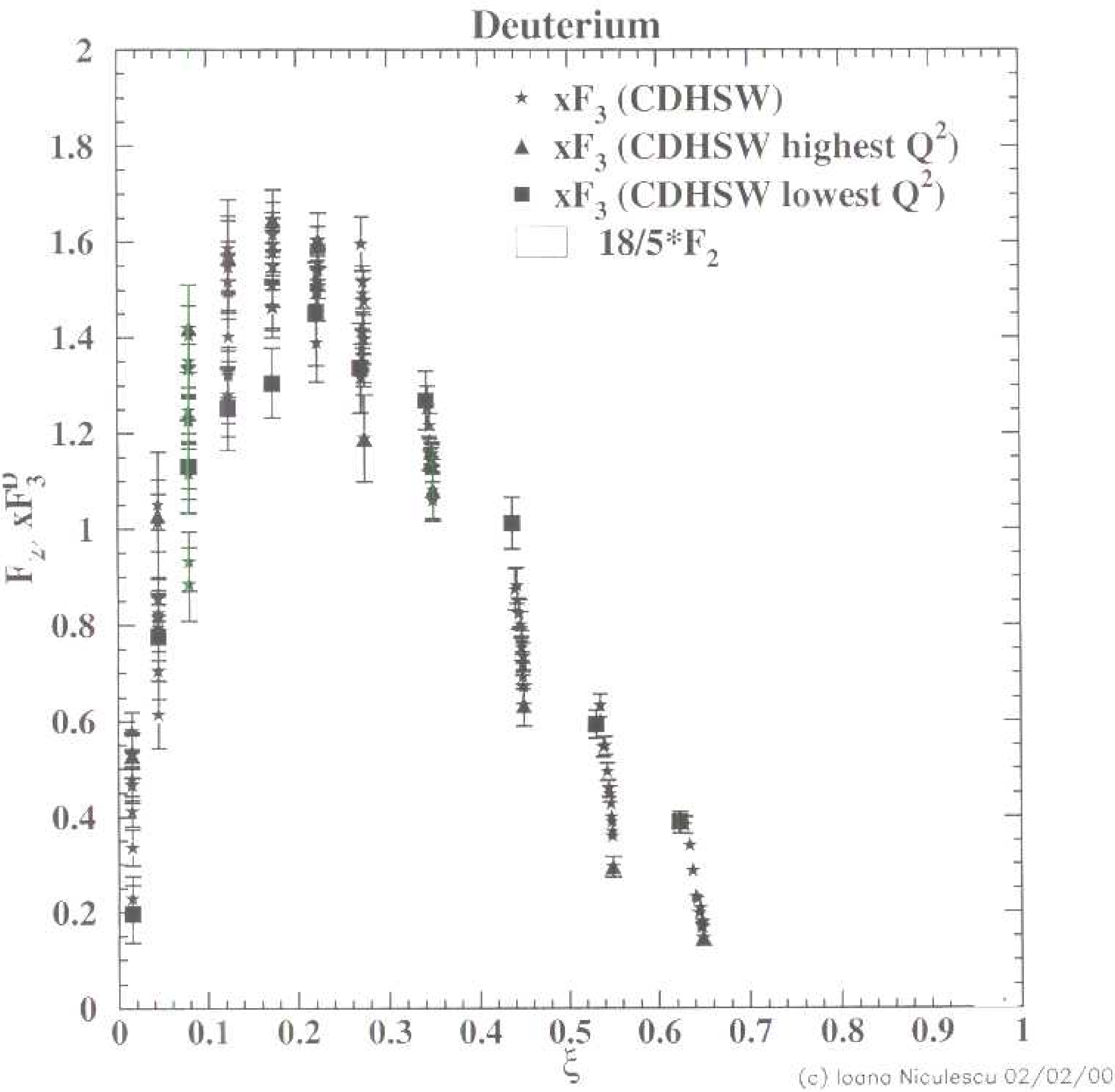
H(e,e')





