Jefferson Lab @ 12 GeV
Jan. 15, 2000

Summary of

PARTON-HADRON DUALITY

Parallel Session

Wally Melnitchouk

Jefferson Lab & CSSM, Adelaide

Quark-Hadron Duality at JLab

- Why is duality interesting?

- How do we understand duality?

- Applications of duality

- How can JLab at 12 GeV contribute?

Why is Duality Interesting?

- Duality probes the relationship between confinement and asymptotic freedom

  Resonances $\Longleftrightarrow$ scaling structure functions

  Hadronic $\Longleftrightarrow$ partonic degrees of freedom

  [Off-forward parton distributions:
  form factors $\longleftrightarrow$ structure functions]

- Intimately related to the nature of the transition between non-perturbative and perturbative QCD

- Quark-hadron duality is quite general, and manifests itself in many processes
  $\Rightarrow$ $e^+e^- \to X$, heavy quark decays, $\cdots$
  $\Rightarrow$ arises in simplest of models/theories which display confinement

- Indicates importance of power corrections to perturbative expansions

e.g. n-th moment of structure function:

$$M_n(Q^2) = A_n^{(0)} + \frac{A_n^{(2)}}{Q^2} + \frac{A_n^{(4)}}{Q^4} + \cdots$$

$A_n^{(0)} \longrightarrow$ leading twist

$\longrightarrow$ <u>single quark scattering</u>

$A_n^{(2,4,\cdots)} \longrightarrow$ higher twist

$\longrightarrow$ <u>quark–gluon correlations</u>

- Understanding duality $\Longleftrightarrow$ high twists

$\Rightarrow$ backgrounds for leading twist vs. signal for non-perturbative QCD

$\Rightarrow$ need to be in "transition region", $0.5 < Q^2 < 5$ GeV^2, to measure, but not be overwhelmed by, $1/Q^2$ corrections

- Why does duality work at all?

Trivial answer: if QCD is the correct theory of hadrons, then a quark description of any process must coincide with a hadronic description

$\Longleftrightarrow$ unitarity, completeness

Question is not whether duality works, but why does it work where it works !

Bloom-Gilman Duality

- "Resonances average to a universal (scaling) curve"

Lowest moment ($n = 2$) of structure function:

$$M_2(Q^2) \; = \; \int_0^1 d\xi \; F_2(\xi, Q^2)$$

$$\frac{dM_2(Q^2)}{dQ^2} \approx 0$$

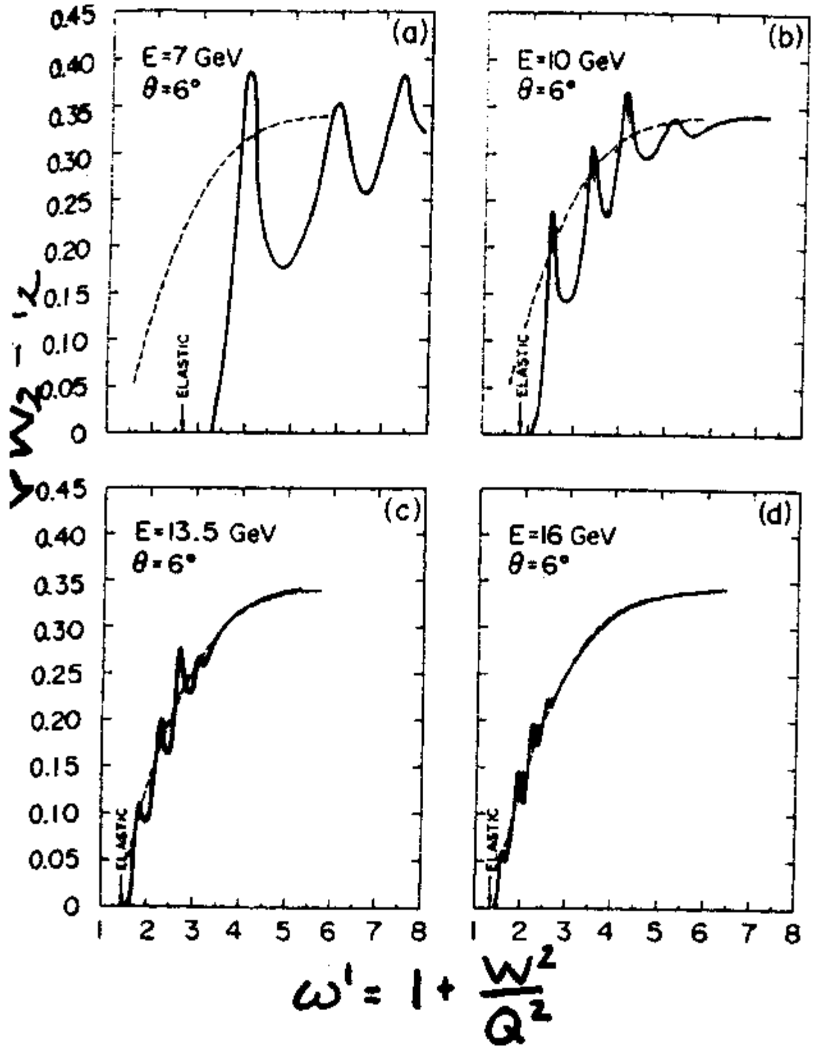
$$\Updownarrow$$

high twists $A_2^{(i \geq 2)}$ are small or cancel

Importance of higher twists — extent to which duality works — obviously depends on moment n

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)



$$\frac{2M}{q^2}\int_0^{\nu_m} d\nu\, \nu W_2(\nu, q^2)$$

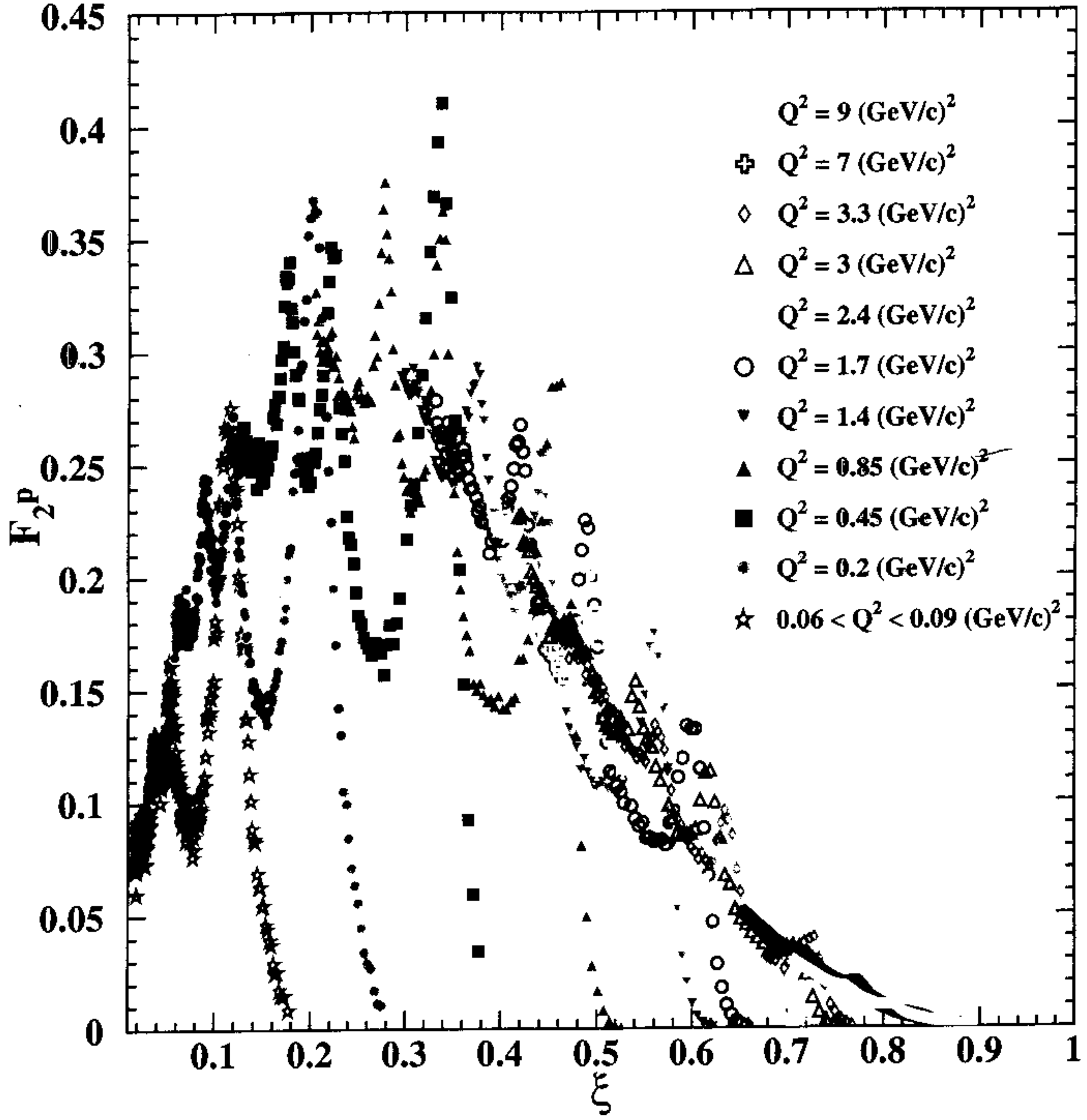
$$=\int_1^{(2M\nu_m + m^2)/q^2} d\omega'\, \nu W_2(\omega')$$

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.

DUALITY WORKS! ... even at low Q^2!

The resonances oscillate around a smooth curve.

Need: precision data $0 \lesssim Q^2 \lesssim 10\ (GeV/c)^2$



NEED UNDERSTANDING / QUANTIFICATION

- How can one construct a scaling structure function from resonances, if the resonances are described by form factors which fall like $(1/Q^2)^N$?

