Hall C @ 12 GeV:

Theoretical Perspective

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Understanding the structure
and interaction of hadrons
in terms of the quark and gluon
degrees of freedom of QCD
is the greatest unsolved problem
of the *Standard Model of*
Nuclear and Particle Physics !

QCD and the Strong Nuclear Force

Of all the forces of Nature, QCD has the most bizarre properties!

- Asymptotic freedom:
  $\longrightarrow$ quarks feel almost no strong force when close together

- Confinement:
  $\longrightarrow$ restoring force between quarks at large distances equivalent to 10 tons no matter how far apart!

QCD in principle describes all of nuclear physics
— at all distance scales —
but *how does it work*?

Quark-Hadron Duality

Complementarity

between quark and hadron

descriptions of observables

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

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

At high energies: interactions between quarks and gluons become weak ("asymptotic freedom")

$\longrightarrow$ efficient description of phenomena afforded in terms of quarks

At low energies: effects of confinement make strongly-coupled QCD highly non-perturbative

$\longrightarrow$ collective degrees of freedom (mesons and baryons) more efficient

Duality between quark and hadron descriptions

$\longrightarrow$ reflects relationship between *confinement* and *asymptotic freedom*

$\longrightarrow$ intimately related to nature of transition from *non-perturbative* to *perturbative* QCD

Theoretical Tools

Theoretical tools currently available are:

- Perturbation theory
  - $\longrightarrow$ calculate in terms of quarks & gluons
  - $\longrightarrow$ expand in powers of α_s
  - $\longrightarrow$ $k \gg \Lambda_{QCD}$

- Chiral effective field theory
  - $\longrightarrow$ use symmetries (e.g.chiral) of QCD
    $+$ hadronic degrees of freedom
  - $\longrightarrow$ expand in powers of k/M_χ
  - $\longrightarrow$ $k \ll \Lambda_{QCD}$

Does not address question of how hadrons are built from quarks and gluons:

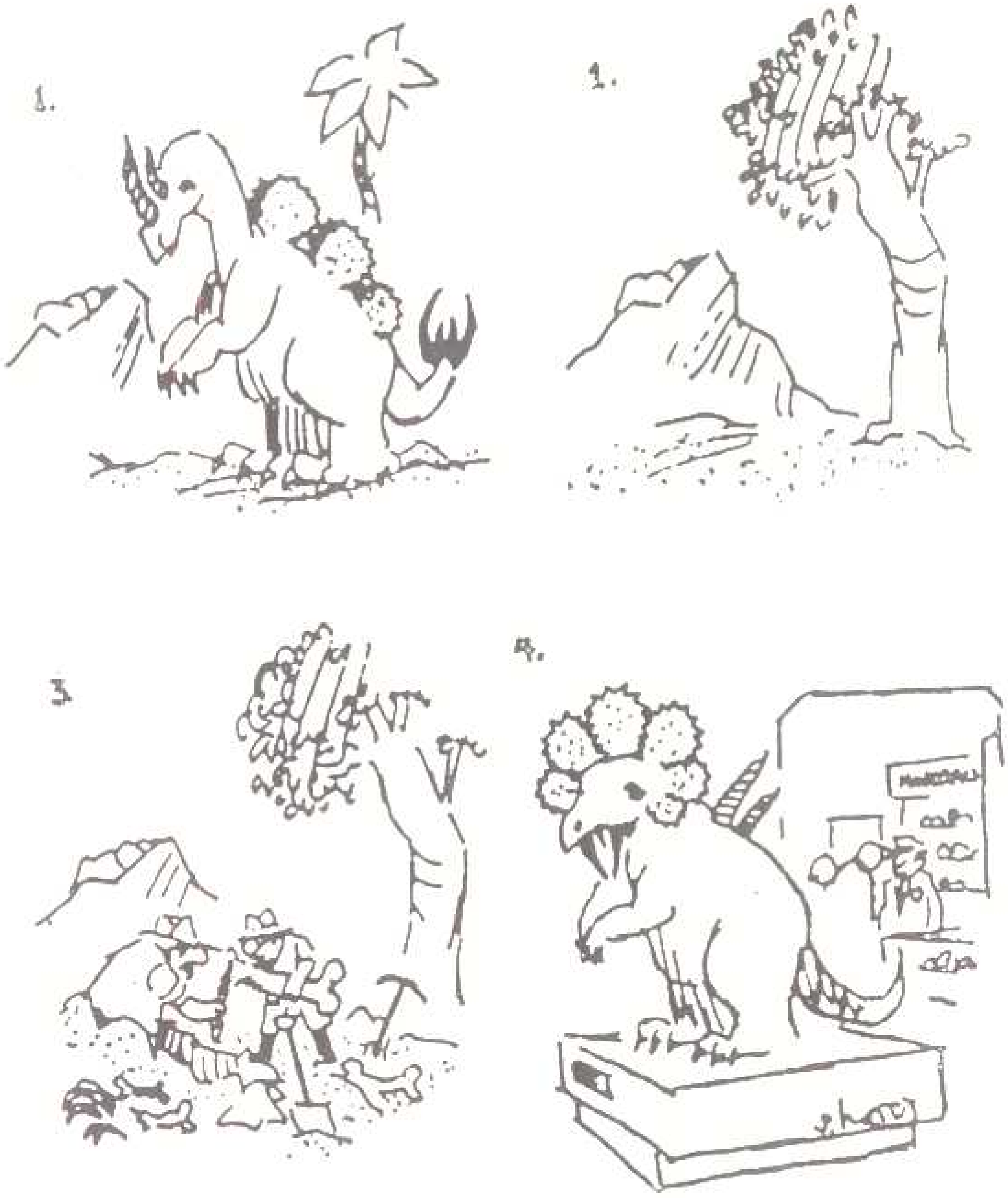
$\longrightarrow$ can *describe* phenomena, but not necessarily *understand* ...