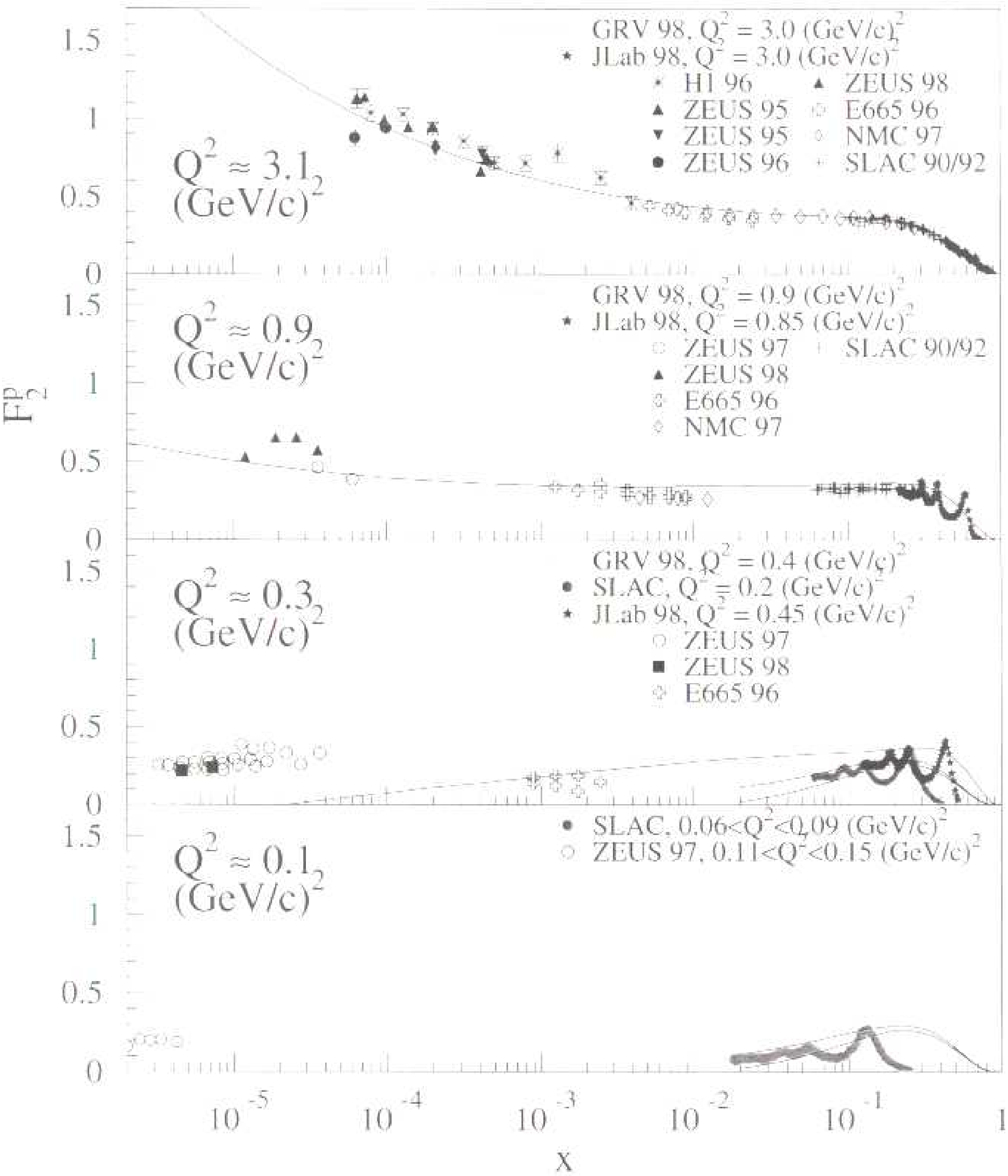
Duality Works !!!