Contribution of (narrow) resonance R to structure function:

$$\nu W_2^{(R)} \approx 2M\nu \left(G_R(Q^2)\right)^2 \delta(W^2 - M_R^2)$$

If $G_R(Q^2) \sim (1/Q^2)^N$, then for $Q^2 \gg M_R$

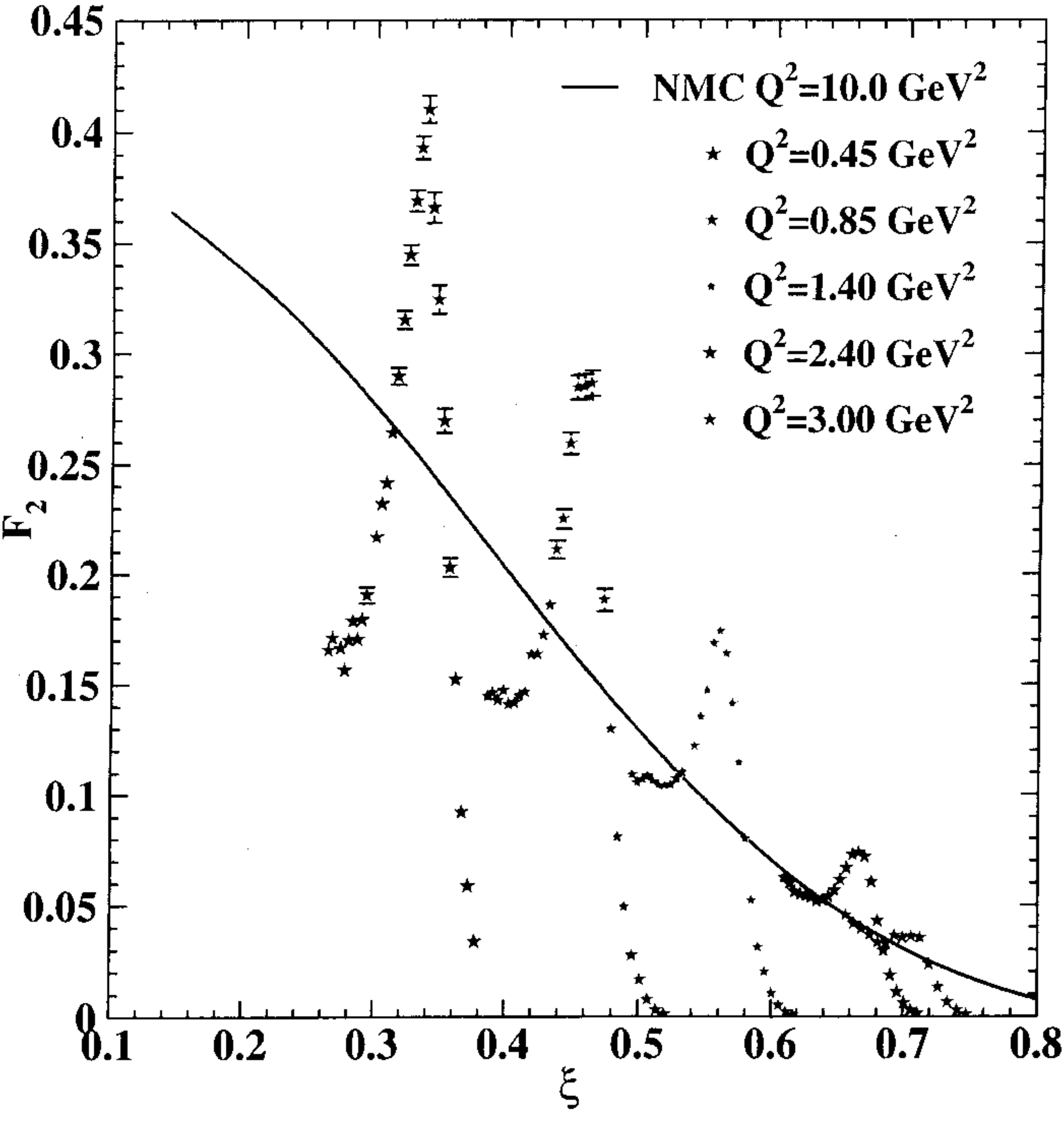
$$\nu W_2^{(R)} \sim (1 - x_R)^{2N-1}$$

with

$$x_R = \frac{Q^2}{M_R^2 - M^2 + Q^2}$$

"Resonance contributions to structure function slide along scaling curve to larger x with increasing Q^2 "

Δ Only



NMC Q^2=10.0 GeV^2
Q^2=0.45 GeV^2
Q^2=0.85 GeV^2
Q^2=1.40 GeV^2
Q^2=2.40 GeV^2
Q^2=3.00 GeV^2
F_2
ξ
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

Exclusive–Inclusive Connection

In perturbative QCD language:
power of Q^2 in form factor given by minimum number of gluon exchanges, or spectator quarks N:

$$G(Q^2) \sim (1/Q^2)^N \iff q(x) \sim (1-x)^{2N-1}$$

e.g. for proton $N = 2$

$$G(Q^2) \sim 1/Q^4, \qquad q(x) \sim (1-x)^3$$

<u>Works!</u>

Appears to fail for the pion?

Duality and Large x Structure Functions

- If local duality holds, can use resonance structure functions to constrain global fits of DIS parton distributions

  $\longrightarrow$ *Exclusive Processes Session*

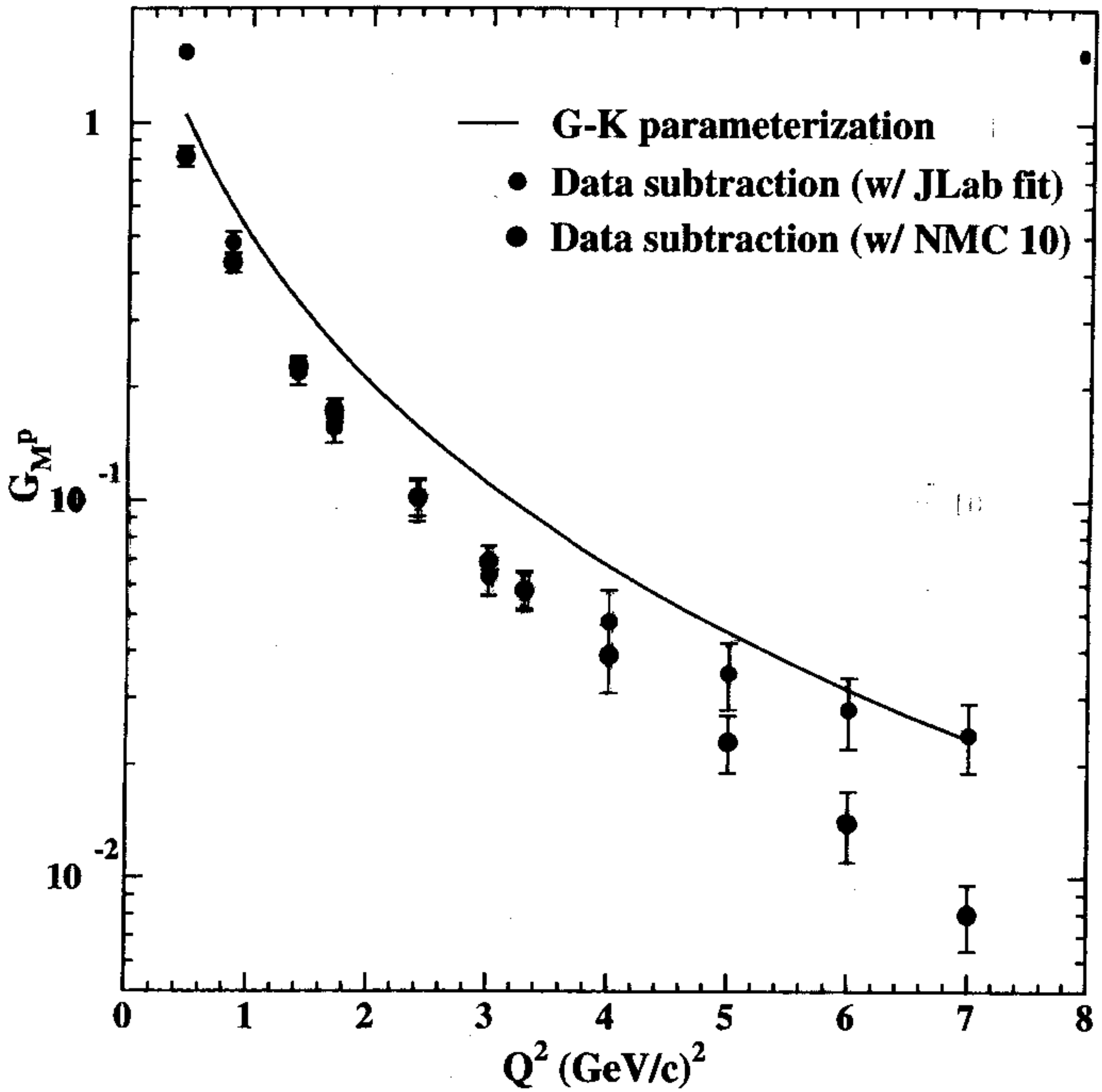
- Duality can be used to connect $x \to 1$ structure functions $\Longleftrightarrow$ elastic form factors

  $\longrightarrow$ *Valence Quark Session*

- Earlier onset of scaling in nuclei $\Rightarrow$ probe nuclear EMC effect at higher x

  $\longrightarrow$ *Hadrons in Medium Session*

Proton Magnetic Form Factor



$$(G_M^p)^2 = \frac{1 + \frac{4M^2}{\nu^2 Q^2}}{1 + \frac{4M^2}{Q^2}} \frac{2-\xi_p}{\xi_p^2} \int_{\xi_\pi}^{1} F_2 \, d\xi$$