Must use nonperturbative methods:

- QCD-inspired models
  $\longrightarrow$ can provide guidance on effective degrees of freedom at low energy
  but *ad hoc*

- Lattice QCD
  $\longrightarrow$ making progress (e.g.LHPC)
  but realistic calculations available only for spectroscopy
  $\longrightarrow$ can only calculate moments, not x, ξ dependence

Phenomenology will remain *essential* for a long time ...
$\longrightarrow$ empirical information will provide critical input from which to reconstruct complete picture ...



Where Are We Now?

What do we know about the quark-gluon structure of hadrons?

- Forward parton distributions (at $x_{Bj} \lesssim 0.6$)

$\longrightarrow F_2^h(x_{Bj}) \sim \sum_X |\psi(h \to q(x) + X)|^2 \delta(x - x_{Bj})$

$\longrightarrow g_1^h(x_{Bj}) \sim \sum_X |\psi(h^\uparrow \to q^\uparrow(x) + X)$

$- \psi(h^\uparrow \to q^\downarrow(x) + X)|^2 \delta(x - x_{Bj})$

$\longrightarrow$ *inclusive*

- Elastic and (some) transition form factors (over modest Q^2 range)

$\longrightarrow F_{hh'}(t) \sim \sum_X \psi(h(p) \to q(xp) + X)$

$\times\ \psi^*(h'(p+q) \to q(xp+q) + X)$

$\longrightarrow$ *exclusive*

Where Are We Going?

- Complete understanding of quark–gluon substructure of hadrons demands *integrated* approach
  $\longrightarrow$ must be tested in exclusive, inclusive, and semi-inclusive, reactions

- Relation between exclusive and inclusive observables — in preasymptotic region — provided by *Quark-Hadron Duality*

- Mathematical framework provided by *Generalized Parton Distributions*

- What is the origin of *precocious scaling?*
  $\longrightarrow$ accident or systematic?

- How is perturbative $\longrightarrow$ nonperturbative (quark $\longrightarrow$ hadron) transition modified in the nuclear environment?

Bloom-Gilman Duality

Individual resonances are strongly Q^2 dependent

But their average remains $\approx Q^2$ independent!

$\Rightarrow$ resembles scaling (leading twist) structure function

(Bloom, Gilman 1970)