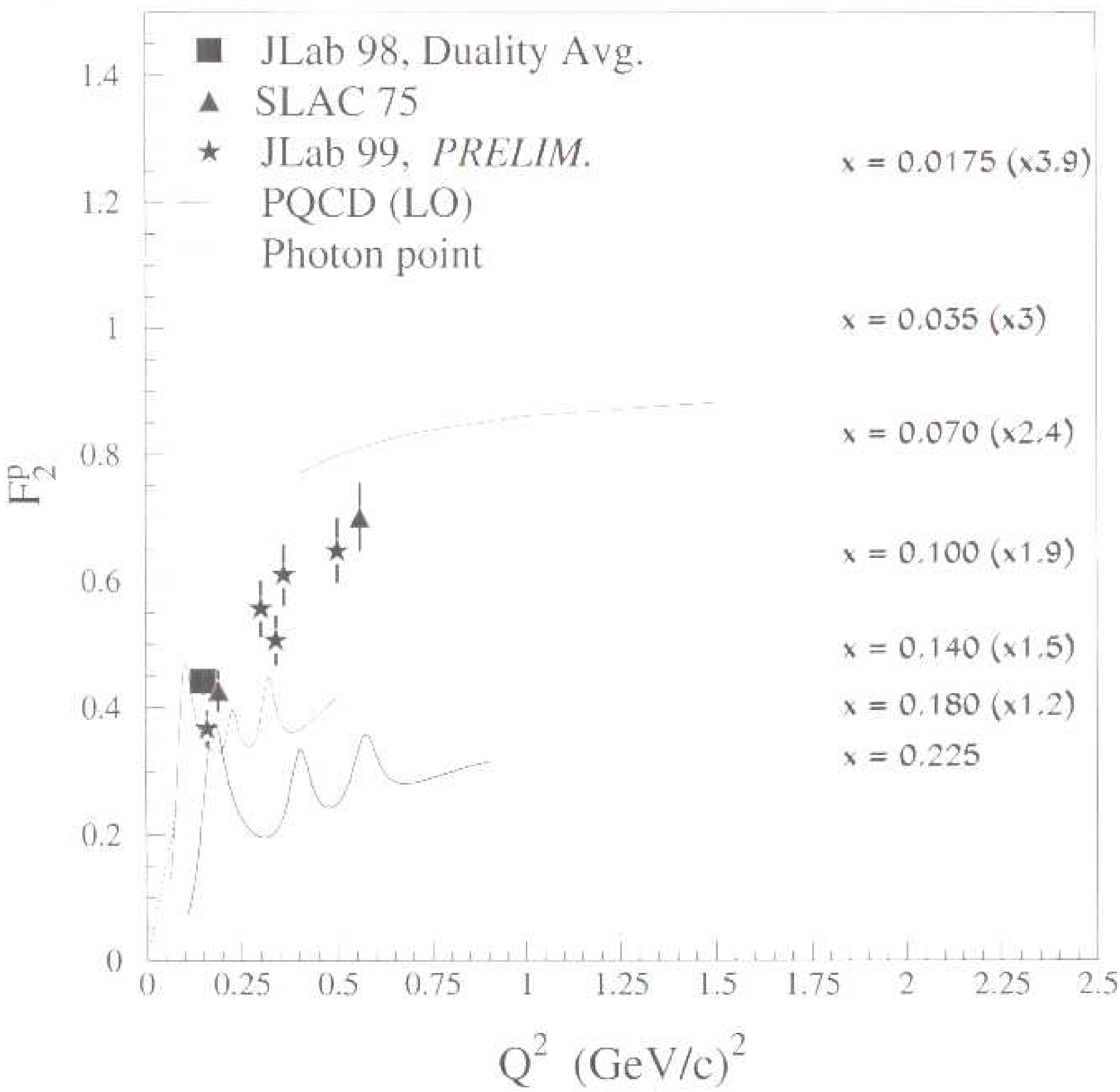
Higher Twist
(on average)
Small !!!


Deuterium
xF3 (CDHSW)
xF3 (CDHSW highest Q2)
xF3 (CDHSW lowest Q2)
18/5*F2
F2, xF3D
ξ
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0.1
0.3
0.5
0.7
0.9
(c) Ioana Niculescu 02/02/00

F_2 at Low Q^2

$$M_n^{C-N}(Q^2) = \int_0^1 x^{n-2} F_2(x, Q^2)\, dx$$





JLab 98, Duality Avg.
SLAC 75
JLab 99, PRELIM.
PQCD (LO)
Photon point
x = 0.0175 (x3.9)
x = 0.035 (x3)
x = 0.070 (x2.4)
x = 0.100 (x1.9)
x = 0.140 (x1.5)
x = 0.180 (x1.2)
x = 0.225
F2p
Q2 (GeV/c)2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0.25
0.5
0.75
1.25
1.5
1.75
2
2.25
2.5

E00-002

F_2^N at low Q^2

December 14, 1999

Submitted by

[redacted] R. Ent, K. Garrow, A. Lung, D. J. Mack, J. Mitchell, S. A. Wood
Jefferson Lab, Newport News, VA

