Summary talk

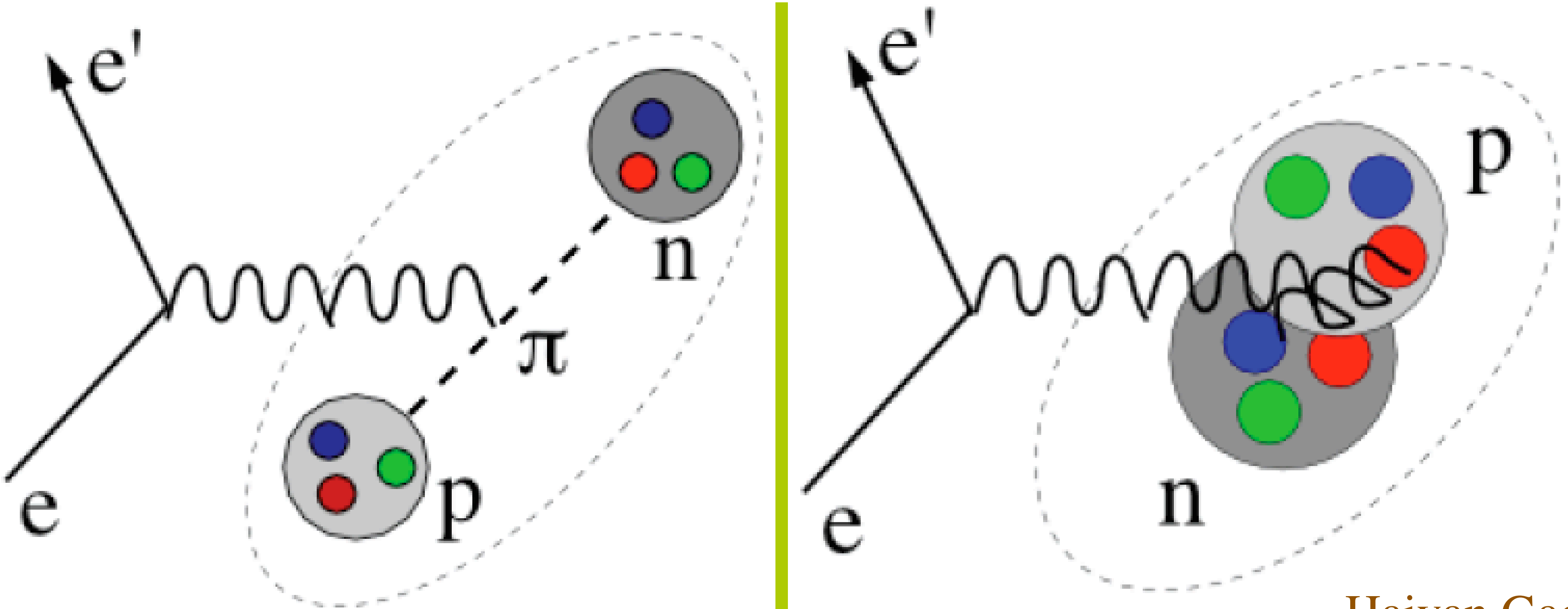
Paul Hoyer
University of Helsinki

First Workshop on Quark-Hadron Duality and the Transition to pQCD

Laboratori Nazionali di Frascati
June 6-8 2005

Amor Sacro e Amor Profano

Quark and Hadron Dynamics in QCD



Haiyan Gao

Click on picture for QCD explanation

(Keynote version only)

Art or Science?

Henk Blok:

Duality: Belief or hold?

p vs. n, L vs. T, $\sigma_{3/2}$ vs. $\sigma_{1/2}$,

semi-incl., excl.?

global, local?

resonance vs. background

Perilous
to leave out
Born term and Δ from
comparisons with inclusive data!

Rolf Ent:

If one integrates over all resonant and non-resonant states, quark-hadron duality should be shown by any model. This is simply unitarity.
However, quark-hadron duality works also, for $Q^2 > 0.5$ (1.0) GeV^2, to better than 10 (5) % for the F_2 structure function in both the N-Δ and N-S_{11} region!
(Obviously, duality does not hold on top of a peak! -- One needs an appropriate energy range)

Why does local quark-hadron duality work so well, at such low energies?
~ quark-hadron transition

Confinement is local ....

Many acknowledgements to:

JLAB-THY-04-266

Quark-Hadron Duality in Electron Scattering

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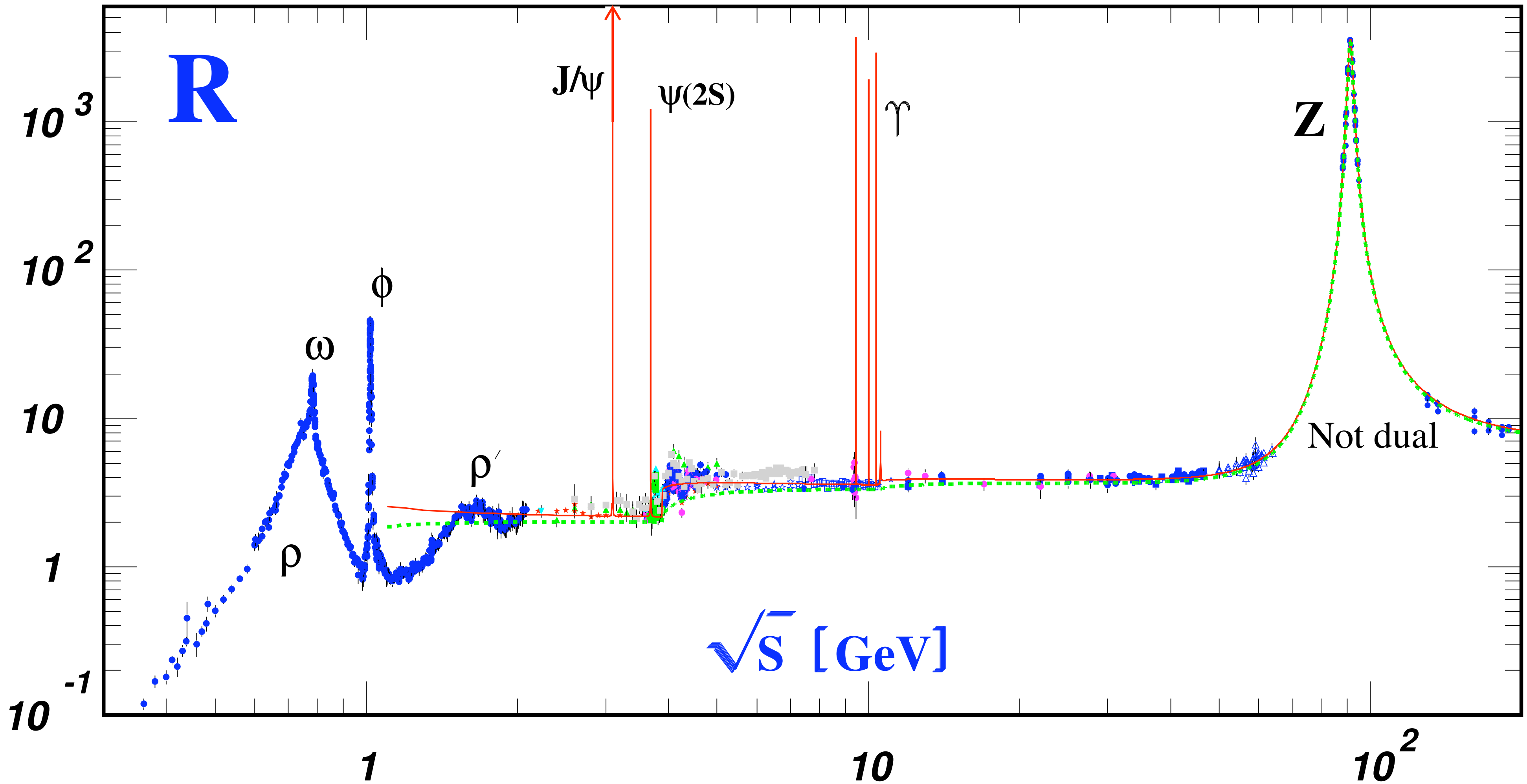
Abstract

The duality between partonic and hadronic descriptions of physical phenomena is one of the most remarkable features of strong interaction physics. A classic example of this is in electron-nucleon scattering, in which low-energy cross sections, when averaged over appropriate energy intervals, are found to exhibit the scaling behavior expected from perturbative QCD. We present a comprehensive review of data on structure functions in the resonance region, from which the global and local aspects of duality are quantified, including its flavor, spin and nuclear medium dependence. To interpret the experimental findings, we discuss various theoretical approaches which have been developed to understand the microscopic origins of quark-hadron duality in QCD. Examples from other reactions are used to place duality in a broader context, and future experimental and theoretical challenges are identified.