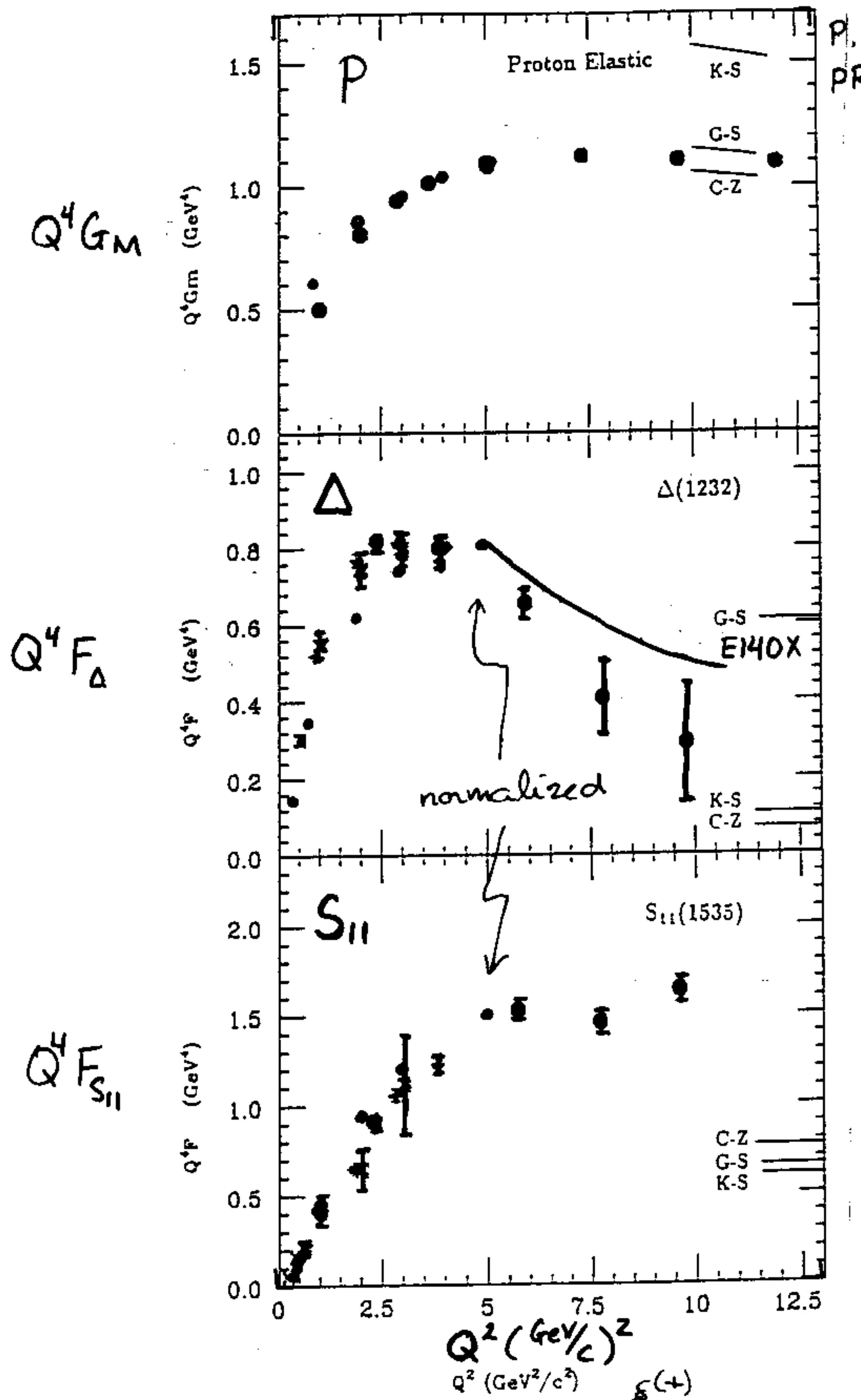
I. NICULESCU

T. Keppel, R. Ent et al.

from model:

RESONANCE FORM FACTOR EXTRACTION

P. Stoler
PRL 66, 1003 (1991)



$$Q^4 F \sim Q^4 \sqrt{F_2 / Q_2} \qquad F_2 = \int_{\xi(-)}^{\xi(+)} F_2(\xi)\, d\xi$$

Duality in Nuclei at 12 GeV

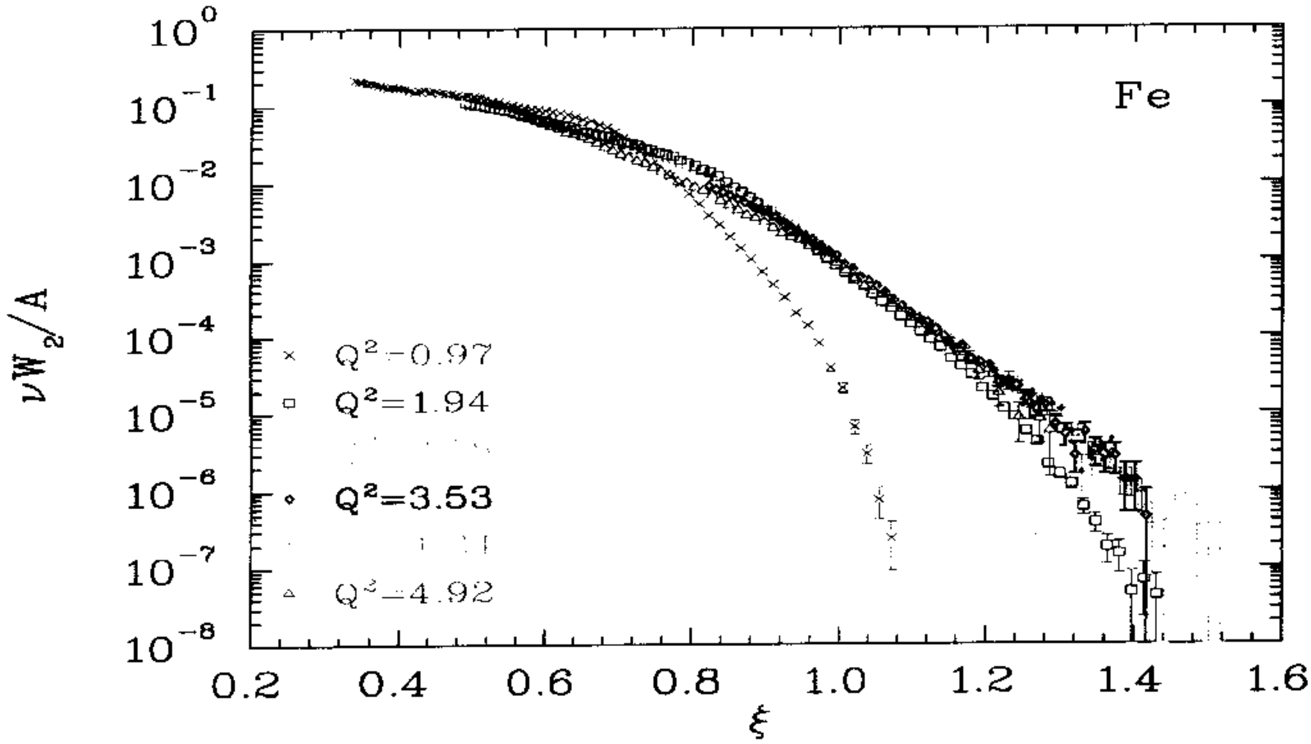
In the proton, the averaged structure function yields the DIS limit.

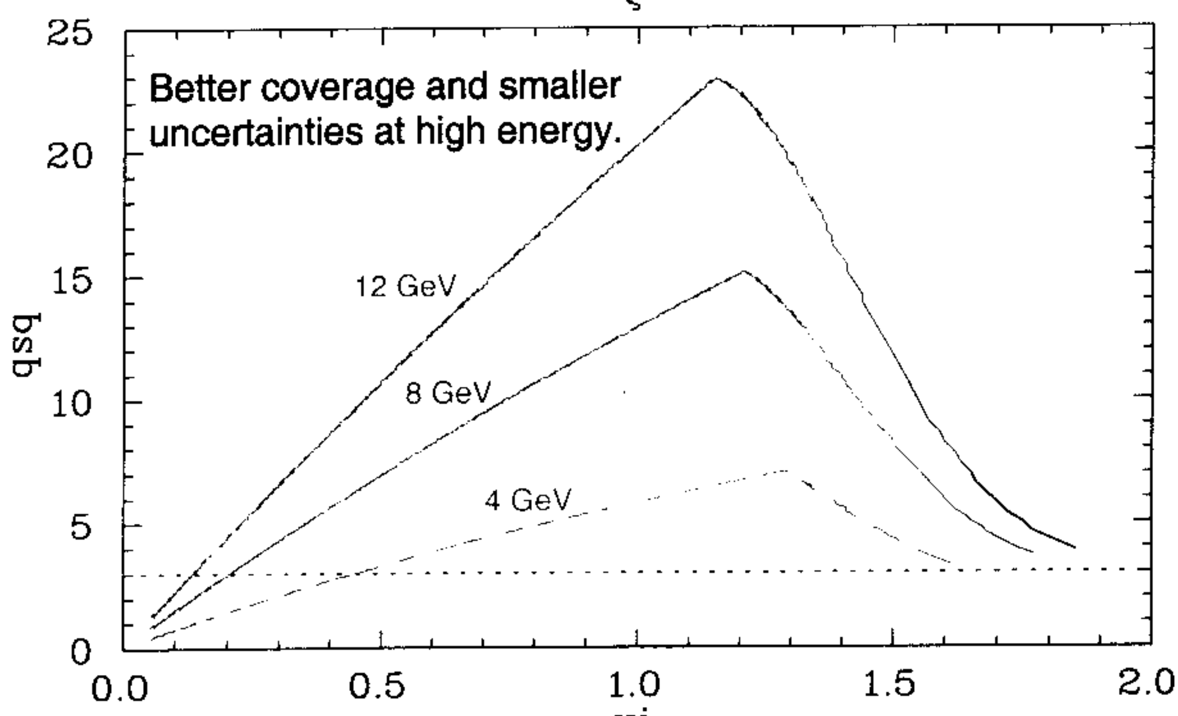
Fermi motion causes an averaging of the structure function, giving ξ–scaling in the resonance (and quasielastic) region.

From the scaling curve, we can extract nuclear structure functions:

EMC effect in new x region.

F_2^n / F_2^p at very high x.