I. Niculescu (spokesperson)
The George Washington University, Washington, DC

D. Meekins
Florida State University, Tallahassee, FL

H. Bitao, M. E. Christy, A. Cochran, P. Guèye, C. Jackson, C. E. Keppel (spokes2)
Hampton University, Hampton, VA

G. Niculescu
Ohio University, Athens, OH

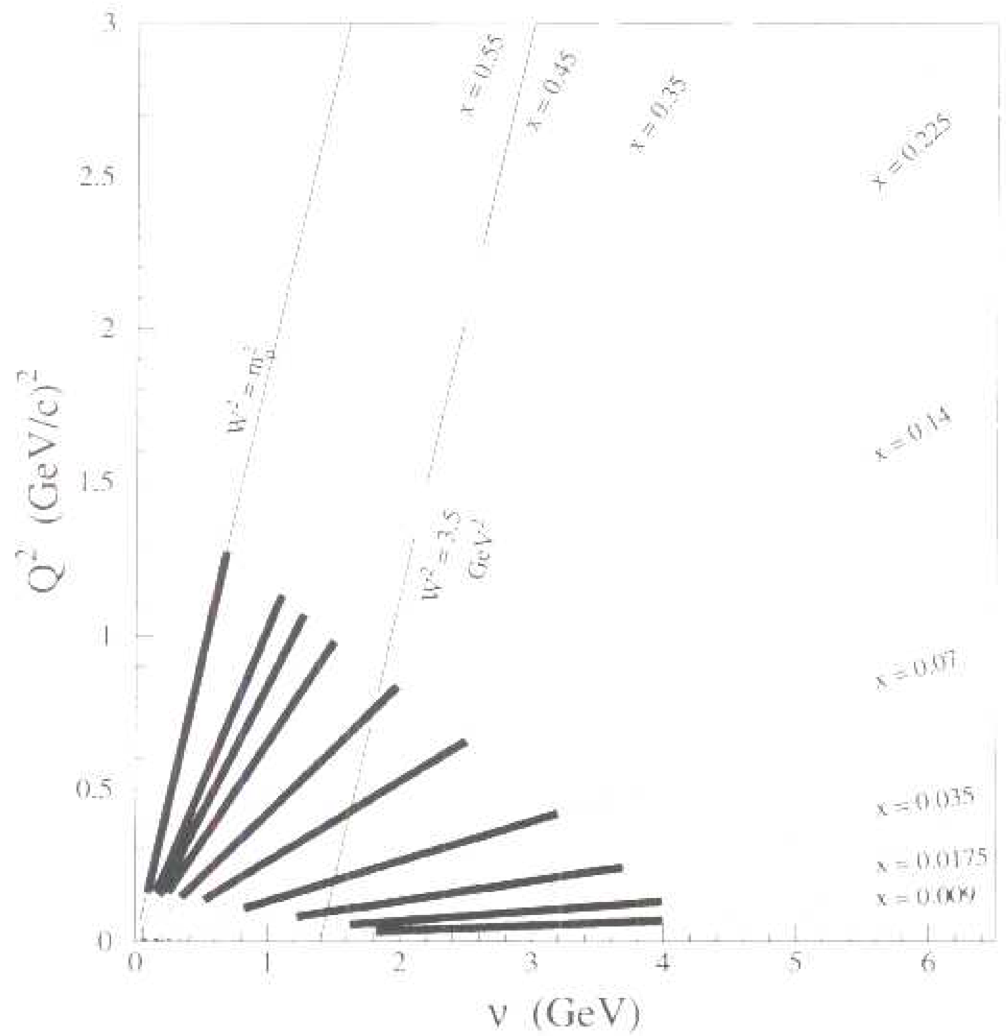
P. Stoler
Rensselaer Polytechnic Institute, Troy, NY

E. Kinney
The University of Colorado at Boulder, Boulder, CO

R. Asaturyan, H. Mkrtchyan, S. Stepanyan, V. Tadevosyan
Yerevan Physics Institute, Armenia

A- approval
8 days
^1H, ^2H
HMS only

Kinematics



— kinematic region of this experiment

Proposed Kinematics

E_b (GeV)	θ_e (deg.)	E' (GeV)	x	Q^2 $(GeV/c)^2$	ε
4.4	16.0	0.4–3.9 (22 settings)	0.016–1	0.13–1.42	0.18–0.95
4.4	10.5	0.4–3.9 (22 settings)	0.007–1	0.05–0.61	0.18–0.98
3.3	10.5	0.4–3.1 (20 settings)	0.007–1	0.04–0.36	0.24–0.98
2.2	10.5	0.4–2.2 (17 settings)	0.008–1	0.03–0.16	0.35–0.98

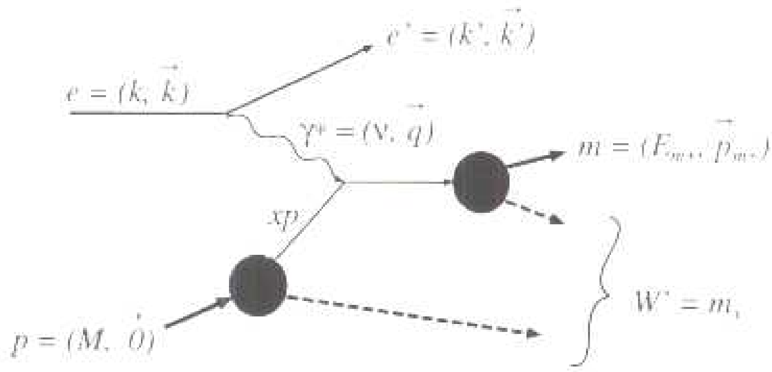
Take data on Hydrogen
Deuterium

Activity	Time (hours)
Data acquisition	68
Configuration changes	70
Beam energy changes	18
Checkout	12
Total	**168** (7 days) +1 (TAC)

Table 2: Beam time request for the proposed experiment.