200 pages
400 references

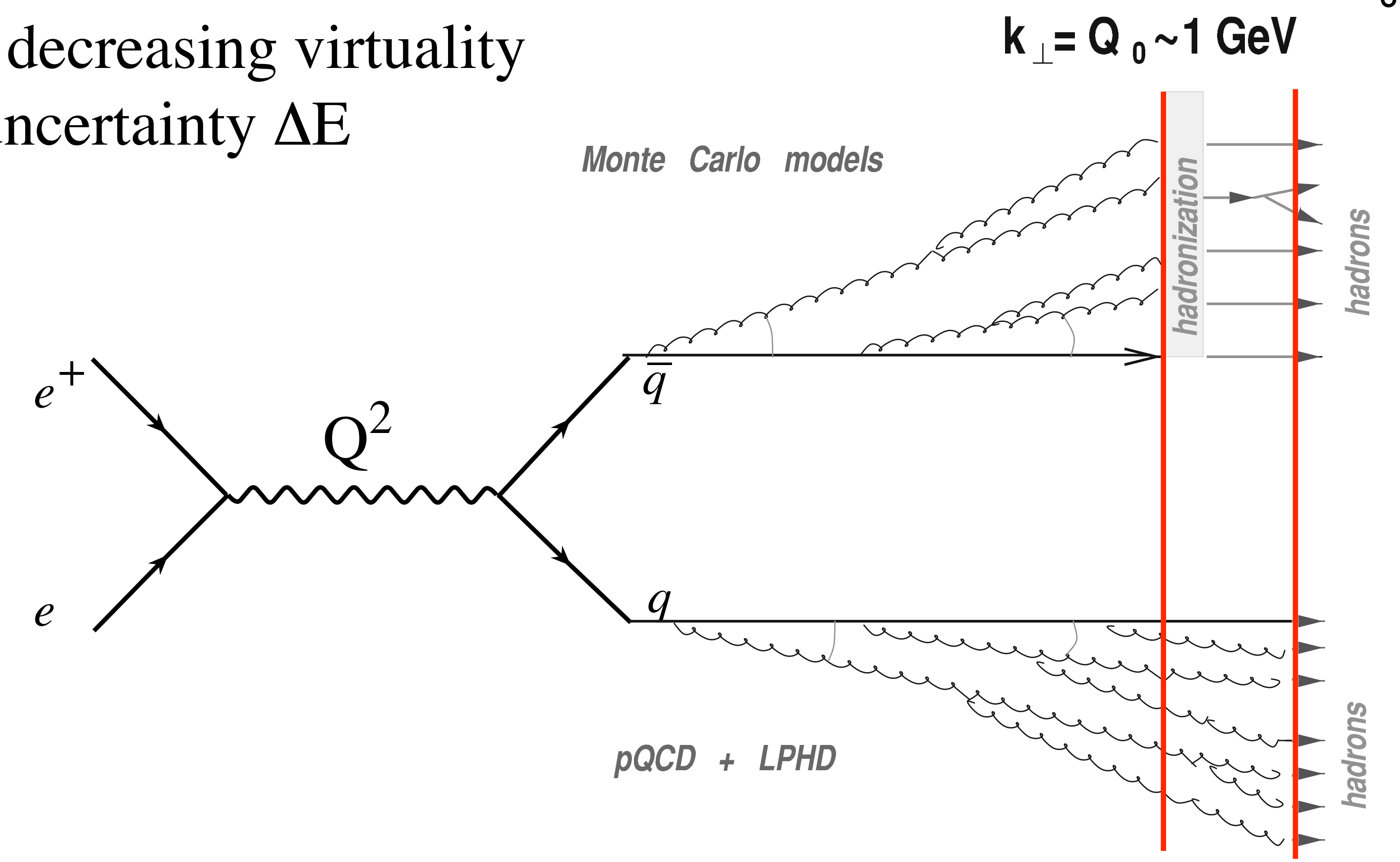
Duality in $e^+e^- \to$ hadrons



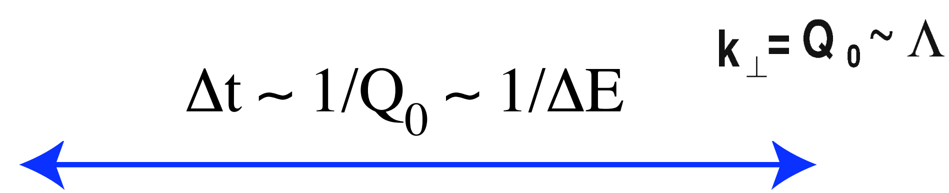
Resonances build the parton subprocess cross section because of a separation of scales between hard and soft processes.

QCD Sum Rules,... SVZ

Final state evolves with decreasing virtuality and decreasing energy uncertainty ΔE



Evolution beyond virtuality $Q_0^{\,2} \sim 2E\Delta E$ involves $k_\perp \sim Q_0$ and is unitary:



Measured cross section in energy uncertainty interval $E_{CM} \pm \Delta E$ must average to pQCD cross section at resolution $Q_0^{\,2}$.

The softer is confinement physics, the smaller Q_0 can be chosen, and the more local is duality.

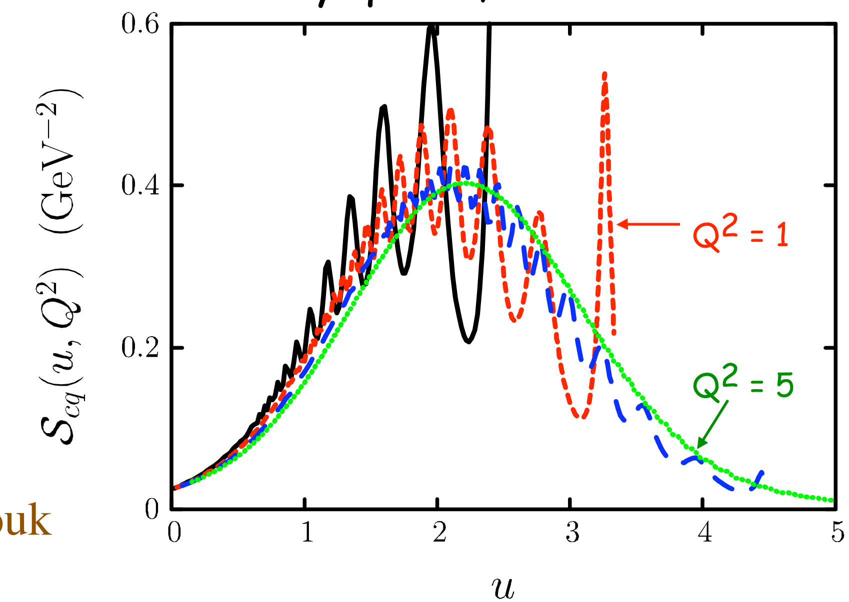
Duality arises as consequence of the separation of time scales between hard and soft physics.

The “higher twist” contributions to an inclusive cross section are naturally of order $(Q_0/Q)^2$, in the absence of another scale.

$\Rightarrow$ Local duality (low Q_0) comes with small higher twist.

These features are built into quantum mechanical resonance models. Wally Melnitchouk

One heavy quark, Relativistic HO

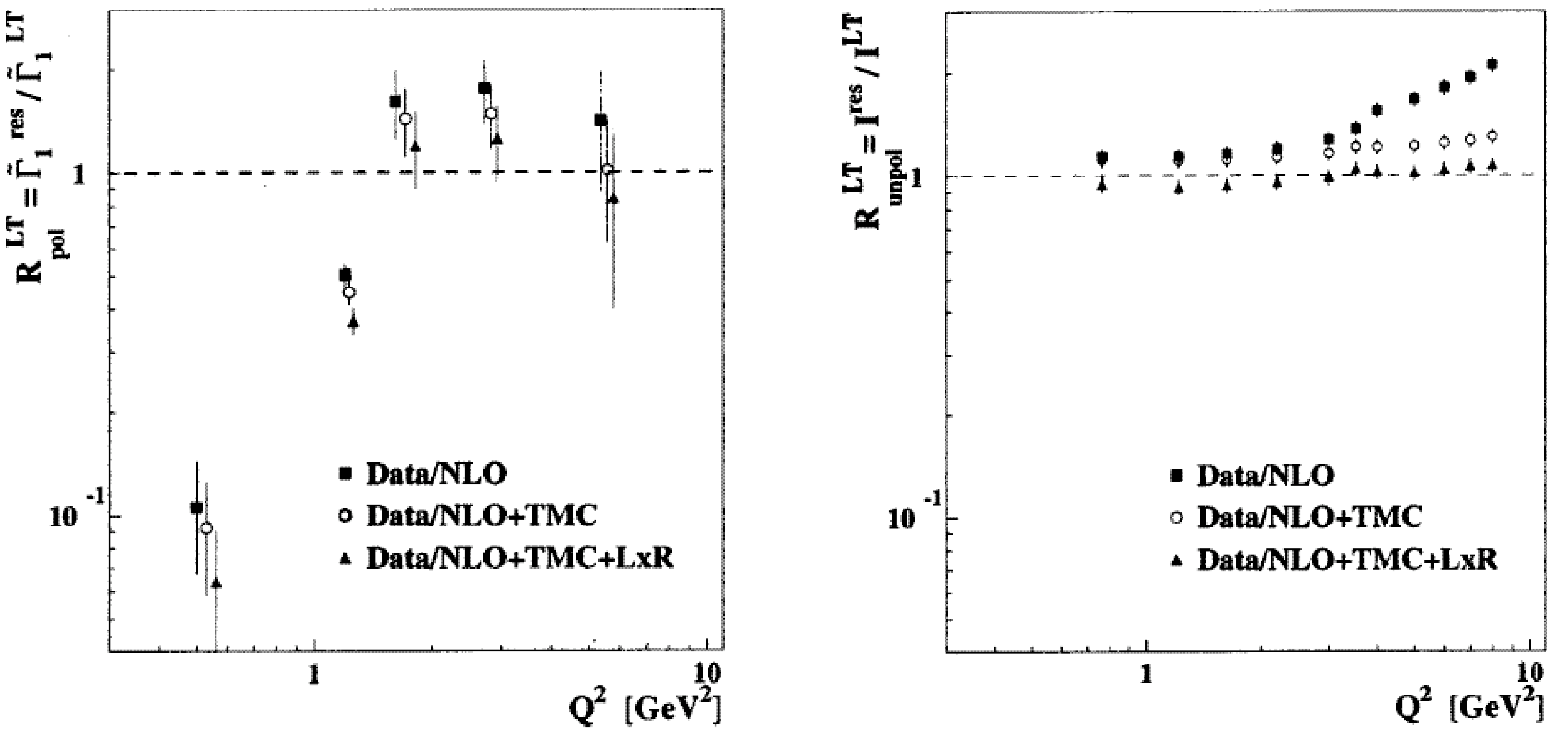


More detailed features such as spin dependent distributions appear to require higher Q^2 and broader averaging.