T. ARRINGTON

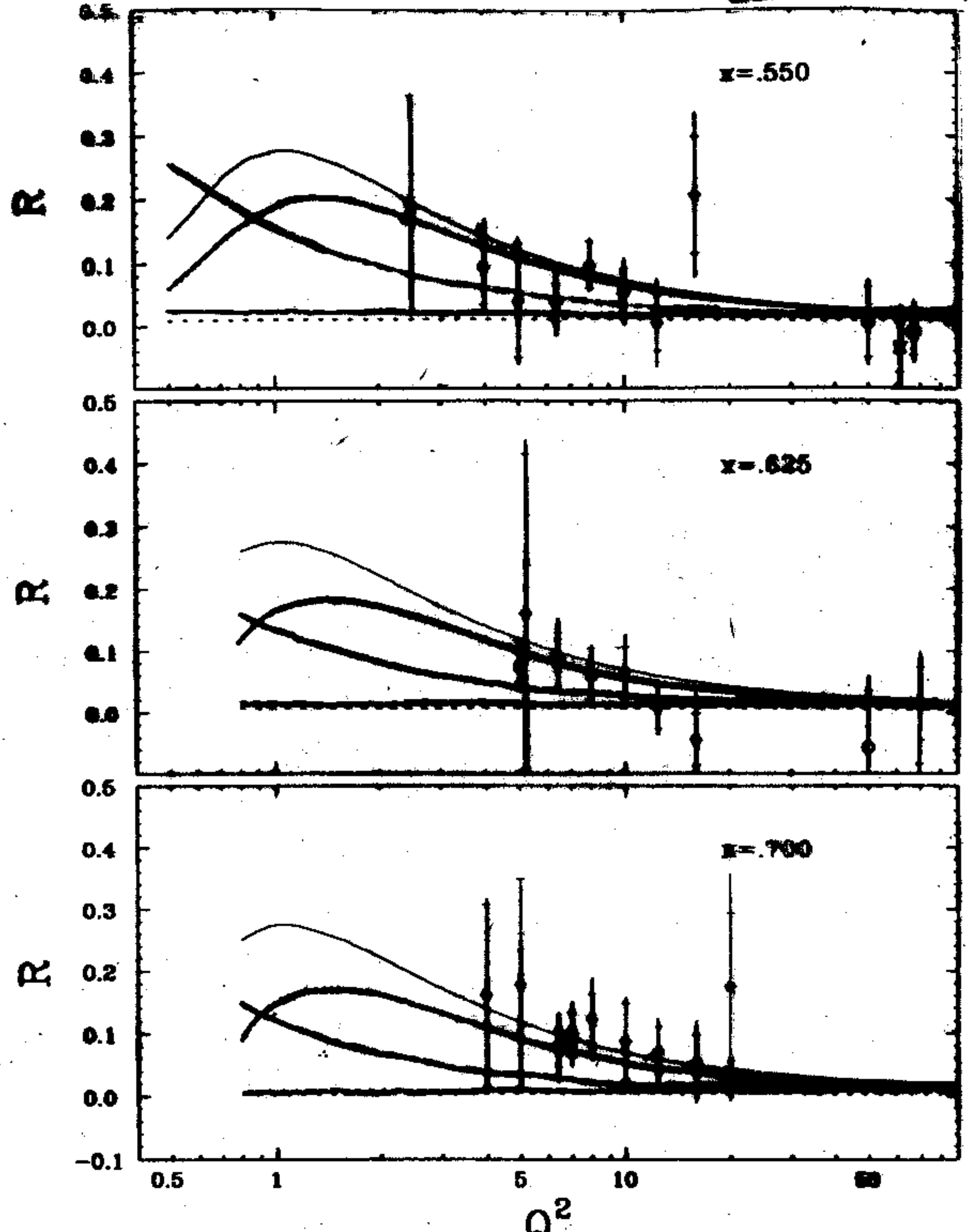
Longitudinal Structure Function

$$R(x, Q^2) = \frac{\sigma_L(x, Q^2)}{\sigma_T(x, Q^2)}$$

Main source of uncertainty in F_2 extraction
— in resonance region and beyond

Expect stronger violation of duality c.f. F_2?

$\mathcal{R} = \sigma_L / \sigma_T$ $\qquad \frac{d^2\sigma}{d\Omega dE'} = \Gamma \sigma_T (1 + \epsilon R)$



— GLOBAL FIT (Whitlow)

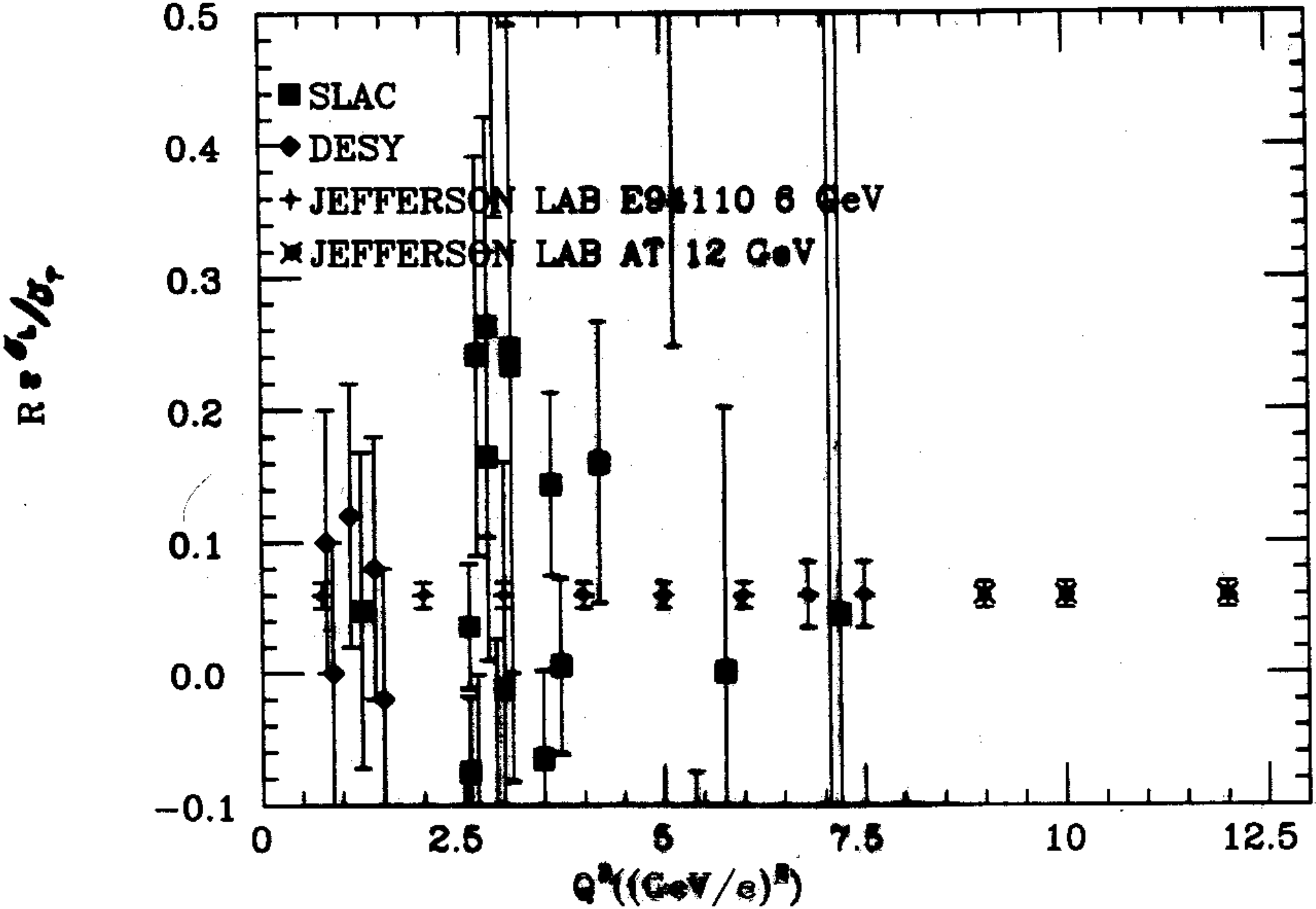
— R^{QCD} (NL+NNL) + TM + HT (W.L. van Neerven)

— R^{QCD} (NL+NNL) + TM

— R^{QCD} (NL + NNL)

L.H. Tao et al. E140X, Z. Phys. C70 (1996) 387

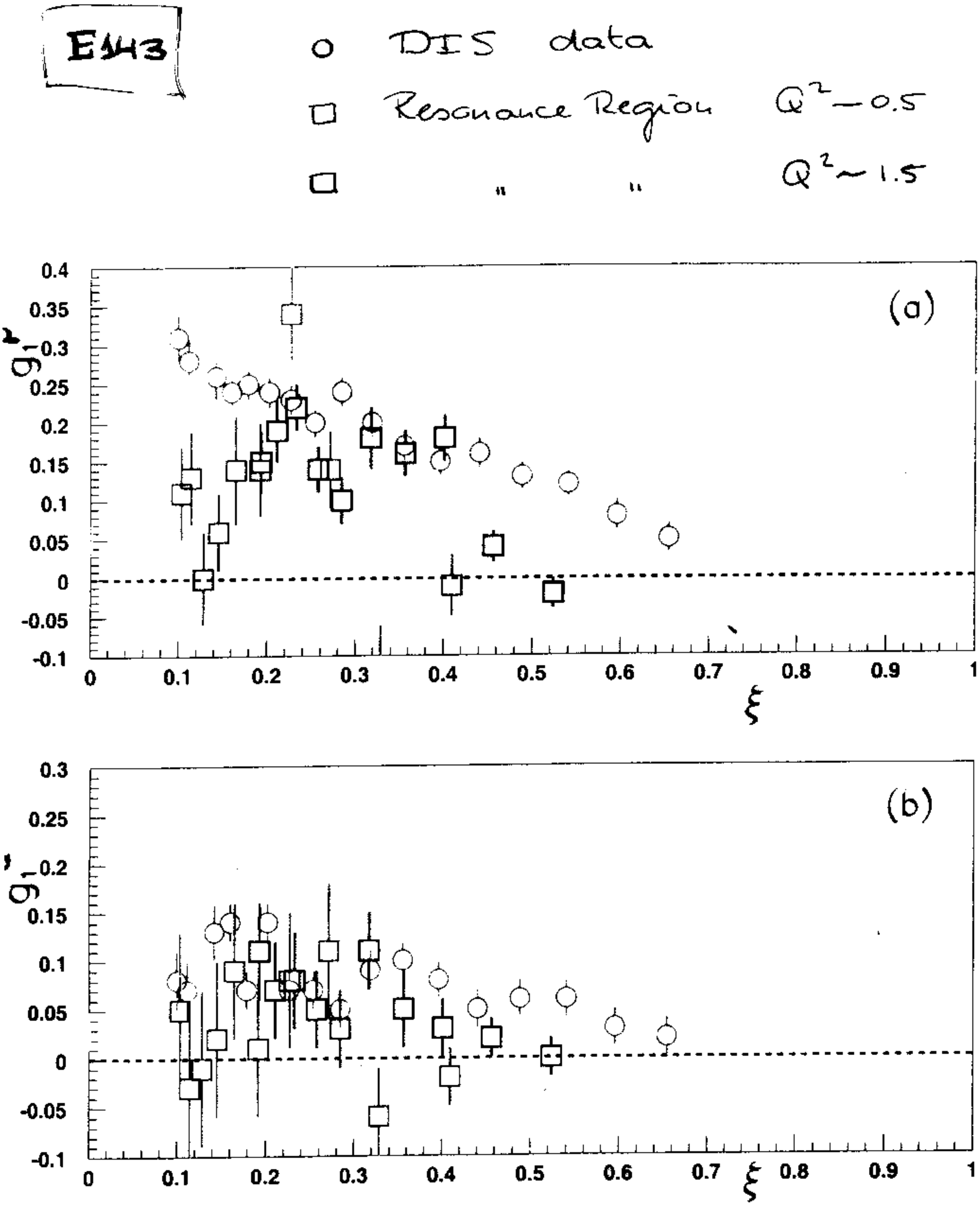
$\mathcal{R}_\Delta = \sigma_L / \sigma_T$