Duality in Meson Electroproduction

Afanasev, Carlson, and Wahlquist, Phys. Rev. D 62, 074011 (2000)



(e,e′) $$W^2 = M_p^2 + Q^2\left(\frac{1}{x} - 1\right)$$

For M_m small, collinear with $\vec{\gamma}$, and $\frac{Q^2}{\nu^2} << 1$

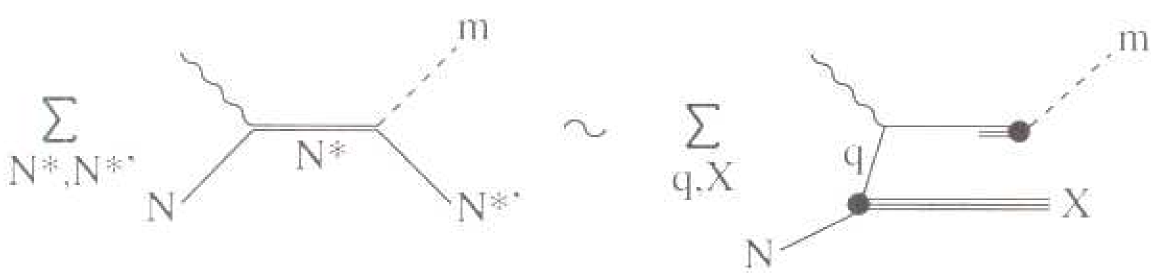
[redacted] $$W'^2 \approx M_p^2 + Q^2\left(\frac{1}{x} - 1\right)(1 - z)$$

$z = E_m/\nu$

Factorization gives (LO QCD)

$$\frac{d\sigma}{dz} \sim \sum_i e_i^2 \left[q_i(x, Q^2) D_{q_i}^m(z, Q^2) + \bar{q}_i(x, Q^2) D_{\bar{q}_i}^m(z, Q^2)\right]$$

In hadronic basis: excitation of N^* resonances and subsequent decays into mesons and lower-lying resonances $N^{*\prime}$



[redacted]

Duality in Electropion Production
Cornell data ('70's)

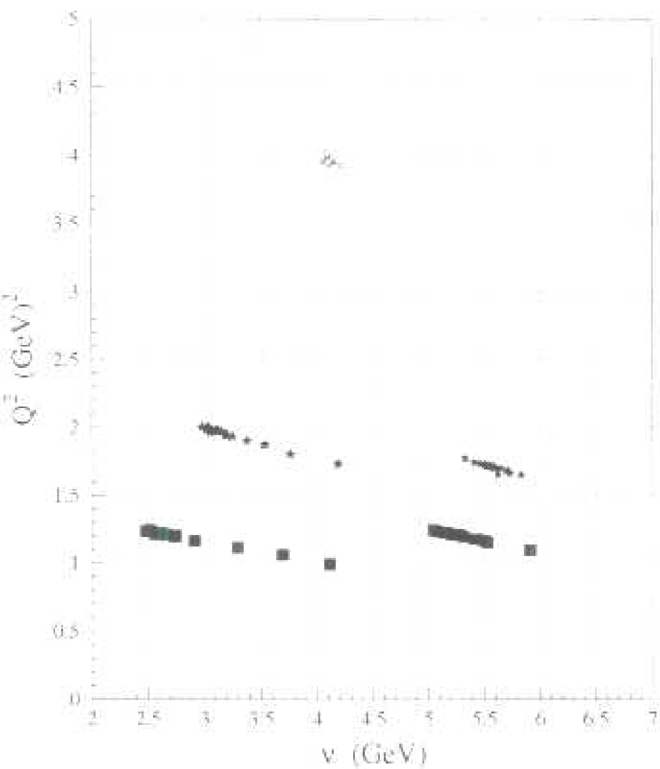
Bebek et al, Phys. Rev. Lett. 34, 75 (1975); Phys. Rev. Lett. 37, 1525 (1976); Phys. Rev. D 15, 3085 (1977)