Rolf Ent:

Comparison of $\Gamma_1^{res} / \Gamma_1^{DIS}$ in same x range

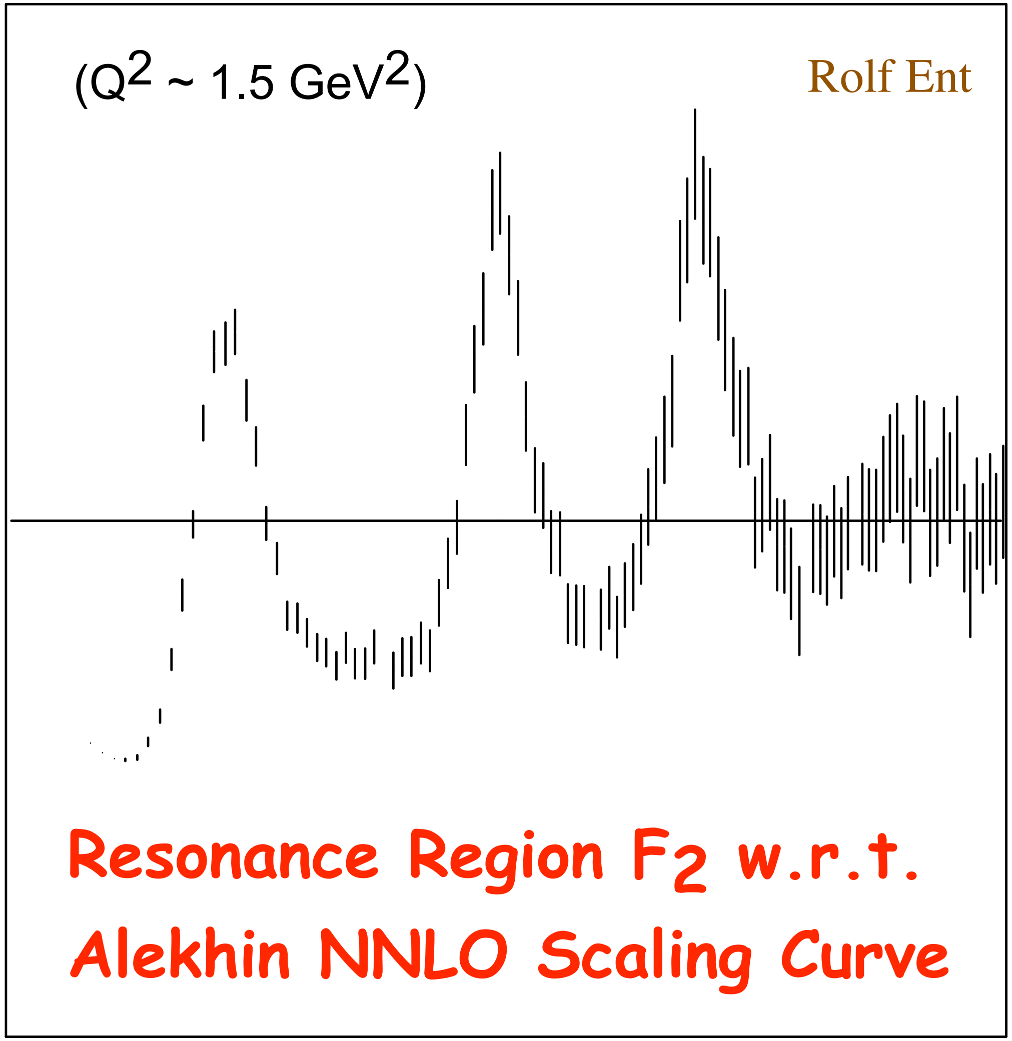
Use PDF



Bianchi, Fantoni & Liuti, PR D69 (2004) 014505

Duality in F_2

Local duality indicates that σ_{DIS} and the form factors $F(p \to N^*)$ are governed by the same hard subprocess and by the same target Fock states.

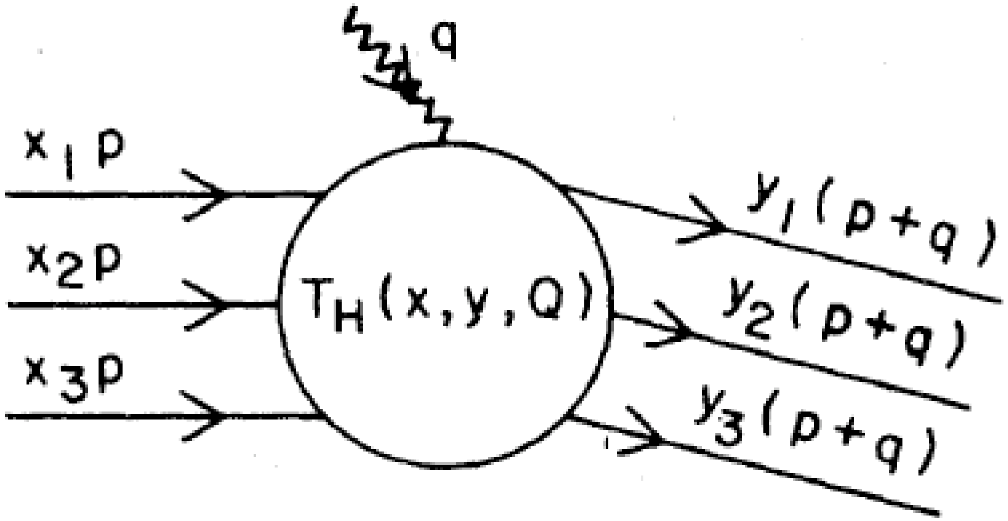


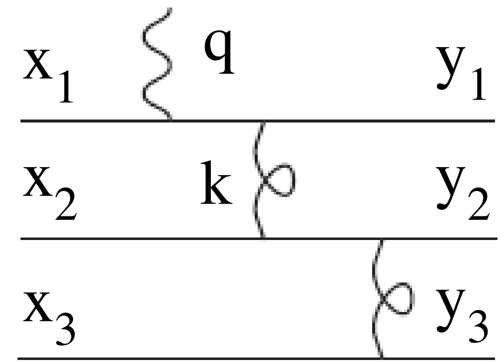
However, it is frequently held that

- DIS occurs via incoherent scattering on a single quark in a general Fock state
- Form factors are governed by coherent scattering on compact Fock states

Brodsky - Lepage

Form factor dynamics





pQCD calculations show that most of the proton form factor arises from gluon exchanges within the hard exclusive subprocess which are much softer than the photon: $k^2 << Q^2$

P. Kroll et al

The transverse size of the Fock states is then $r_\perp >> 1/Q$
Hence the virtual photon scatters incoherently on the constituents.

This could solve the problem of coherent scattering on several quarks:

Wally Melnitchouk:

Coherence vs. incoherence

Exclusive form factors

→ *coherent* scattering from quarks

$$d\sigma \sim \left(\sum_i e_i\right)^2$$

Inclusive structure functions

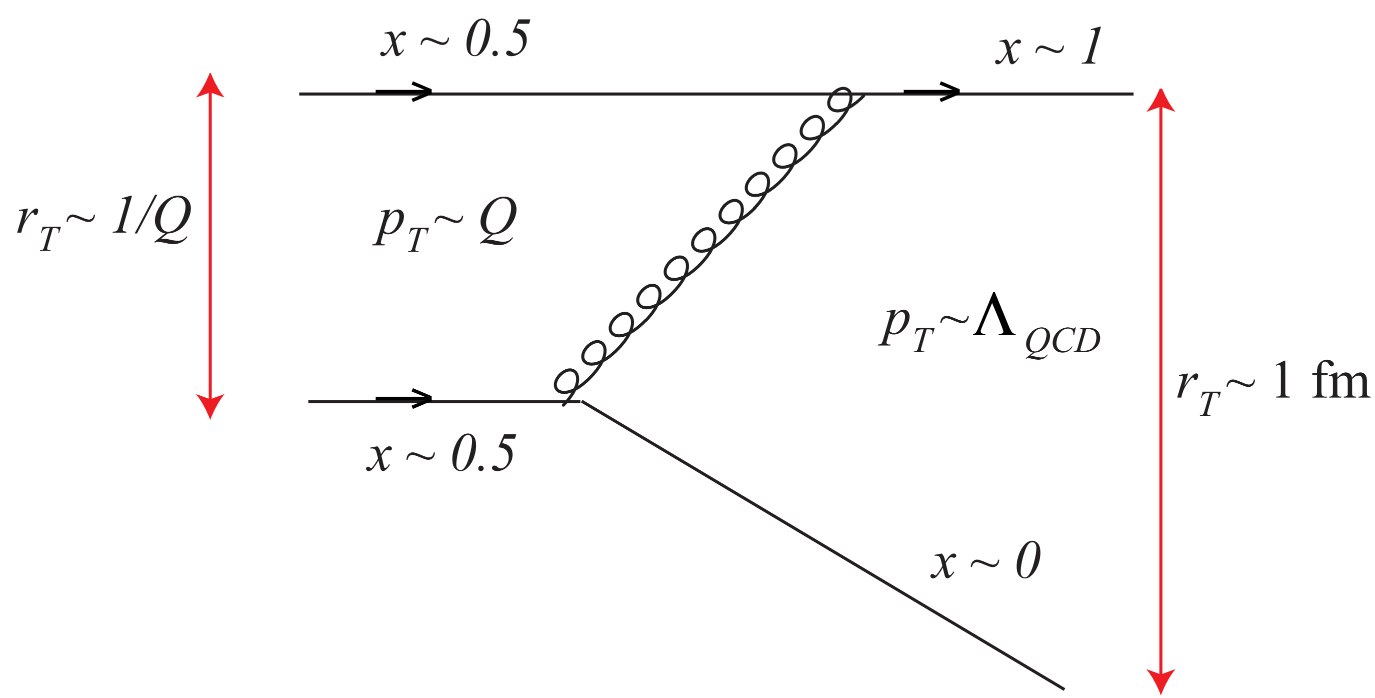
→ *incoherent* scattering from quarks

$$d\sigma \sim \sum_i e_i^2$$

→ How can the *square of a sum* become the *sum of squares*?

Moreover:

There are fast transitions between compact Fock states and non-compact ones, where one quark nearly carries all the momentum. Both states have short lifetimes, similar to the virtual photon.



$$E \simeq \frac{Q^2}{p} \sim \frac{\Lambda^2_{QCD}}{p(1-x)} \quad \text{for} \quad Q^2(1-x) \simeq \Lambda^2_{QCD} \simeq M^2_{N^*} - M^2_p$$

If the virtual photon scatters from the x ~ 1 quark the scattering is incoherent and qualitatively similar to DIS at large x.