~ SAME FOR OTHER RESONANCES, DIS

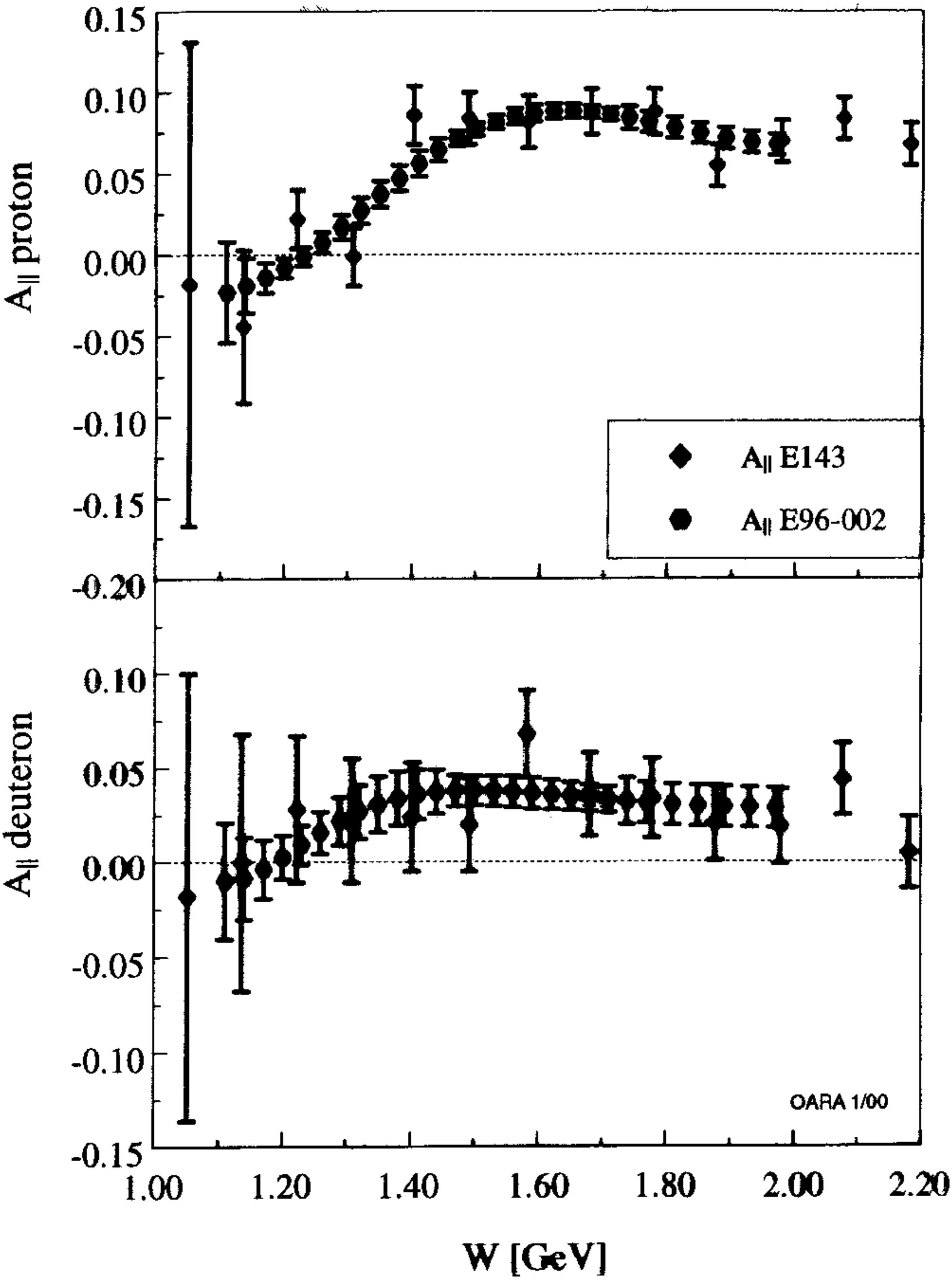
Spin Dependence

- To what extent is duality spin-dependent?
- Are higher twist corrections larger for g_1 than for F_2?
- How does $g_1(x, Q^2)$ at low Q^2 approach the scaling curve?
- Complete absence of data in resonance region at high x!
- Extend A_1 into resonance region for $x > 0.8$
- Is g_1 as valence-like as F_2?



E143
DIS data
Resonance Region $Q^2 - 0.5$
" " $Q^2 \sim 1.5$
(a)
g_1^p
ξ
(b)
g_1
ξ

Y. KONDON



0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
$A_{\parallel}$ proton
$A_{\parallel}$ E143
$A_{\parallel}$ E96-002
0.10
0.05
0.00
-0.05
-0.10
-0.15
$A_{\parallel}$ deuteron
OARA 1/00
1.00
1.20
1.40
1.60
1.80
2.00
2.20
W [GeV]

[redacted]

- There is a large effort to measurer spin structure functions at high x in the DIS region.
- This would allow testing predictions from many theoretical models.
- However, kinematic constraints make is very difficult to measure structure functions at high x in the DIS region.
- **If the duality is established between resonance and DIS regions, the measurements in the Resonance region can be used to study the high x behavior.**
- In the resonance region it is relatively easy to access the high x region.
  - Not kinematically restricted
  - Q^2 corresponding to a certain value of x is much lower in the Resonance region than in the DIS region $\rightarrow$ Higher cross sections.
- **6 GeV - 12 GeV beam at Jefferson Lab would provide perfect conditions to access high x spin structure function in the Resonance region.**

Rough Time estimates

All time estimates are for Hall A ^{3}He target assuming 15μA beam current 80% beam polarization, 40% target polarization, and a 10 msr solid angle.

[redacted]

Θ_e	E'	Q^2	ΔA1	T‖	T⊥	T_{tot}
12.5°	4.558	1.802	0.015	8.7	7.1	15.8
	4.208	1.663	0.015	3.6	2.5	6.1
	3.884	1.535	0.015	2.2	1.3	3.5
	3.585	1.417	0.015	2.0	1.0	2.9
	3.310	1.308	0.015	1.9	0.8	2.6
	3.055	1.208	0.015	1.7	0.6	2.3
16.5°	4.014	2.808	0.015	51.1	35.8	86.9
	3.706	2.592	0.015	12.5	7.7	20.2
	3.421	2.393	0.015	8.2	4.5	12.7
	3.157	2.209	0.015	6.9	3.4	10.3
	2.914	2.039	0.015	6.7	2.9	9.6
	2.690	1.882	0.015	5.6	2.2	7.7
21.0°	3.002	4.666	0.020	151.4	83.6	235.0
	2.772	4.307	0.020	30.7	15.8	46.5
	2.558	3.976	0.020	17.6	8.4	26.0
	2.362	3.670	0.020	13.6	6.0	19.6
	2.180	3.388	0.020	11.2	4.6	15.8
	2.012	3.127	0.020	10.5	4.0	14.6

total time is about 640 h

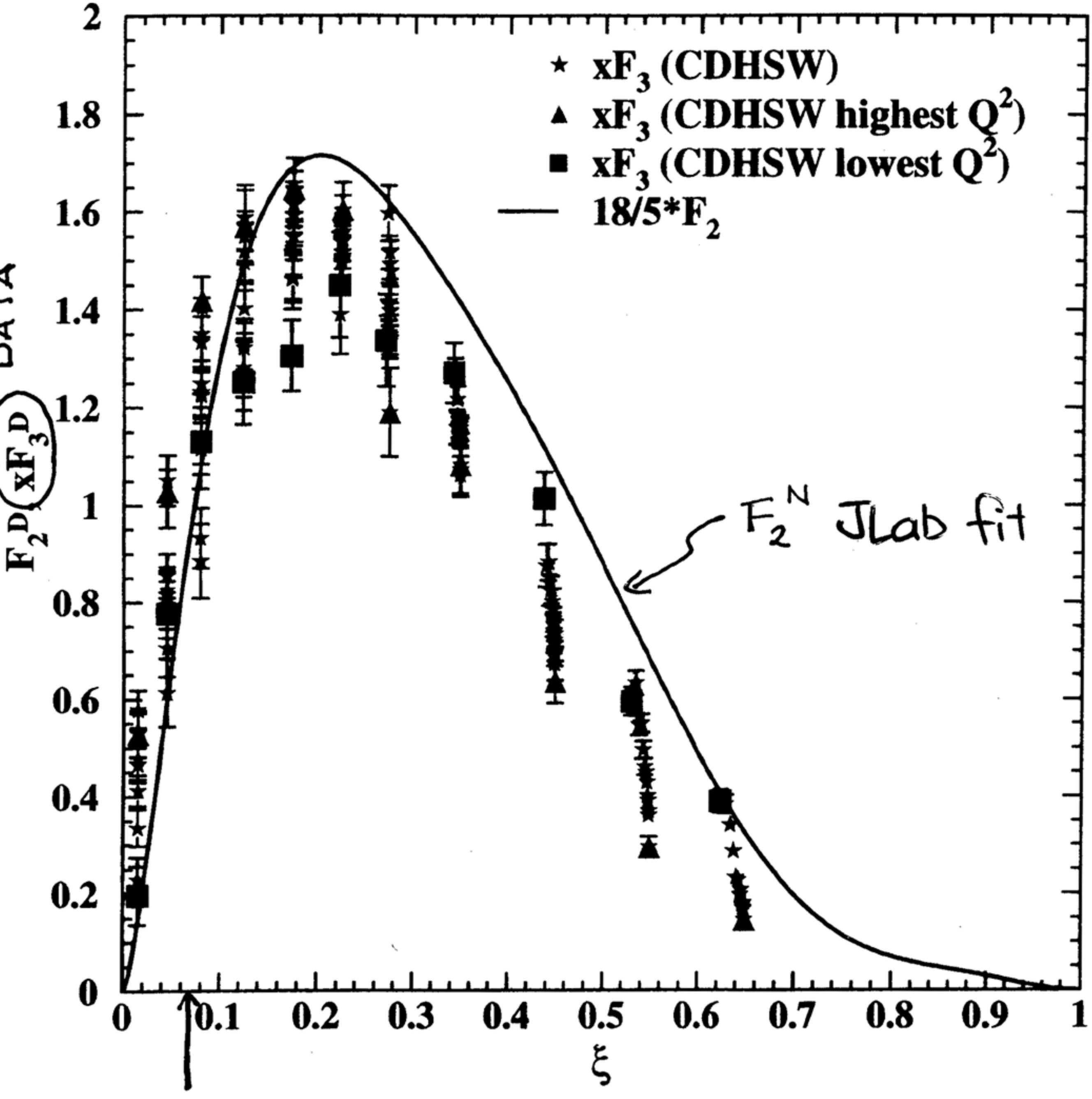
Rough Time estimates

All time estimates are for Hall A ^{3}He target assuming 15μA beam current 80% beam polarization, 40% target polarization, and a 7 msr solid angle.