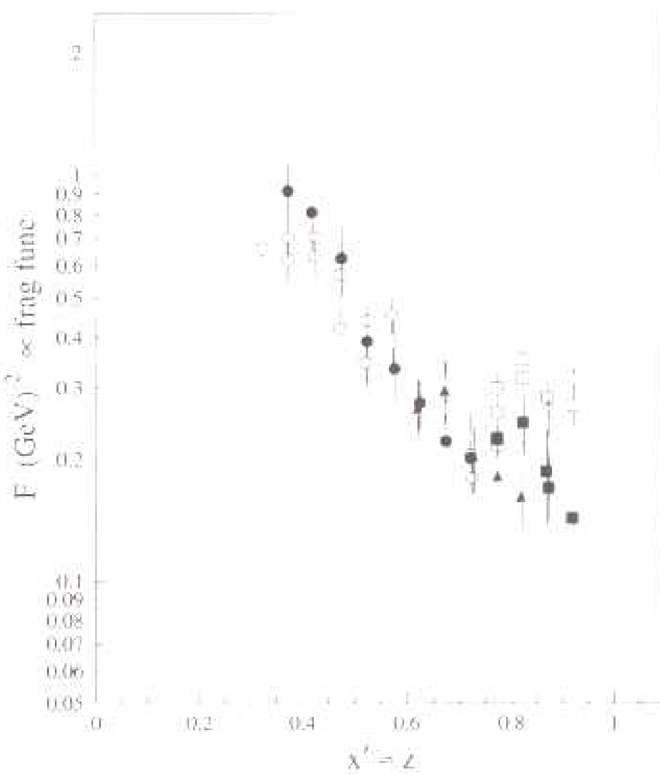
Data obtained at moderate Q^2 and ν

Typical pion momenta only ≈ 2 GeV/c!!

Analyze in terms of fragmentation function $\boxed{F(x') \sim D_u^\pi(z)}$ [The authors conclude that F has no Q^2 dependence, and only weak W^2 dependence]

Concentrate on the resonance region: $1.3 < W'^2 < 3.1$ GeV^2





□	$1.3 < W'^2 < 1.9$	Open: $Q^2 < 2.2$	Closed: $Q^2 > 2.2$
△	$1.9 < W'^2 < 2.5$		
○	$2.5 < W'^2 < 3.1$		

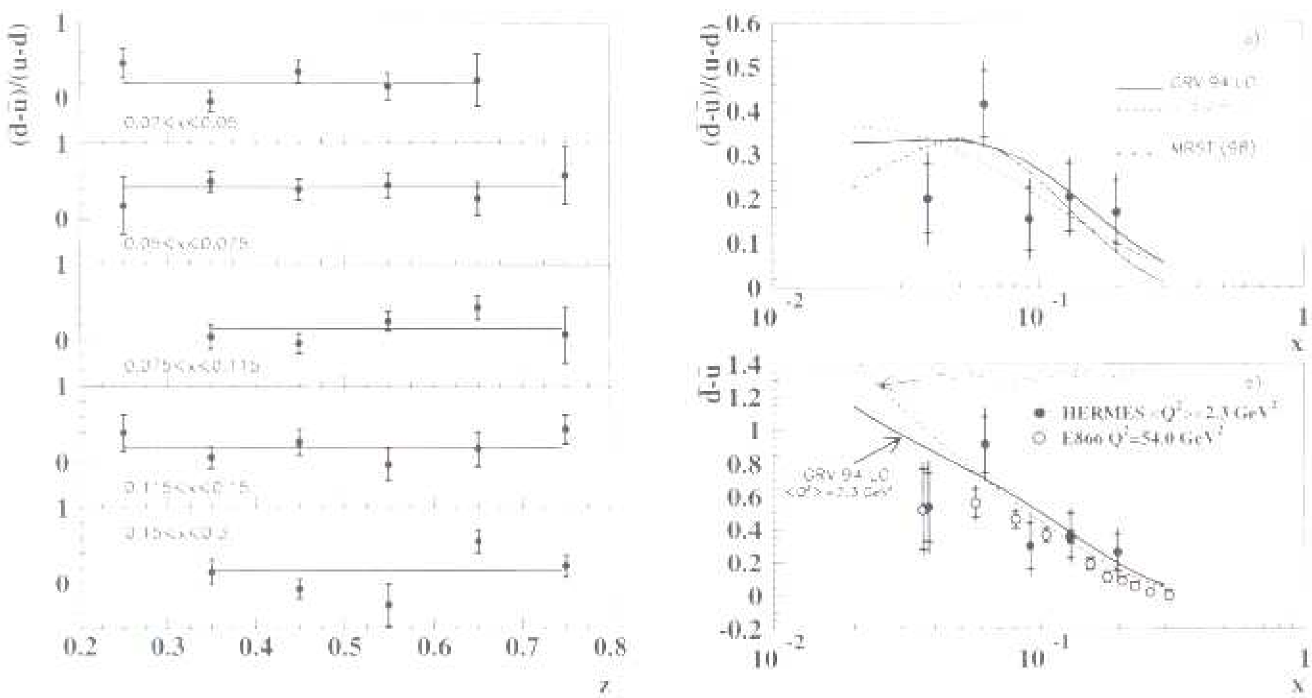
[redacted]