Summing up: The QCD dynamics of hadron form factors is still controversial

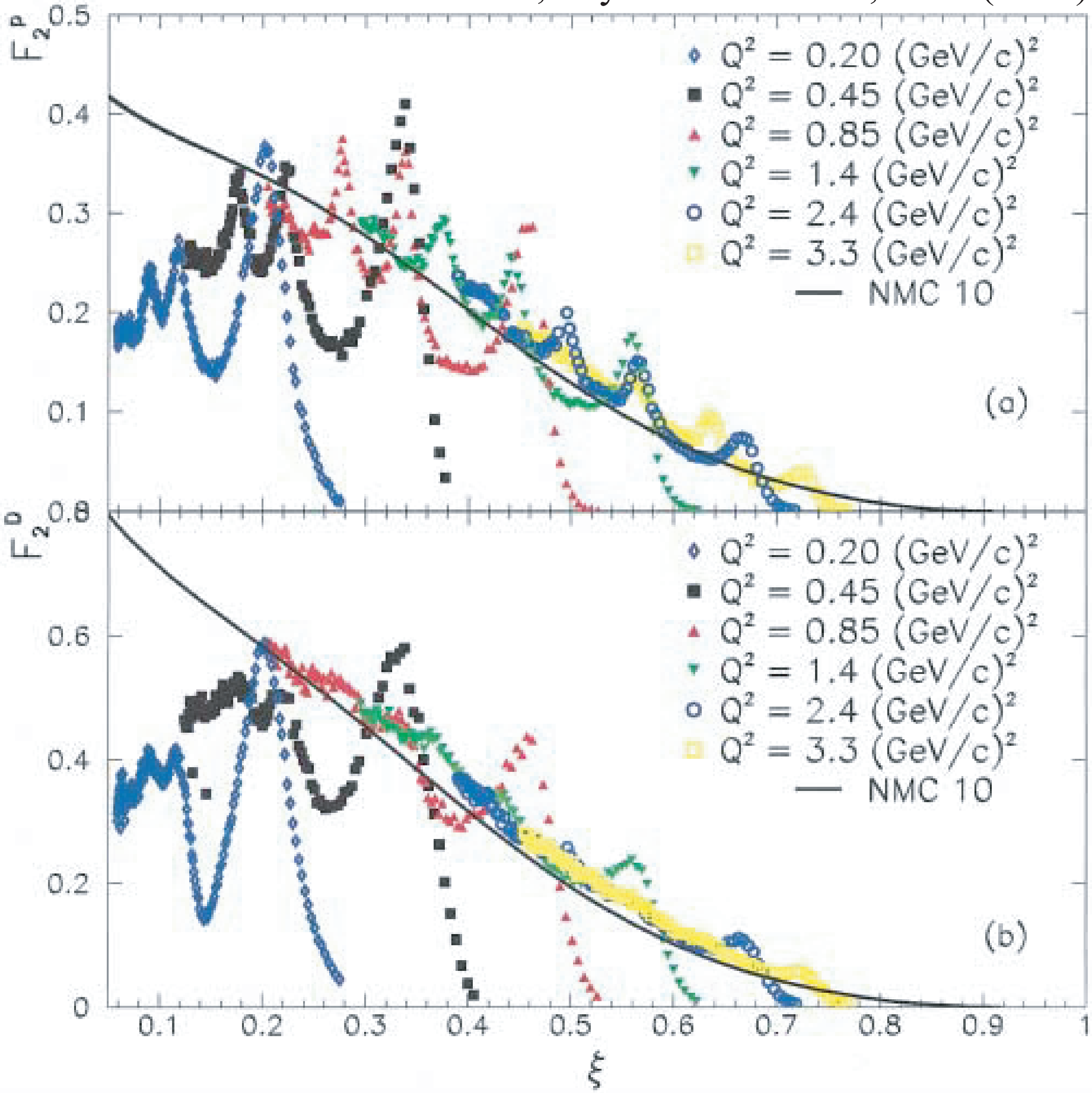
Duality gives important clues, and indicates that “end-point” regions are important. These involving transversally large Fock states where one quark carries most of the momentum.

The photon scatters incoherently off such states, hence interference terms $\propto e_q e_q$, do not contribute.

This makes local duality possible for both proton and neutron targets.

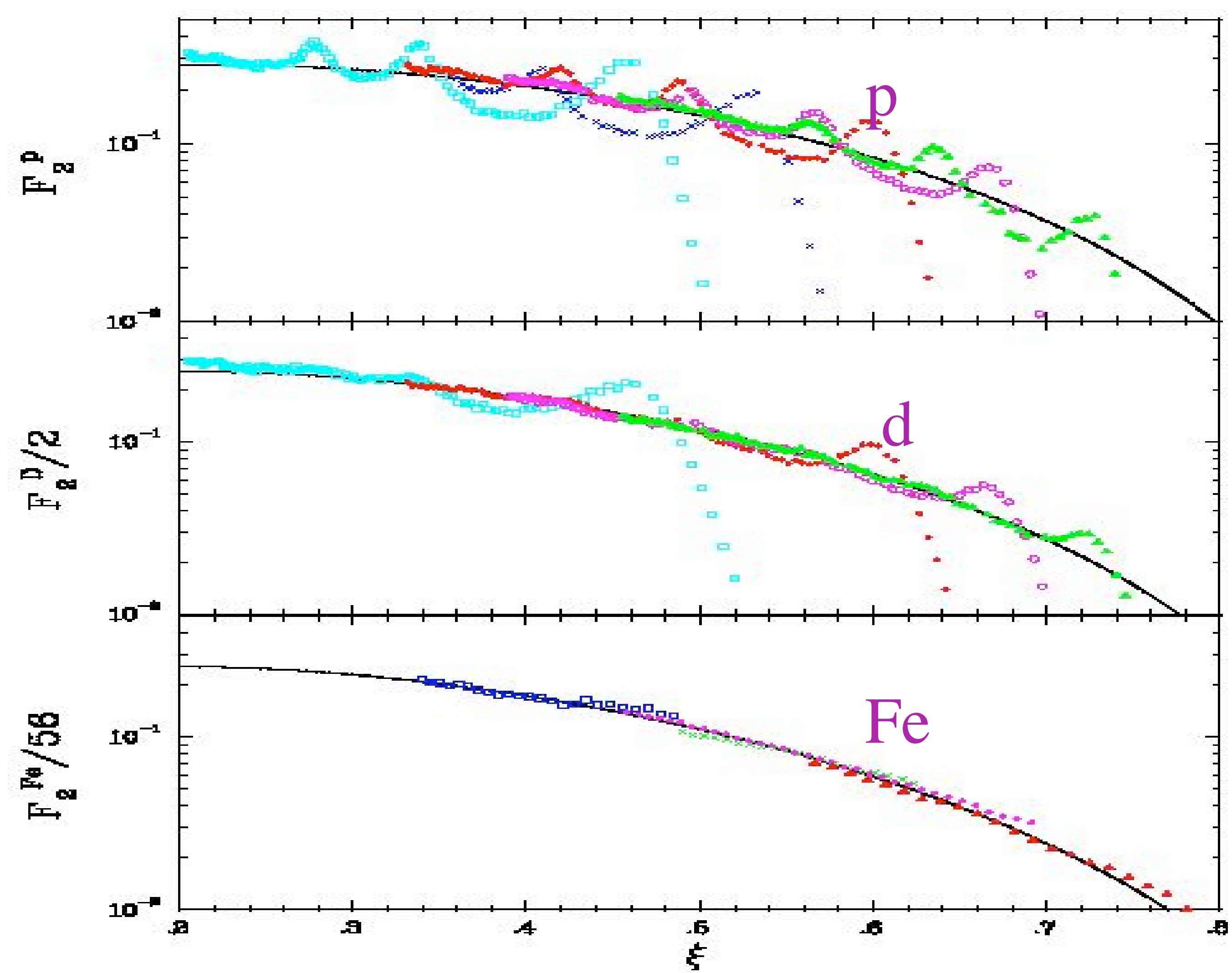
Isgur - Llewellyn-Smith
Radyushkin

I. Niculescu et al, Phys. Rev. Lett. 85, 1182 (2000)



Duality in F_2…let the nucleus do the averaging

- Data in resonance region, spanning Q^2 range 0.7 - 5 GeV^2
- GRV curve
- The nucleus does the averaging
- For larger A, resonance region indistinguishable from DIS



$$\xi = 2x/[1 + (1 + 4M^2x^2/Q^2)^{1/2}]$$

Cynthia Keppel

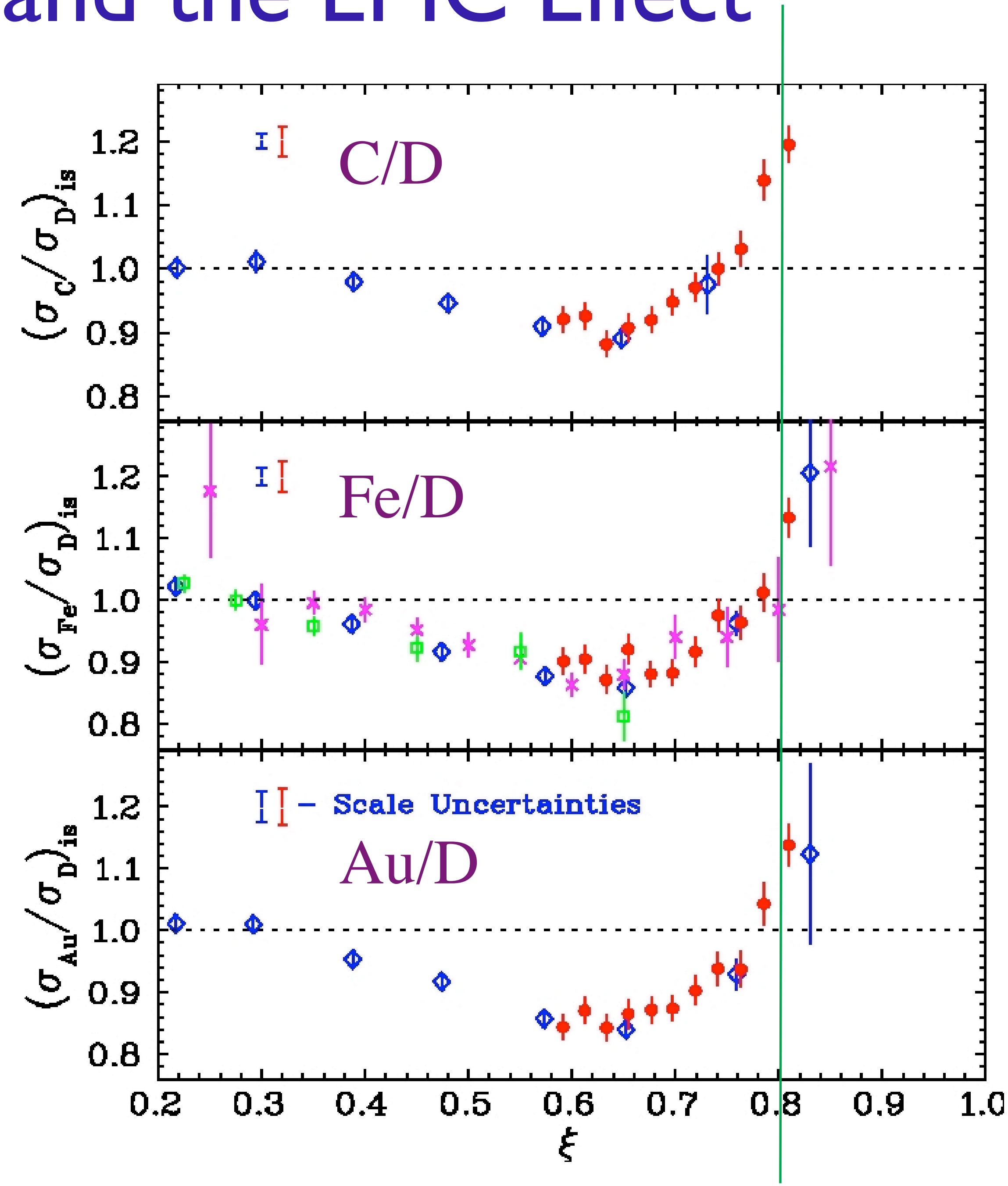
Duality and the EMC Effect

Red = resonance region data

Blue, purple, green = deep inelastic data from SLAC, EMC

Medium modifications to the structure functions ***are the same*** in the resonance region as in the DIS