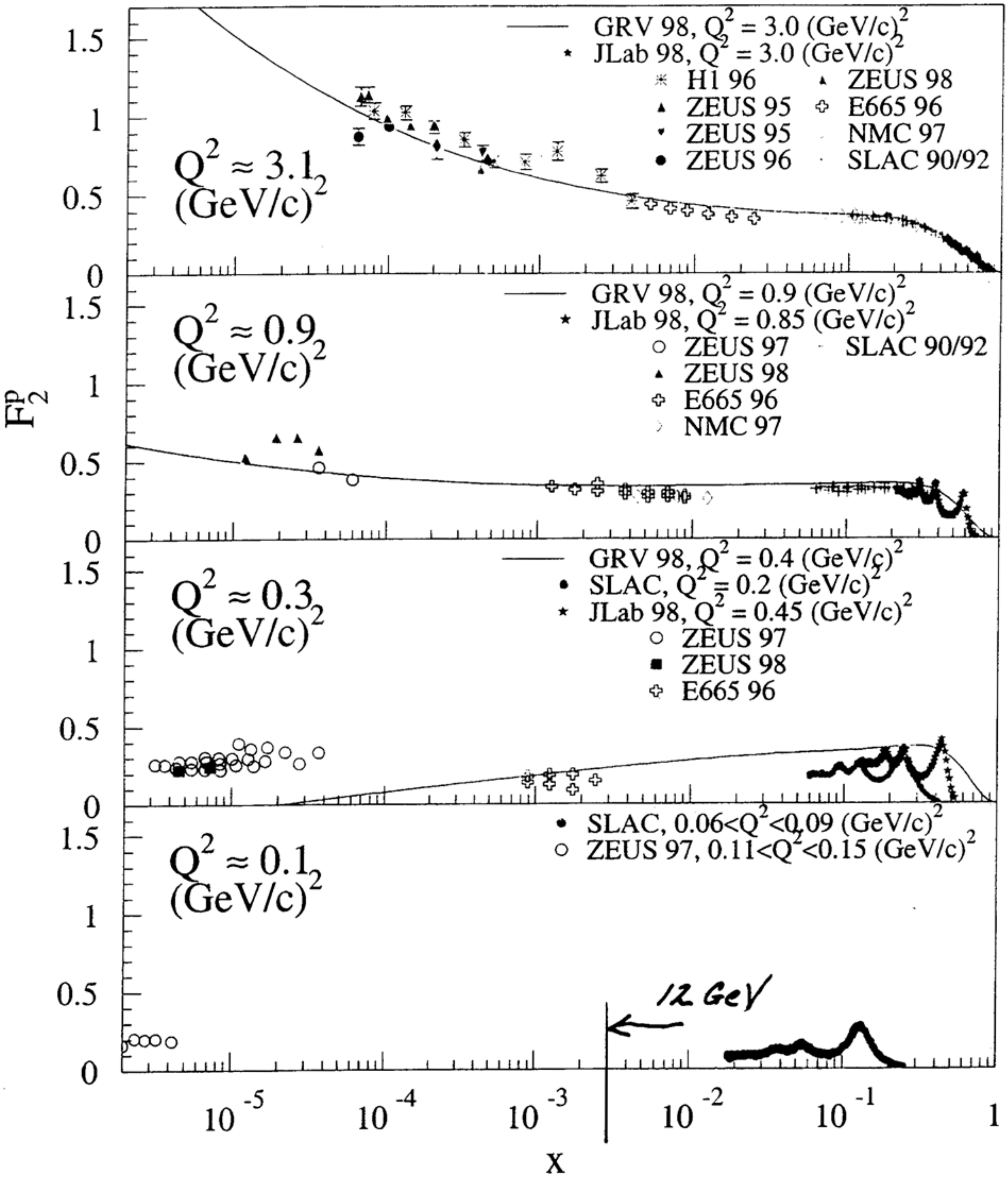
[redacted]

Θ_e	E'	Q^2	ΔA1	T‖	T⊥	T_{tot}
12.5°	8.229	4.291	0.020	7.2	4.7	11.9
	7.596	3.961	0.020	2.9	1.6	4.5
	7.011	3.656	0.020	1.7	0.7	2.4
	6.472	3.375	0.020	1.4	0.5	1.9
	5.974	3.115	0.019	1.5	0.5	2.0
	5.515	2.876	0.017	1.7	0.5	2.2
15.5°	7.510	5.630	0.035	15.7	9.3	25.0
	6.932	5.196	0.026	6.6	3.4	10.0
	6.399	4.797	0.022	5.6	2.4	8.0
	5.906	4.428	0.020	5.8	2.2	8.0
	5.452	4.087	0.019	6.0	2.0	8.0
	5.033	3.773	0.017	6.1	1.9	8.0
18.0°	6.673	7.185	0.038	97.7	52.3	150.0
	6.159	6.632	0.023	51.0	24.0	75.0
	5.685	6.122	0.020	35.2	14.8	50.0
	5.248	5.651	0.019	29.0	11.0	40.0
	4.844	5.216	0.019	22.4	7.6	30.0
	4.472	4.815	0.026	11.4	3.6	15.0

total time is about 550.0 h



xF3 (CDHSW)
xF3 (CDHSW highest Q2)
xF3 (CDHSW lowest Q2)
18/5*F2
F2D (xF3D) DATA
ξ
F2N JLab fit
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.2
1.4
1.6
1.8
2



GRV 98, Q^2 = 3.0 (GeV/c)^2
JLab 98, Q^2 = 3.0 (GeV/c)^2
H1 96
ZEUS 98
ZEUS 95
E665 96
ZEUS 95
NMC 97
ZEUS 96
SLAC 90/92
$Q^2 \approx 3.1$ (GeV/c)^2
GRV 98, Q^2 = 0.9 (GeV/c)^2
JLab 98, Q^2 = 0.85 (GeV/c)^2
ZEUS 97
SLAC 90/92
ZEUS 98
E665 96
NMC 97
$Q^2 \approx 0.9$ (GeV/c)^2
GRV 98, Q^2 = 0.4 (GeV/c)^2
SLAC, Q^2 = 0.2 (GeV/c)^2
JLab 98, Q^2 = 0.45 (GeV/c)^2
ZEUS 97
ZEUS 98
E665 96
$Q^2 \approx 0.3$ (GeV/c)^2
SLAC, 0.06<Q^2<0.09 (GeV/c)^2
ZEUS 97, 0.11<Q^2<0.15 (GeV/c)^2
$Q^2 \approx 0.1$ (GeV/c)^2
12 GeV
F_2^p
x

How Local is Duality?

"Global Duality"

$$\frac{d\sigma}{dQ^2} \sim \int dx \; F(x,Q^2) \sim M_2(Q^2)$$

$$\Downarrow$$

"Local Duality"

$$\frac{d^2\sigma}{dQ^2 dx} \sim F(x,Q^2)$$

$$\Downarrow$$

"Fragmentation Duality"

$$\frac{d^3\sigma}{dQ^2 dx dz} \sim F(x,Q^2) \; D(z,Q^2)$$

Duality in Semi-inclusive Scattering

- Flavor dependence
  $\Rightarrow u$, d separation

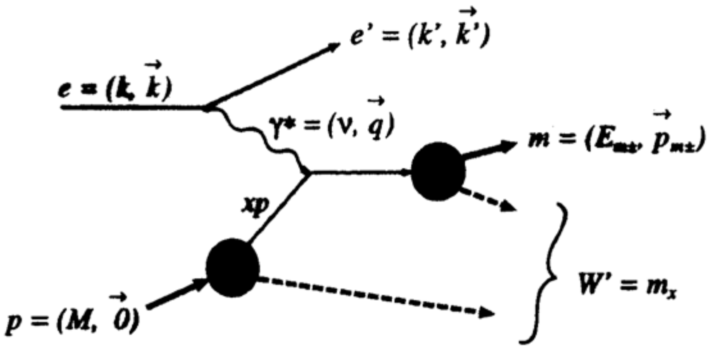
- Factorization
  $\Rightarrow$ Semi-inclusive cross section

$$\frac{d^3\sigma}{dQ^2 dx dz} \sim \sum_q e_q^2 \; xq(x,Q^2) \; D_q(z,Q^2)$$

  $\Rightarrow$ Can we expect it to work at JLab ν?
  $\longrightarrow$ test it!

- Duality for fragmentation function?
  $\Rightarrow$ Confirmation of factorization and duality would open the way to an enormously rich semi-inclusive program, allowing unprecedented quark spin and flavor decomposition (c.f. HERMES)