Low-Energy Factorization?

Flavor Asymmetry of the Light Quark Sea

$$\frac{\bar{d}(x) - u(x)}{u(x) - d(x)} \sim f(D^+(z)/D^-(z)) \frac{N_p^{\pi^-}(x,z) - N_n^{\pi^-}(x,z)}{N_p^{\pi^+}(x,z) - N_n^{\pi^+}(x,z)}$$

HERMES Collaboration, Phys. Rev. Lett. **81**, 5519 (1998)



- Data do, within statistics, confirm independence of x and z dependence, for $z \geq 0.25$
- HERMES data at $Q^2 \sim 2.3$ GeV^2 agree well with FNAL Drell-Yan data at Q^2 = 54 GeV^2

$x \approx$ **0.1**, $Q^2 \approx$ **2.3** $\rightarrow W^2 \approx$ **25**

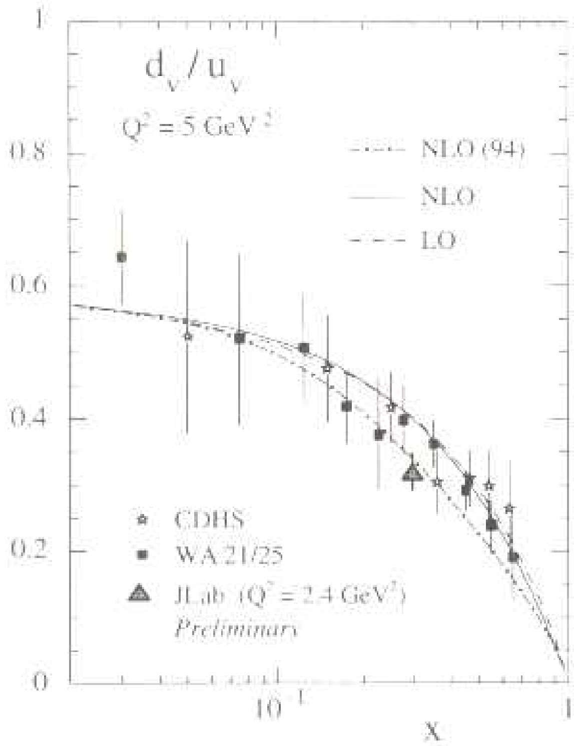
Low-Energy Factorization at JLab?

^{1}H(e,e$'\pi^{+}$) and ^{2}H(e,e$'\pi^{+}$) data

8 hours only !!!

$\nu \approx$ 4 GeV, Q^2 = 2.3 GeV^2, W^2 = **5 GeV^2, $z > 0.5$**

- Extracted fragmentation functions agree reasonably well with NLO fragmentation function fit to high-energy e^+e^- data



- Extraction of d_v/u_v agrees well with high energy data

E00-108 approved for 20 days to test factorization over large x and z range

'f factorization holds, large research area of quark fragmentation opens up

E00-108

Duality in Meson Electroproduction

June 1, 2000

Submitted by

R. Ent (spokesperson), H. Fenker, K. Garrow, D. J. Mack, D. Meekins, J. H. Mitchell, A. Lung, G. Smith, W. F. Vulcan, S. Wood, C. Yan
Jefferson Laboratory, Newport News, VA

H. Mkrtchyan (spokesperson), R. Asaturyan, S. Stepanyan, V. Tadevosyan
Yerevan Physics Institute, Armenia

G. Niculescu (spokesperson)
Ohio University, Athens, OH

O. K. Baker, M. E. Christy, A. Cochran, A. Gasparian, P. Gueye, B. Hu, C. Jackson, C. E. Keppel, Y. Liang, V. Nazarian, L. Tang, A. Uzzle
Hampton University, Hampton, VA