Cross-over can be studied with new data



J. Arrington, et al., submitted

Coherent vs Incoherent Rescattering in Nuclei

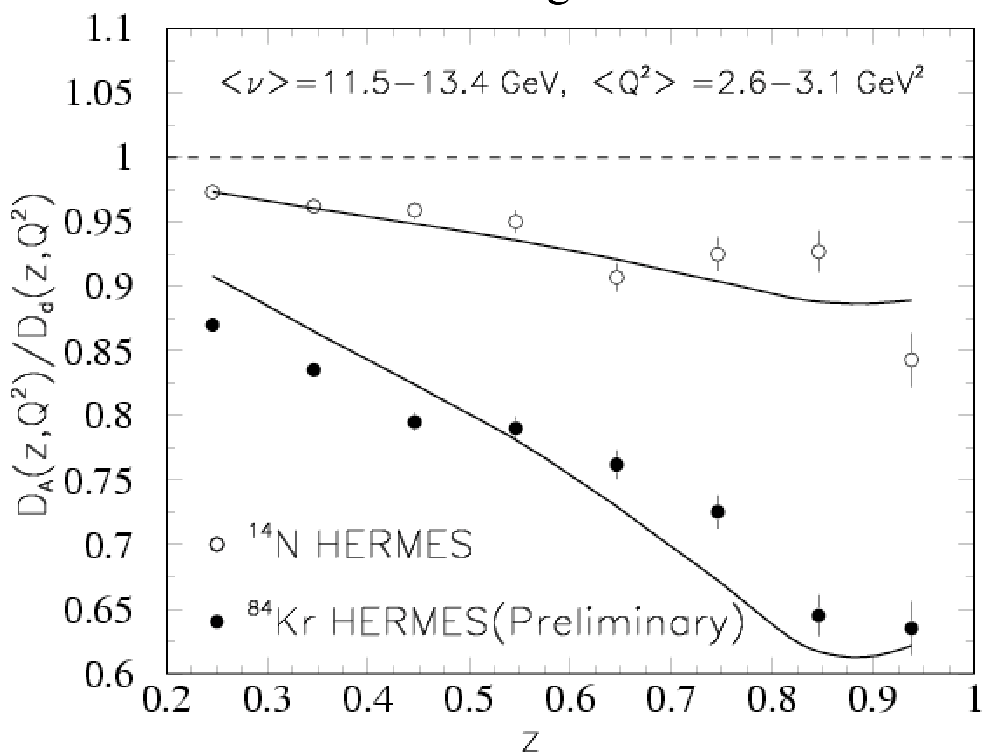
The inclusive DIS cross section (including resonance region) is influenced only by rescattering which happens within the coherence length of the virtual photon

$$L_I = \frac{1}{Q} \cdot \frac{\nu}{Q} = \frac{\nu}{Q^2} = \frac{1}{2m x_B} \quad \approx 0.1 \text{ fm at } x_B = 1$$

Thus the nucleon G_E and G_M extracted by Rosenbluth separation should not be affected by rescattering in the nuclear environment.

Xin-Nian Wang

E. Wang & XNW PRL 2000



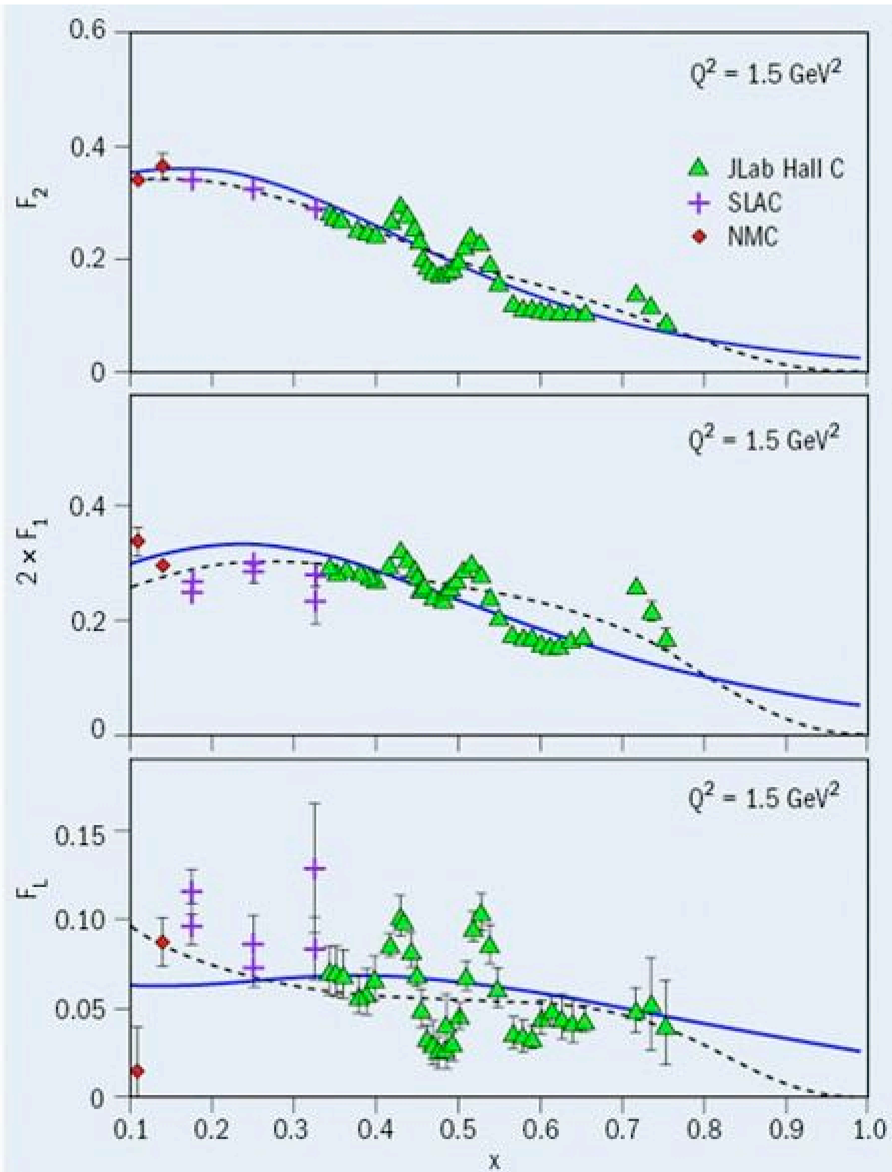
Hadrons observed after traversal through the nucleus, as in SIDIS e A → e+h+X, are affected by incoherent rescattering.

Thus G_E and G_M measured through spin transfer to the final nucleon can be sensitive to spin flips in nuclear rescattering.

Duality works in both σ_L and σ_T

Rolf Ent

E94-110 : Precise Measurement of Separated Structure Functions in Nucleon Resonance Region



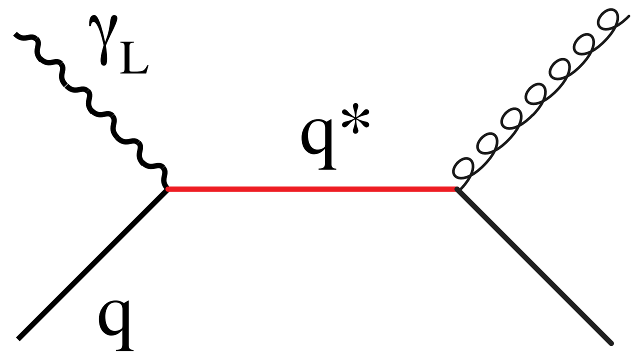
- The resonance region is, on average, well described by NNLO QCD fits.
- This implies that Higher-Twist (FSI) contributions cancel, and are on average small.
- The result is a smooth transition from Quark Model Excitations to a Parton Model description, or a smooth quark-hadron transition.
- This explains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

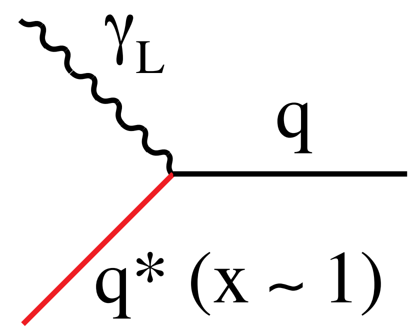
(CERN Courier, December 2004)

σ_L is not suppressed at large x

In the Bjorken limit: $Q^2 \to \infty$ at fixed x
σ_L is of order α_s and arises when γ_L couples to a virtual quark.



For $x \to 1$ the initial quark goes off-shell.
When $Q^2(1-x)$ is held fixed the quark virtuality is commensurate with the photon resolution, and $\sigma_L \sim \sigma_T$ is not suppressed.



In local duality $Q^2(1-x) = M_{N^*}{}^2 - M_p{}^2$ is fixed: This is not the Bj limit!