Duality in Meson Electroproduction

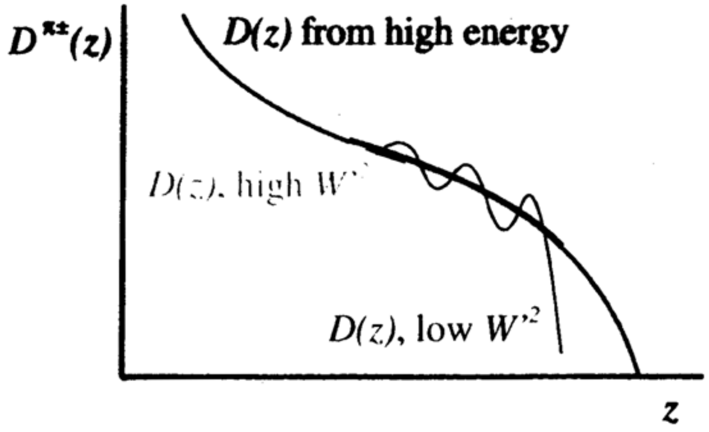


$$W^2 = m_p^2 + Q^2\left(\frac{1}{x} - 1\right)$$

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

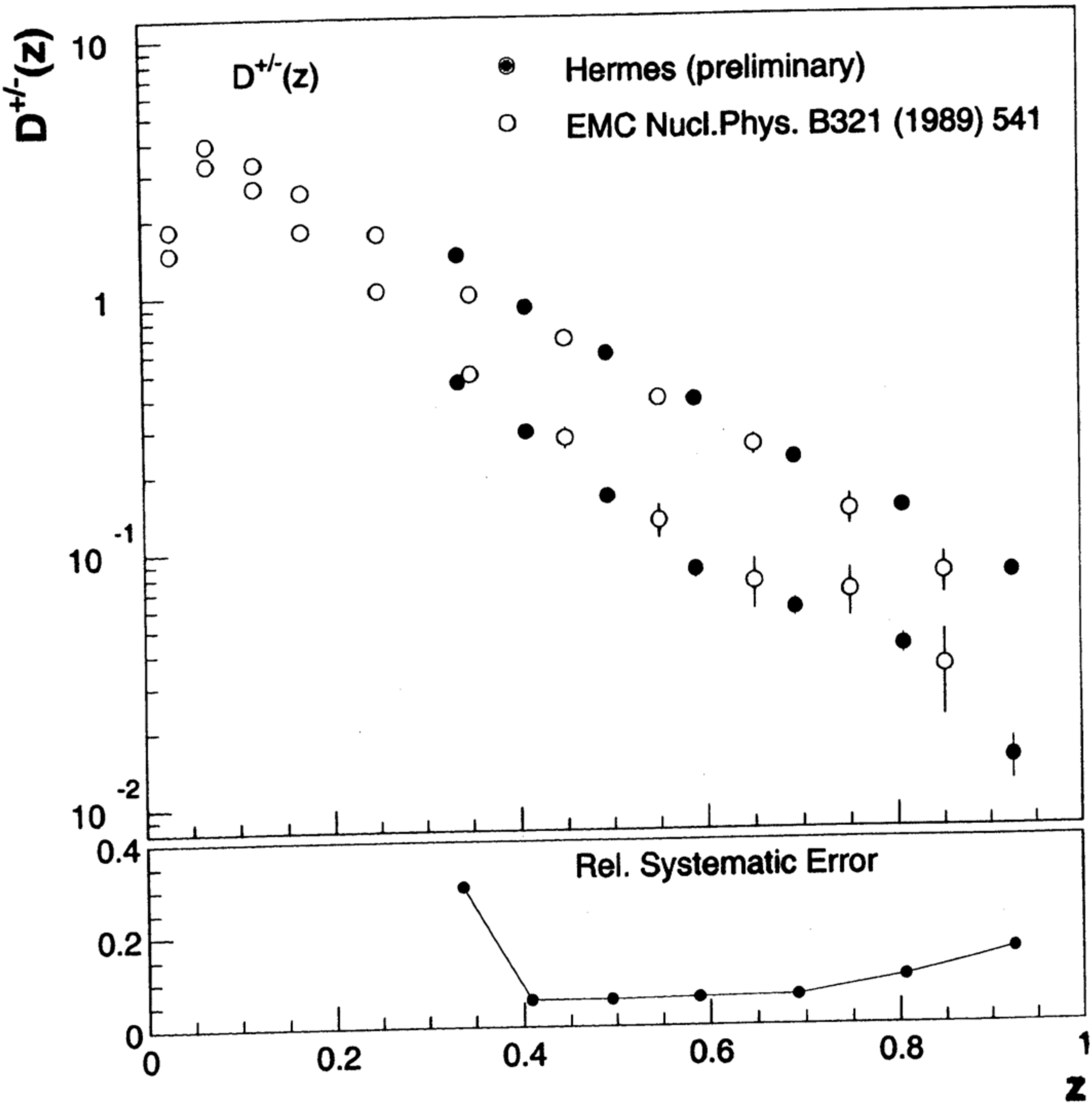
Factorization: $\sigma \propto f(z, Q^2)\, g(x, Q^2)$

$$N^{\pi^\pm}(x, z) \propto \sum_i e_i^2 \left[q_i(x)\, D_{q_i}^{\pi^\pm}(z) + \bar{q}_i(x)\, D_{\bar{q}_i}^{\pi^\pm}(z) \right]$$



C. ARMSTRONG

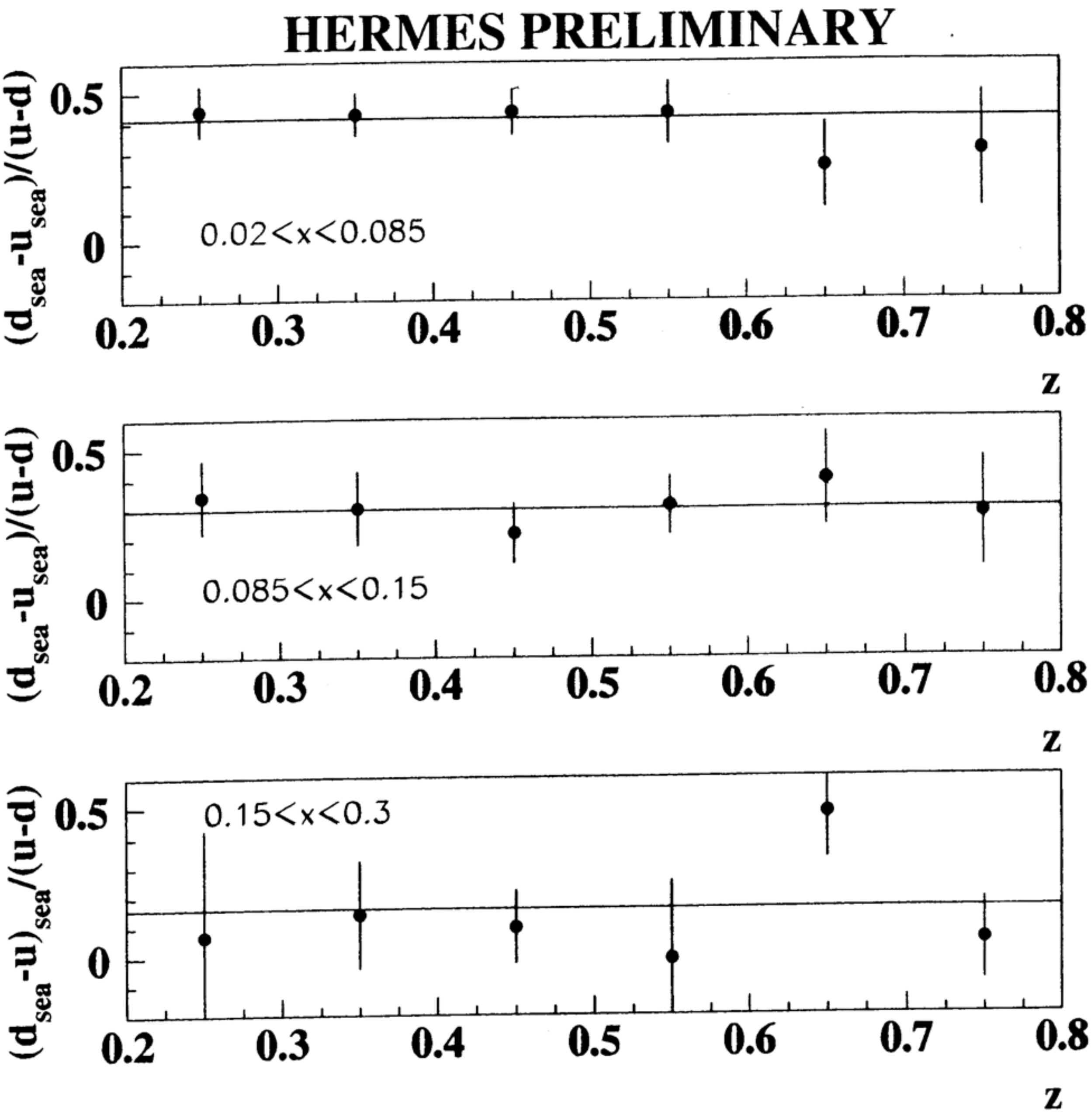
Pion Fragmentation Functions



A. BRÜLL

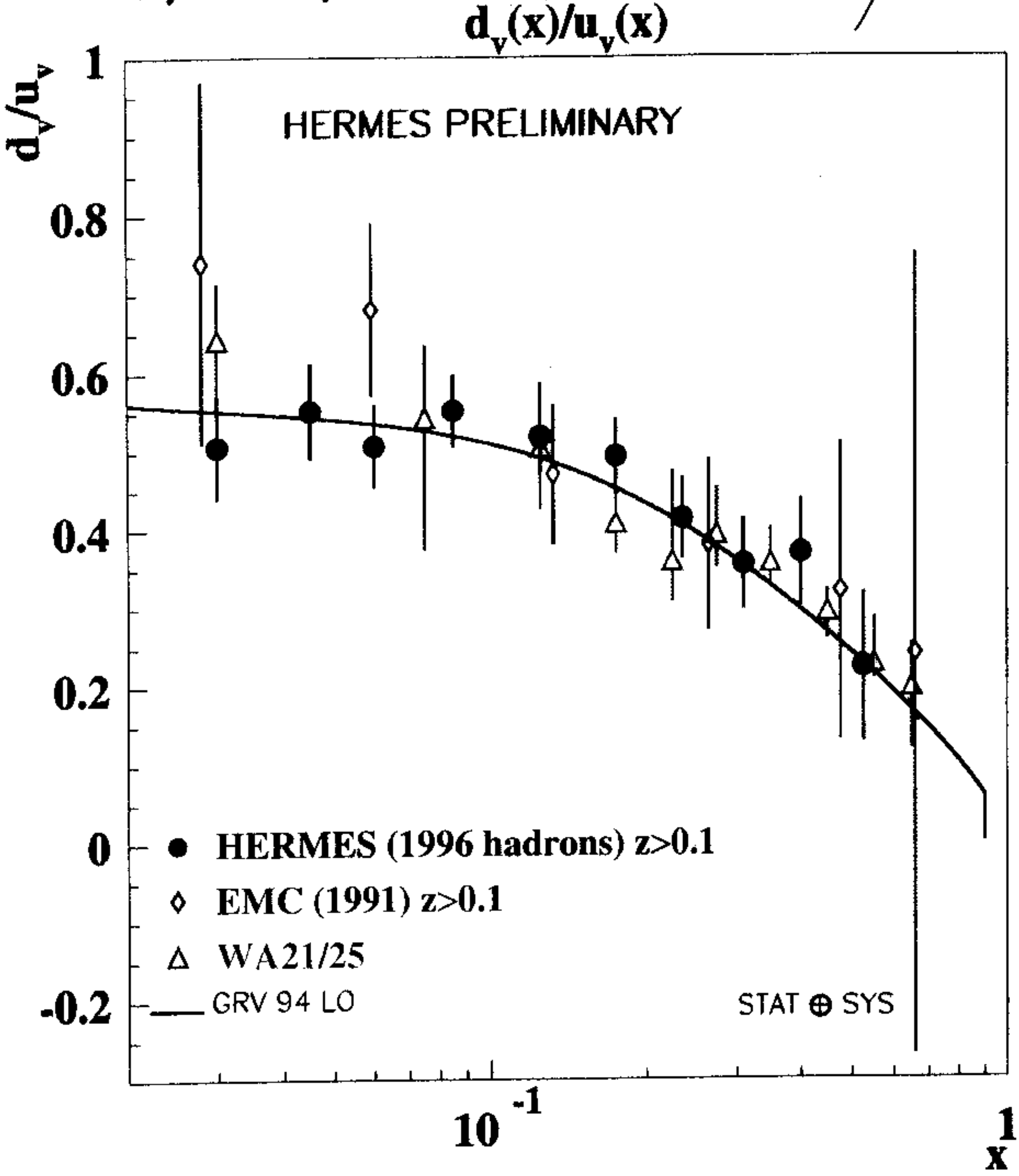
Flavour Asymmetry of the Light Quark Sea

Separate x and z dependence!