I. Niculescu
George Washington University, Washington, DC

P. Stoler
Rensselaer Polytechnic Institute, Troy, NY

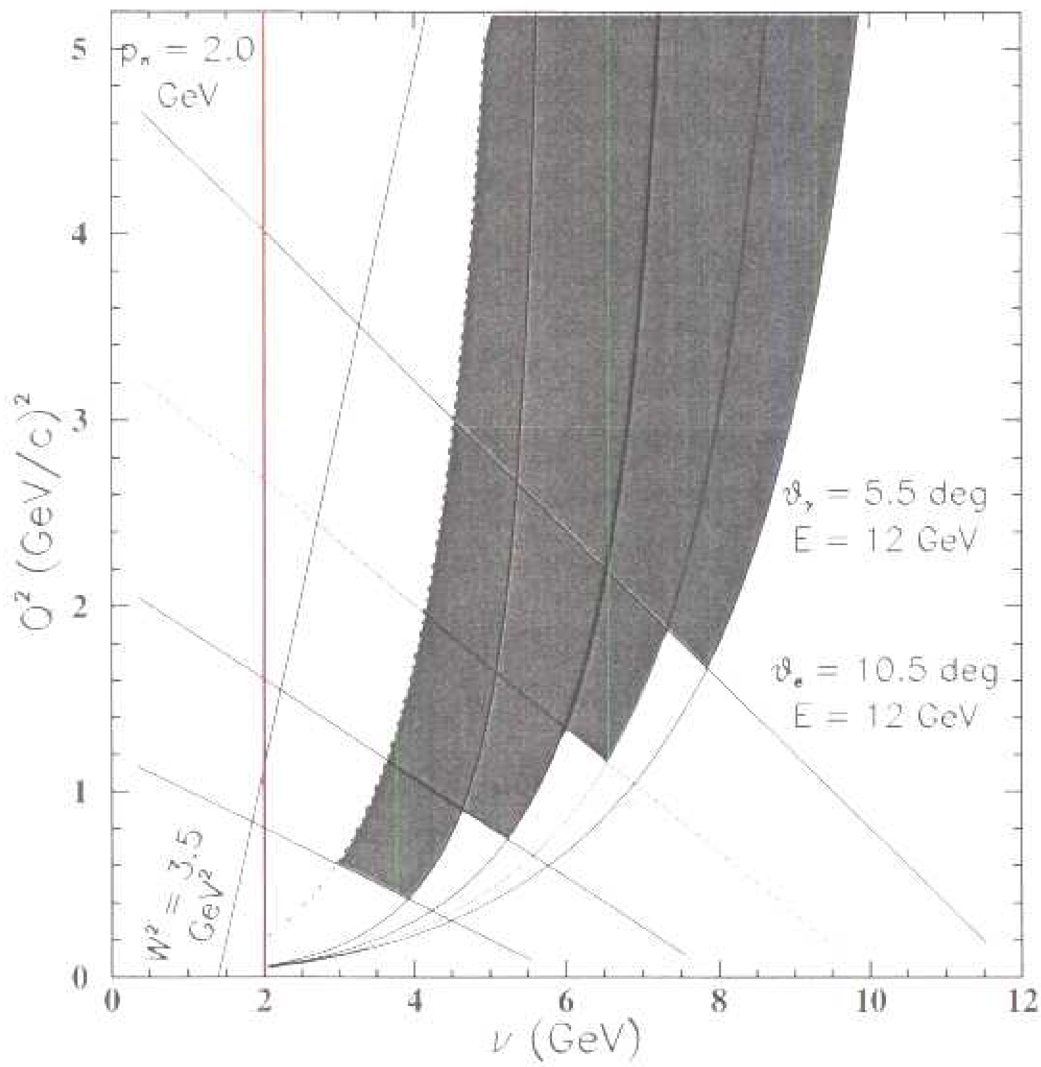
D. B. Day, M. Zeier
University of Virginia, Charlottesville, VA

J. Reinhold
Florida International University, Miami, FL

Hall C 12 GeV Kinematics
HMS + SHMS

Essential for two magnetic spectrometer setup to have

- One spectrometer with momentum ≈ beam energy (z = 1 , $Q^2 \approx$ 18)
- Spectrometers can reach forward angles
- Spectrometers can reach forward angles **at the same time**



Since $z = E_h/\nu$, and factorization gets better at large ν (or W^2), but not large Q^2, we want to access large ν $\longrightarrow$ small angles!

z range = [0.3-0.8] , x range = [0.2-0.7], Q^2 range = [1 - 10] (GeV/c)^2