$\Rightarrow$ There is no twist expansion, hence one cannot properly talk about "higher twist corrections"

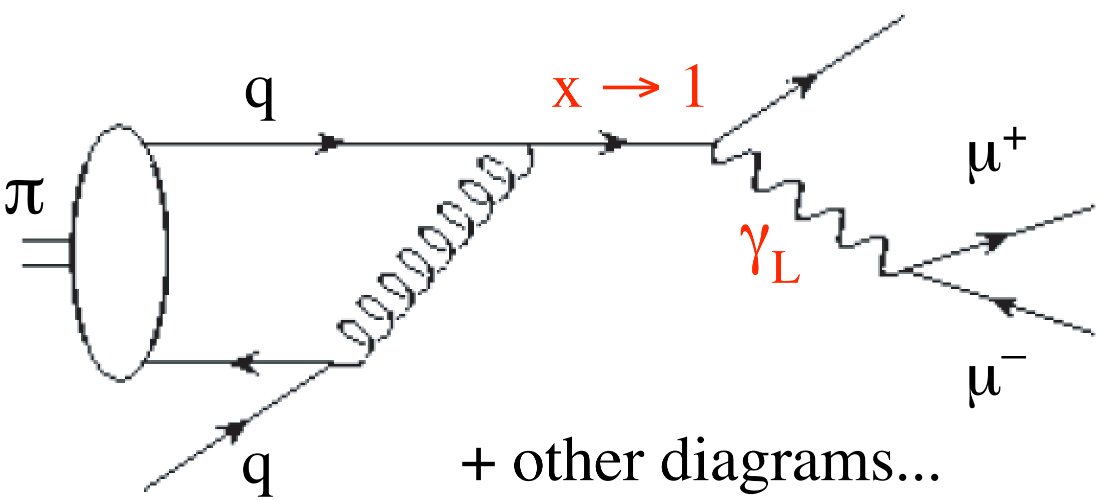
Experimental evidence for dominance of σ_L at high x

In $\pi N \to \mu^+ \mu^- X$ the angular distribution of the $\mu^+ \mu^- \propto 1 + \lambda \cos^2\theta$ reveals directly the polarization of the (timelike) virtual photon:

$\lambda = +1$: Transverse polarization

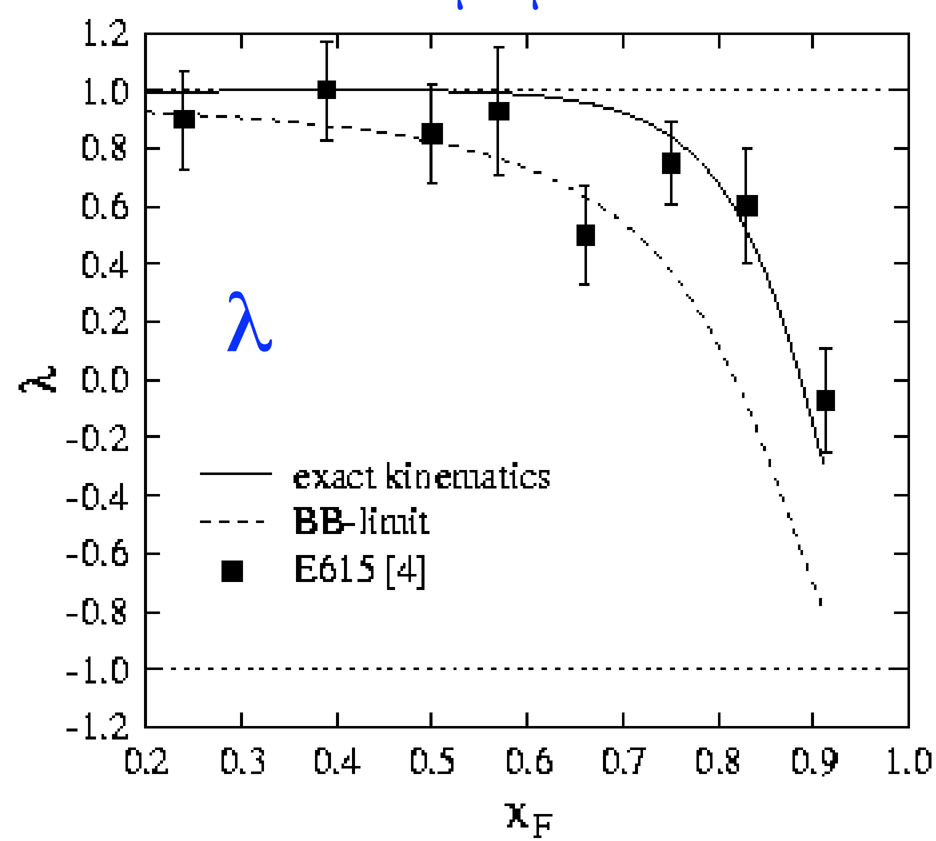
$\lambda = -1$: Longitudinal polarization

For $x_F(\mu^+ \mu^-) \to 1$ the quark in the pion carries $x \to 1$ and goes off-shell. In effect the (scalar) pion scatters coherently via a longitudinal photon.



+ other diagrams...

$\pi N \to \mu^+ \mu^- X$



Local duality for the pion

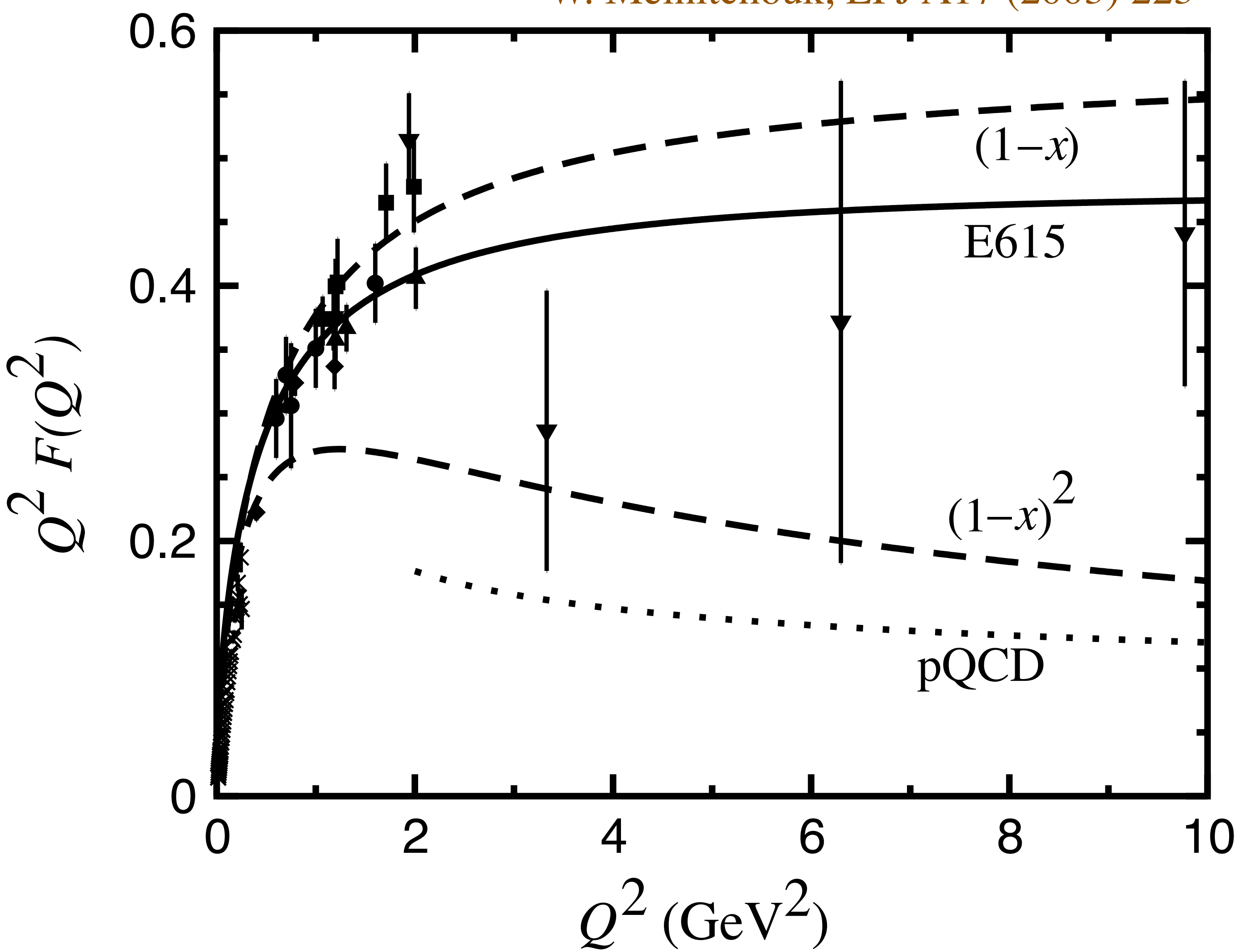
Duality for a pion "target" can be studied by comparing $f_{q/\pi}(x)$ measured in Drell-Yan (which contains σ_L) with the pion e.m. form factor (which only has contributions from σ_L).

In pQCD, $f_{q/\pi}(x) \propto (1-x)^2$ for σ_T in the Bj limit.

The E615, $f_{q/\pi}(x) \sim (1-x)^1$ indicating substantial σ_L (as seen above).

Insofar as σ_L dominates in DY at large x, this is another succesful test of local duality, now for the pion pole.