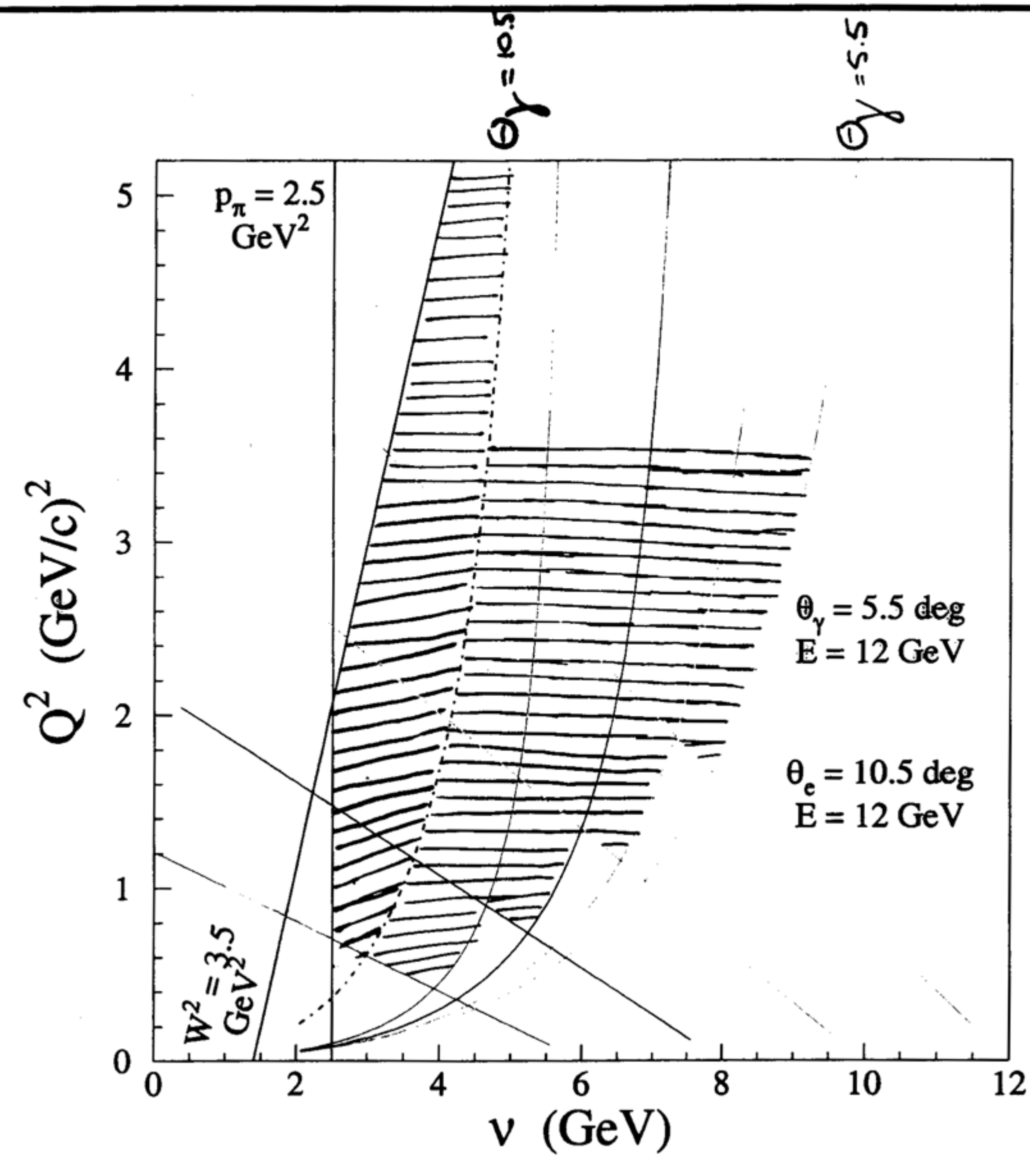


Valence Quark Distributions

$$\frac{d_v}{u_v} \propto \left(\frac{4 N_d^{h^+} - N_d^{h^-}}{N_p^{h^+} - N_p^{h^-}} \right)$$



Expanded Kinematics at High Energies

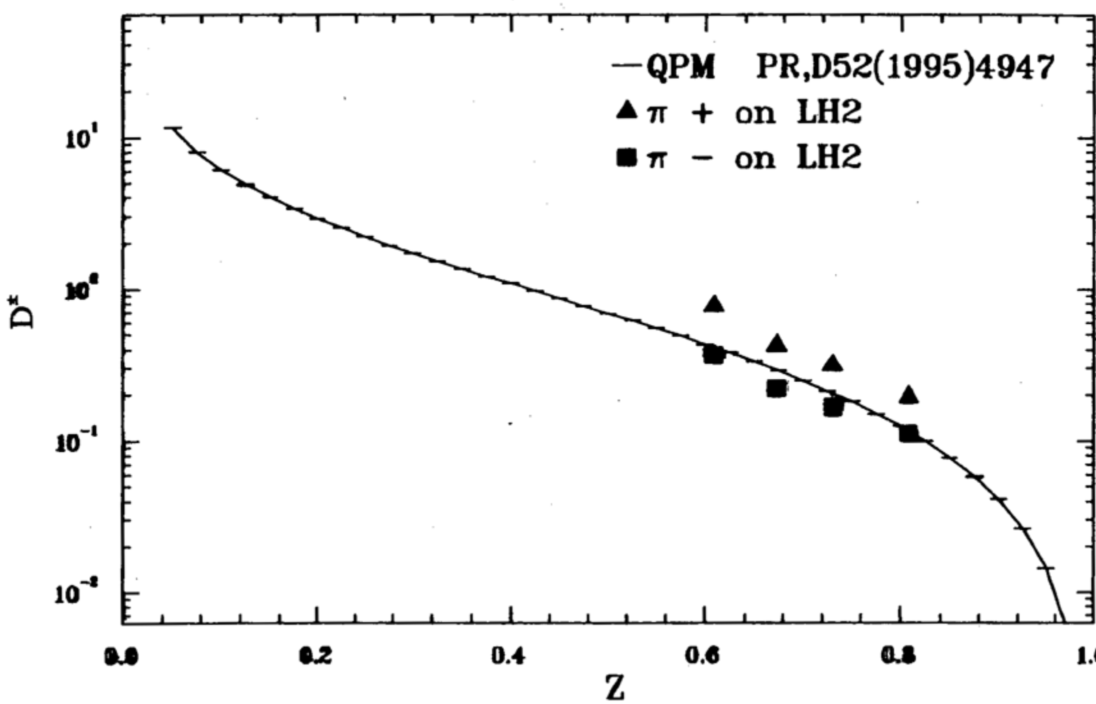


Since $z = \frac{E_m}{\nu}$, and factorization is expected to improve with ν, we really want access to large energy losses!

JLab Test Runs: Factorization at Low Energies?

PRELIMINARY !

$\pi^{\pm}$ Fragmentation Functions

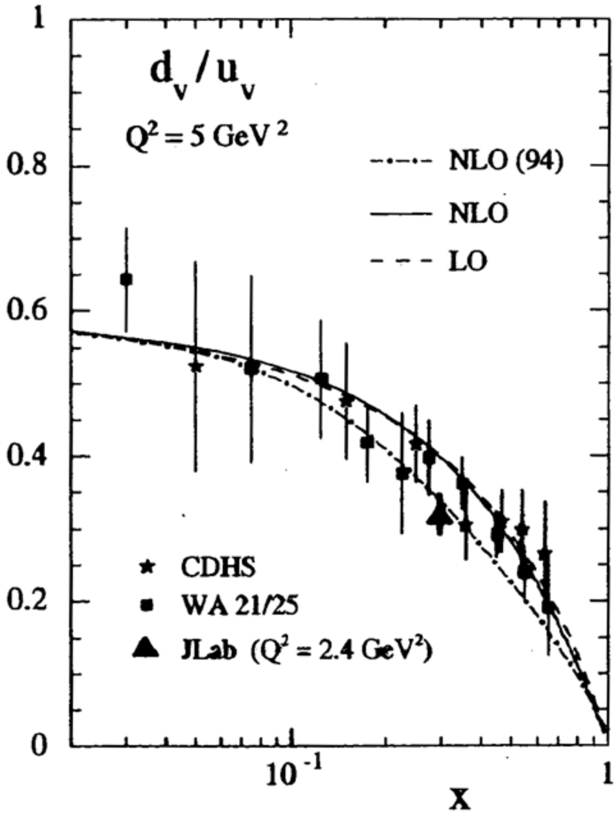


Fragmentation functions extracted from recent test runs agree reasonably well with a NLO fragmentation function[3] fit to high-energy e^+e^- scattering (evaluated at our Q^2).

[3]J. Binnewies *et al.*, Phys. Rev. D 52, 4947 (1995)

JLab Test Runs: Factorization at Low Energies?

PRELIMINARY !



Assumption of factorization allows extraction of d_v/u_v from the test runs. Result is in agreement with high energy data.[4]

[4] M. Gluck *et al.*, e-print hep-ph/9806404 (1998)

Experiments at 12 GeV

- Inclusive structure functions

  Planned Hall C SHMS (HMS) optimized for inclusive studies over wide range of Q^2 ($0 < Q^2 < 15$ GeV^2) up to large x

  $\Rightarrow$ map out complete ξ range

  $\Rightarrow F_2$: $0 < Q^2 < 20$ GeV^2 $\longrightarrow x \leq 0.95$
  F_L: $0 < Q^2 < 12$ GeV^2 $\longrightarrow x \leq 0.9$

  Spin-dependent structure functions better in CLAS?
  $\Rightarrow g_1, g_2$: $0 < Q^2 < 10$ GeV^2 $\longrightarrow x \leq 0.85$

- Semi-inclusive scattering

  $\Rightarrow$ Flavor dependence of duality
  $\Rightarrow$ Factorization at low ν? $\Rightarrow$ test it!

"Killer Application"

If duality can be understood
well enough to be used as a tool

$\Downarrow$

access more extreme kinemaic regions,
previously believed unaccessible
to quark descriptions,
via resonances + duality

Road to June 2000

- Workshop at MIT, October 1999

- Series of 'local' duality meetings (expt + theory), Nov. 1999 – April 2000

- Mini-workshop, April 2000

- Contacts: Thia Keppel, Rolf Ent