W. Melnitchouk, EPJ A17 (2003) 223



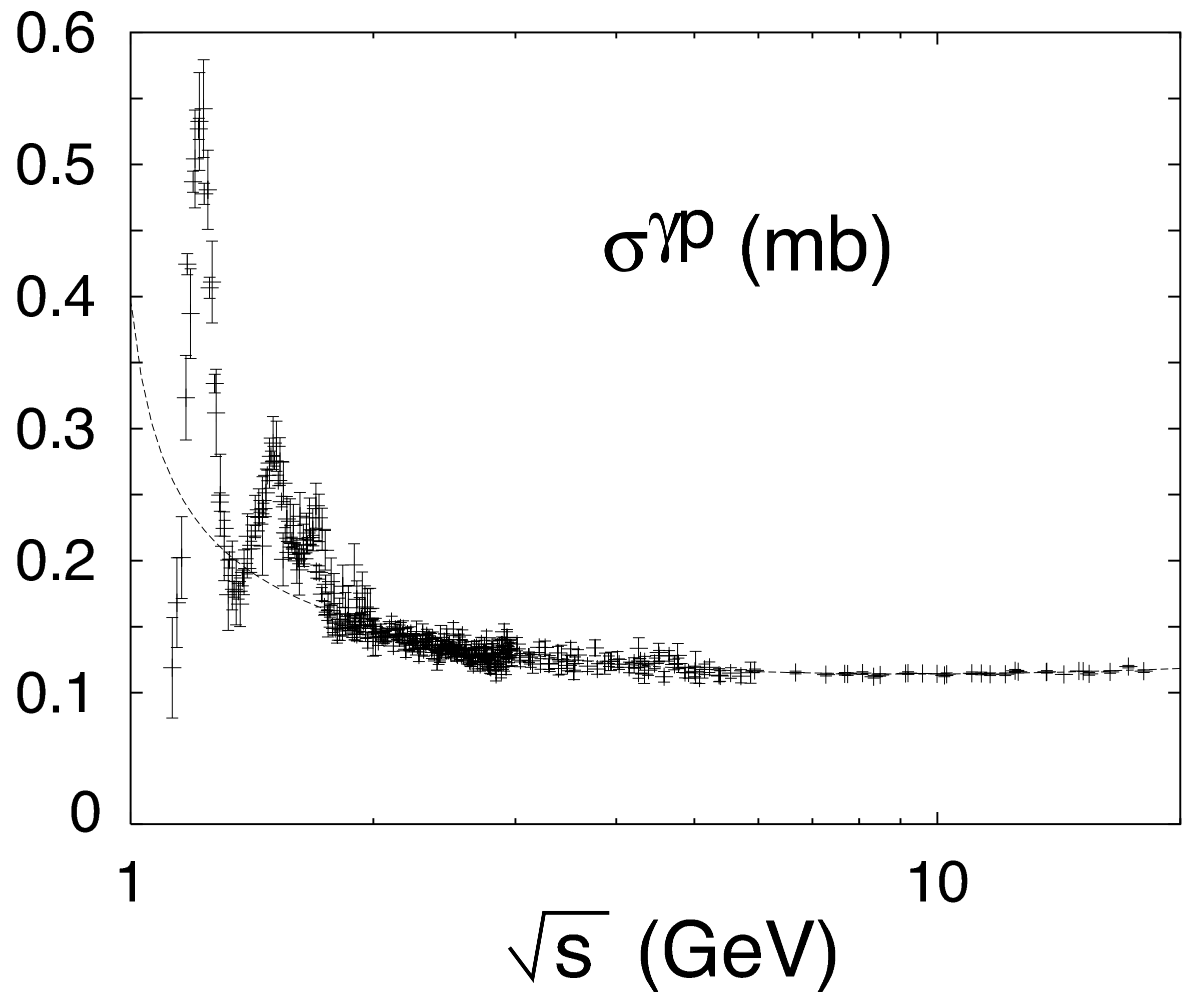
Local duality at $Q^2 = 0$

Alexander Donnachie

The spin-averaged photoproduction total cross section obeys the duality of soft hadron scattering: Resonances are dual to Regge exchange
"Background" is dual to "Pomeron" exchange

Regge duality was a very succesful phenomenology in the 60-70's, and led to the Veneziano model, whence to string theory.

The QCD origins of Regge duality is more obscure than that of Bloom-Gilman duality, since it involves only soft physics.

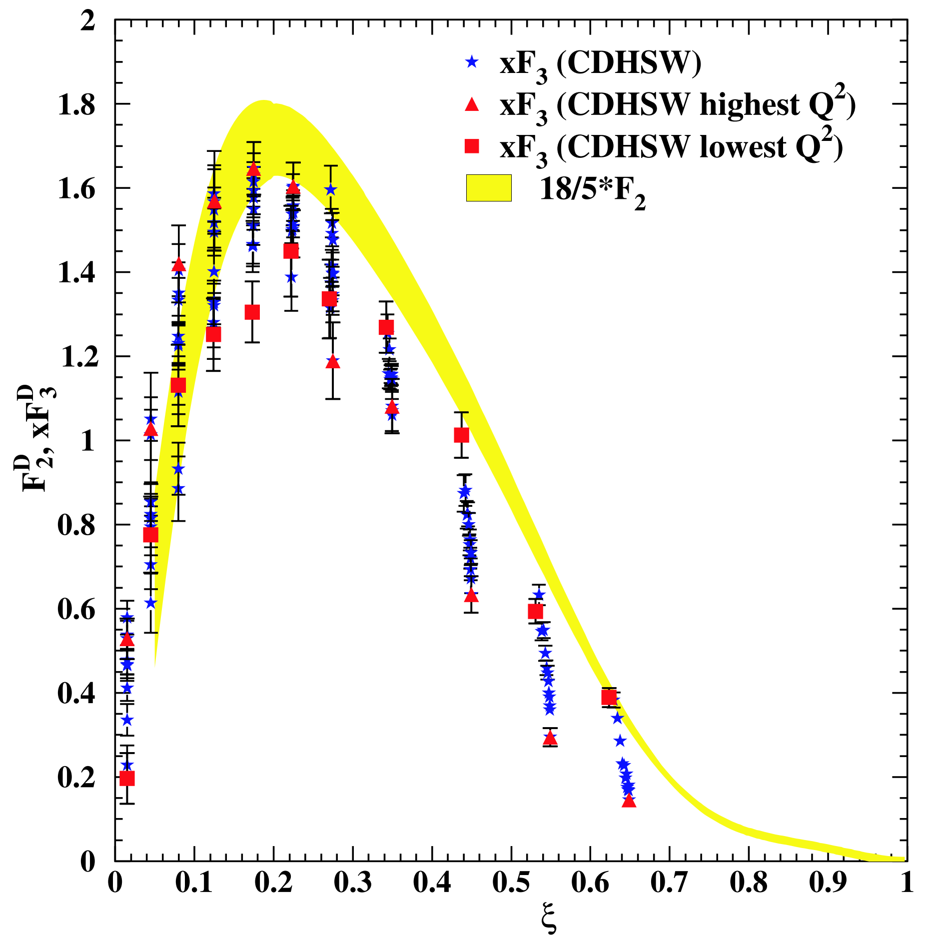


Resonances dual to valence quark distribution

At high x, the contribution from gluons and sea quarks is small.

At low x and Q^2 , the relation between resonances and DIS is close to Regge duality, where two-component duality has been shown to hold.

Niculescu et al, PRL 85 (2000) 1182

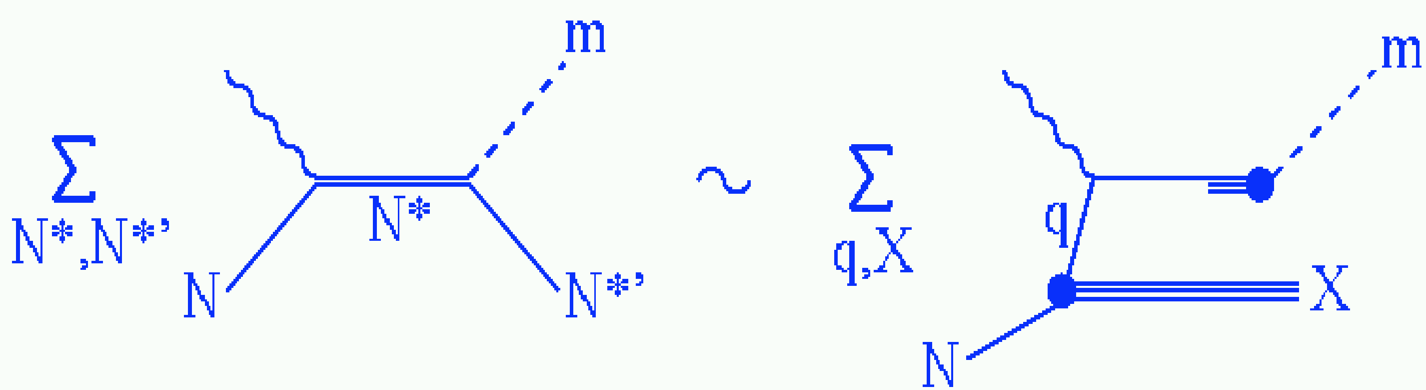


The success of Bloom-Gilman duality in the valence quark distribution at low x may thus be a consequence of Regge duality.

Rolf Ent

Duality in Meson Electroproduction

hadronic description　　　　quark-gluon description



$$\sum_{N'^*}\left|\sum_{N^*} F_{\gamma^* N\to N^*}(Q^2,W^2)\; \mathcal{D}_{N^*\to N'^* M}(W^2,W'^2)\right|^2$$

$$\sum_q e_q^2\, q(x)\, D_{q\to M}(z)$$

Transition Form Factor　　Decay Amplitude　　Fragmentation Function

Requires non-trivial cancellations of decay angular distributions If duality is not observed, factorization is questionable

Duality and factorization possible for $Q^2, W^2 \leq 3$ GeV^2 (Close and Isgur, Phys. Lett. B509, 81 (2001))

Unpolarized SIDIS: new test

Peter Bosted

Simple picture in valence region:

$\sigma_p(\pi^+) = 4u(x)D^+(z) + d(x)D^-(z)$

$\sigma_p(\pi^-) = 4u(x)D^-(z) + d(x)D^+(z)$

$\sigma_d(\pi^+) = [u(x)+d(x)]\ [4D^+(z) + D^-(z)]$

$\sigma_d(\pi^-) = [u(x)+d(x)]\ [4D^-(z) + D^+(z)]$

$R_{pd} = [\sigma_p(\pi^+) + \sigma_p(\pi^-)] / [\sigma_d(\pi^+) + \sigma_d(\pi^-)]$

$= [4u(x) + d(x)] / 5[u(x)+d(x)]$

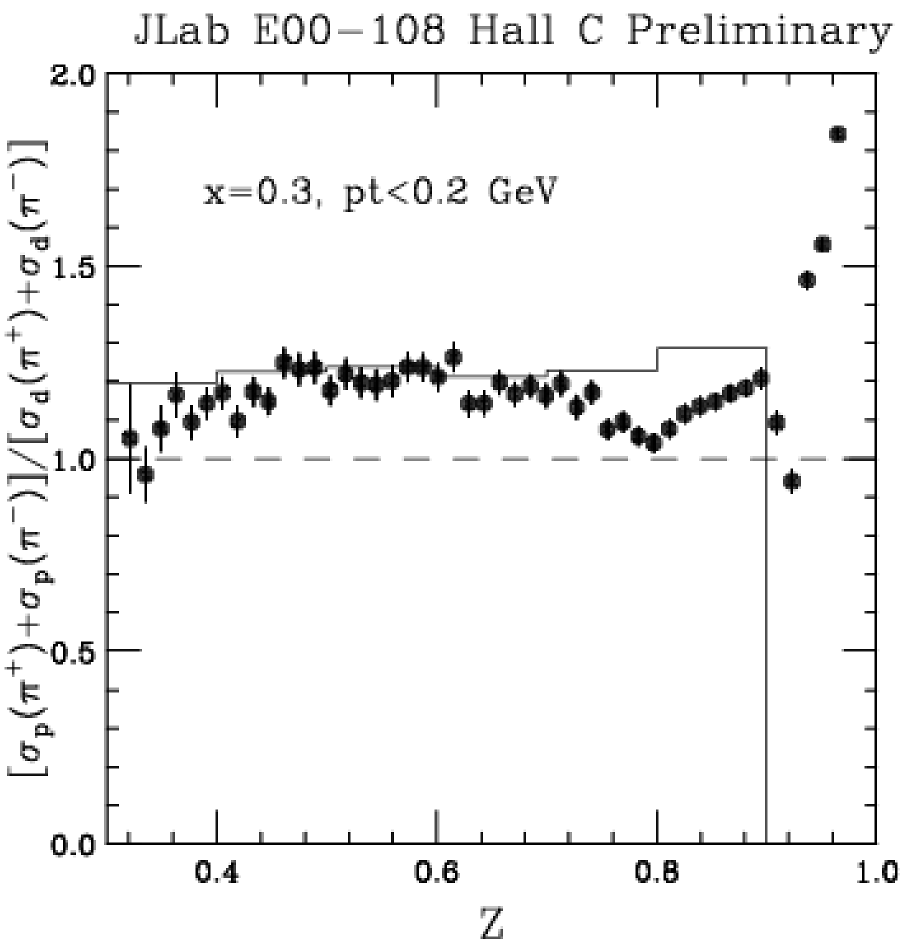
$= \sigma_p(x)/\sigma_d(x)$

R_{pd} should be independent of z and p_t

x-dependence of R_{pd} should be same as inclusve $\sigma_p(x)/\sigma_d(x)$ in valence region

Unpolarized SIDIS: new test

Peter Bosted



R_{pd} is independent of z for 0.4<z<0.7 for W=2.5 GeV, Q^2=2.5 GeV^2, x=0.3, low p_t

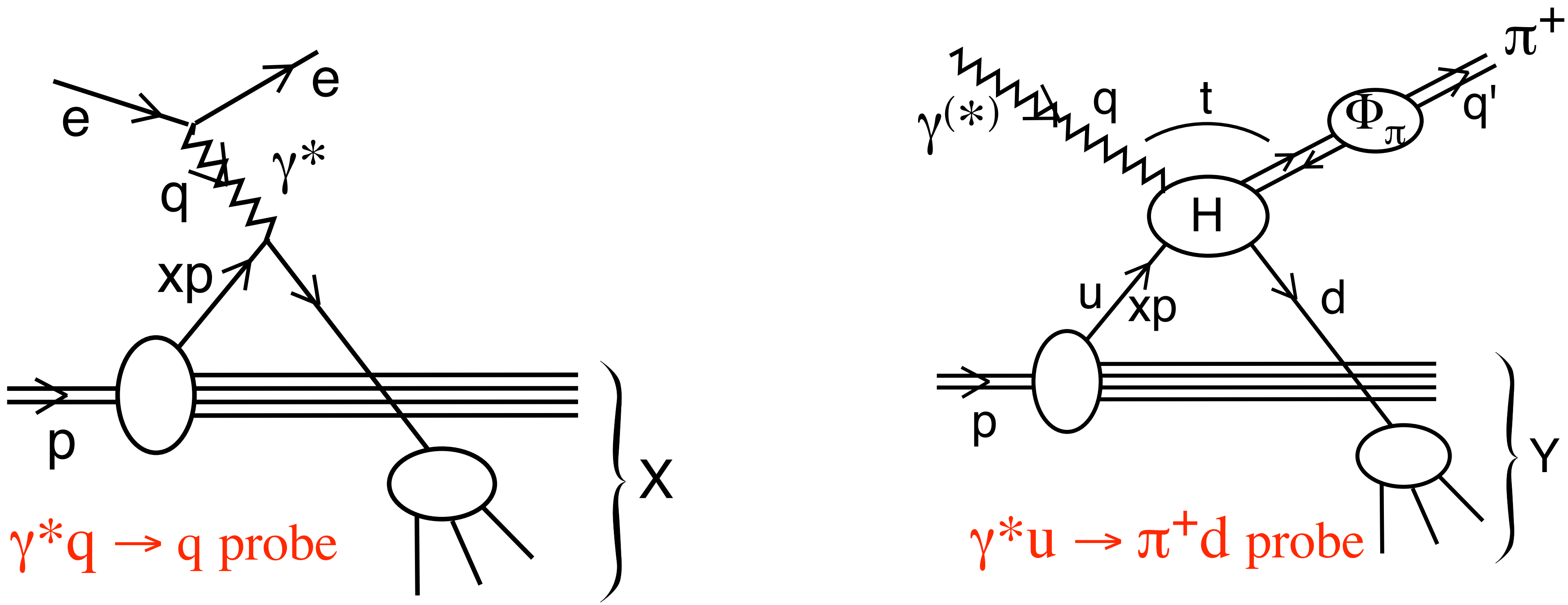
Good agreement GRV (using PEPSI MC, solid histogram)

10% level deviations for z>0.7 (M_x>1.4 GeV) Influence of Delta?

Extending duality: Semi-exclusive processes

C. Carlson et al
S. Brodsky et al

Replace short-distance probe of DIS ($\gamma^* q \to q$) by some other compact subprocss, e.g., $\gamma^*\, u \to \pi^+\, d$, with hard scale given by t and/or Q^2 .



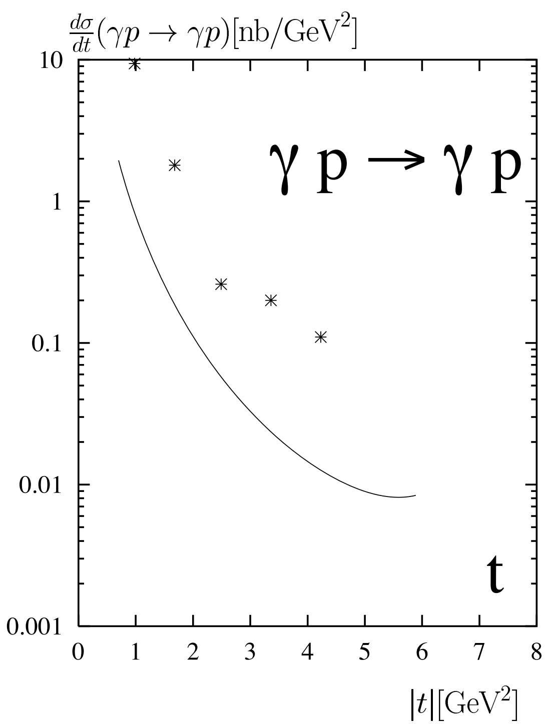
The cross sections for $\gamma^{(*)}\, p \to \gamma\, Y$, $\gamma^{(*)}\, p \to \pi^+\, Y$, ... can then be predicted in the limit where $\Lambda^2_{QCD} << M^2_Y << W^2$.

Note: Data on semi-exclusive processes such as $\gamma^* p \to \gamma Y$ is very welcome!

Using duality as in DIS ($W^2 \to M^2_N$) one may try to extrapolate $M^2_Y \to M^2_N$

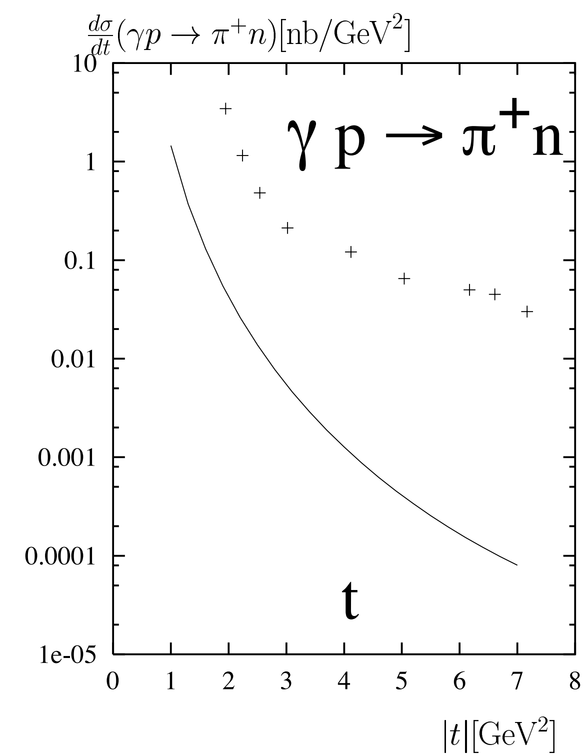
The calculated result is below the data by ≥ factor 10.

D. M. Scott
P. Eden et al



Failure may be due to duality extrapolation or to an incorrect dynamics for the semi-exclusive process, or...

Either way, we are learning something!



Summary Conclusions

- Duality is a vibrant and promising field, which is driven by experiment.

- Duality is hinting that QCD is scale (Q^2) invariant

  $\Rightarrow$ Conformal Field Theory? Dimensional scaling rules. Guy de Teramond

  Yet in confinement region, the Λ_{QCD} scale is relevant Arkady Vainshtein

- QCD dynamics of hadron form factors should resemble DIS dynamics

  $\Rightarrow$ Incoherent scattering on single quark?

- Two limits: 1. $Q^2 \to \infty$ with x fixed, then $x \to 1$ (Bj, twist expansion)

  2. $Q^2 \to \infty$ with $Q^2(1\text{-}x)$ fixed (No twist expansion)

Local duality for a given resonance requires limit 2.

- Duality suggests principal features of confinement region, but our field theory tools are limited in this region.

Lattice measurements $\alpha_{MS}(M_Z)$ Howard Trottier

Schwinger-Dyson approximations Limited applications

⇒ Need to develop description of relativistic bound states moving in color fields – using hints from duality.

- Duality developments likely to be driven by data also in the future

Spin dependence may yet be a challenge also to PQCD

- Progress requires close collaboration between experiment and theory