Resonances, Scaling & Higher Twist

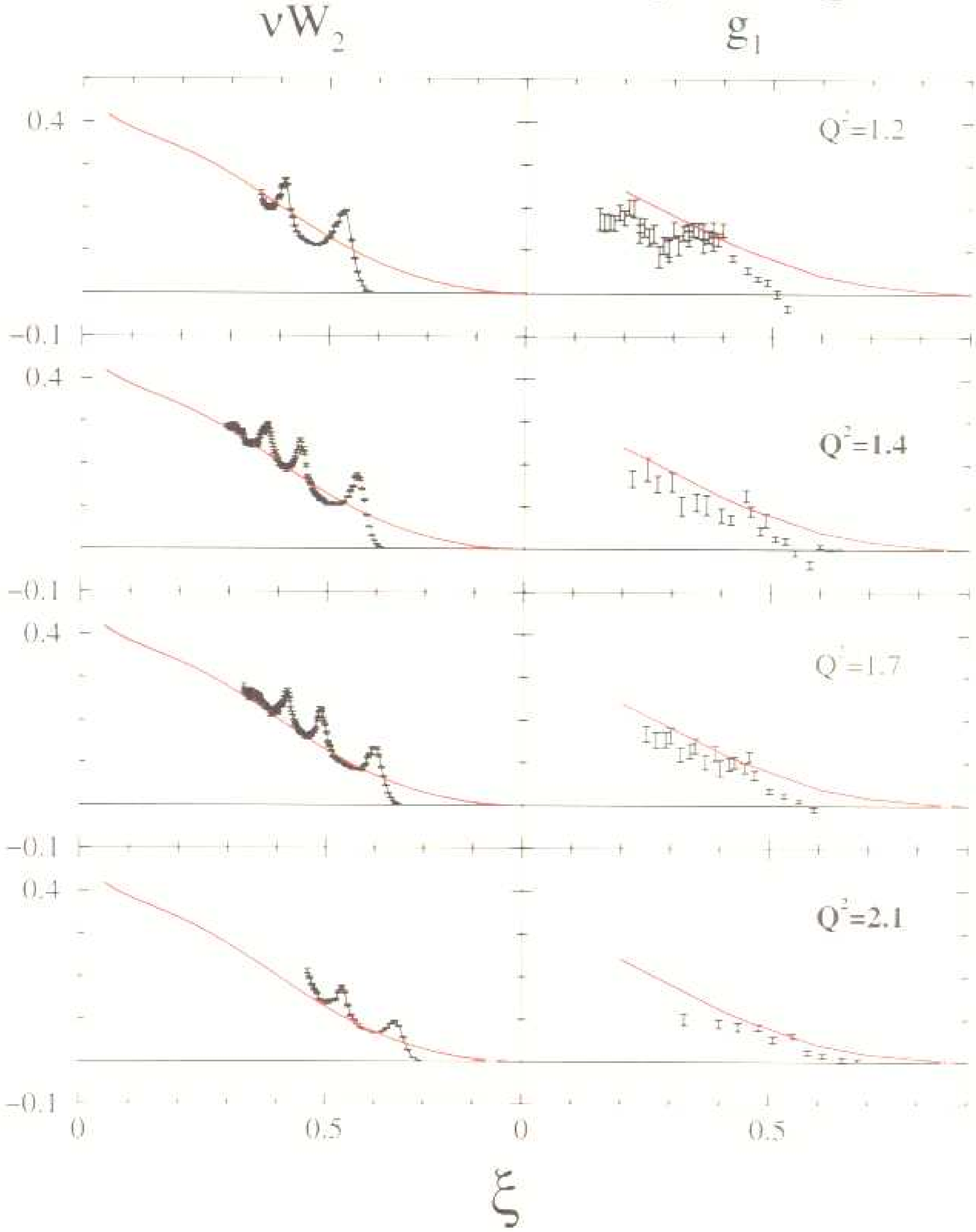
- Bloom-Gilman duality $\Rightarrow$ distinction between "resonance" and "DIS" regions is *artificial*

- *E.g.* at $Q^2 = 1$ GeV^2 about 70% of F_2 comes from $W < 2$ GeV

- *But*, because of duality, resonances and DIS continuum conspire to produce $\sim$ 10% higher twist $(1/Q^2)$ contribution!

Resonances are an integral part of the scaling structure functions !

Can we Test Duality for g1?



Local Duality

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"

Exclusive–Inclusive Connection

"Drell-Yan – West relation"

$$G(Q^2) \sim (1/Q^2)^N$$

$$\Updownarrow$$

$$q(x) \sim (1-x)^{2N-1}$$

E.g. for proton, $N = 2$:

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

Local duality can be used to
relate large x structure functions to
(elastic & transition) form factors

Local Elastic Duality

Threshold relations:

$$\int_{\xi_{th}}^{1} d\xi \; \xi^n \; F_1(\xi, Q^2) \; = \; \frac{\xi_0^{n+2}}{4 - 2\xi_0} \, G_M^2$$

$$\int_{\xi_{th}}^{1} d\xi \; \xi^n \; F_2(\xi, Q^2) \; = \; \frac{\xi_0^{n+2}}{2 - \xi_0} \, \frac{\left(G_E^2 + \tau G_M^2\right)}{(1 + \tau)}$$

$$\int_{\xi_{th}}^{1} d\xi \; \xi^n \; g_1(\xi, Q^2) \; = \; \frac{\xi_0^{n+2}}{4 - 2\xi_0} \, \frac{G_M \left(G_E + \tau G_M\right)}{1 + \tau}$$

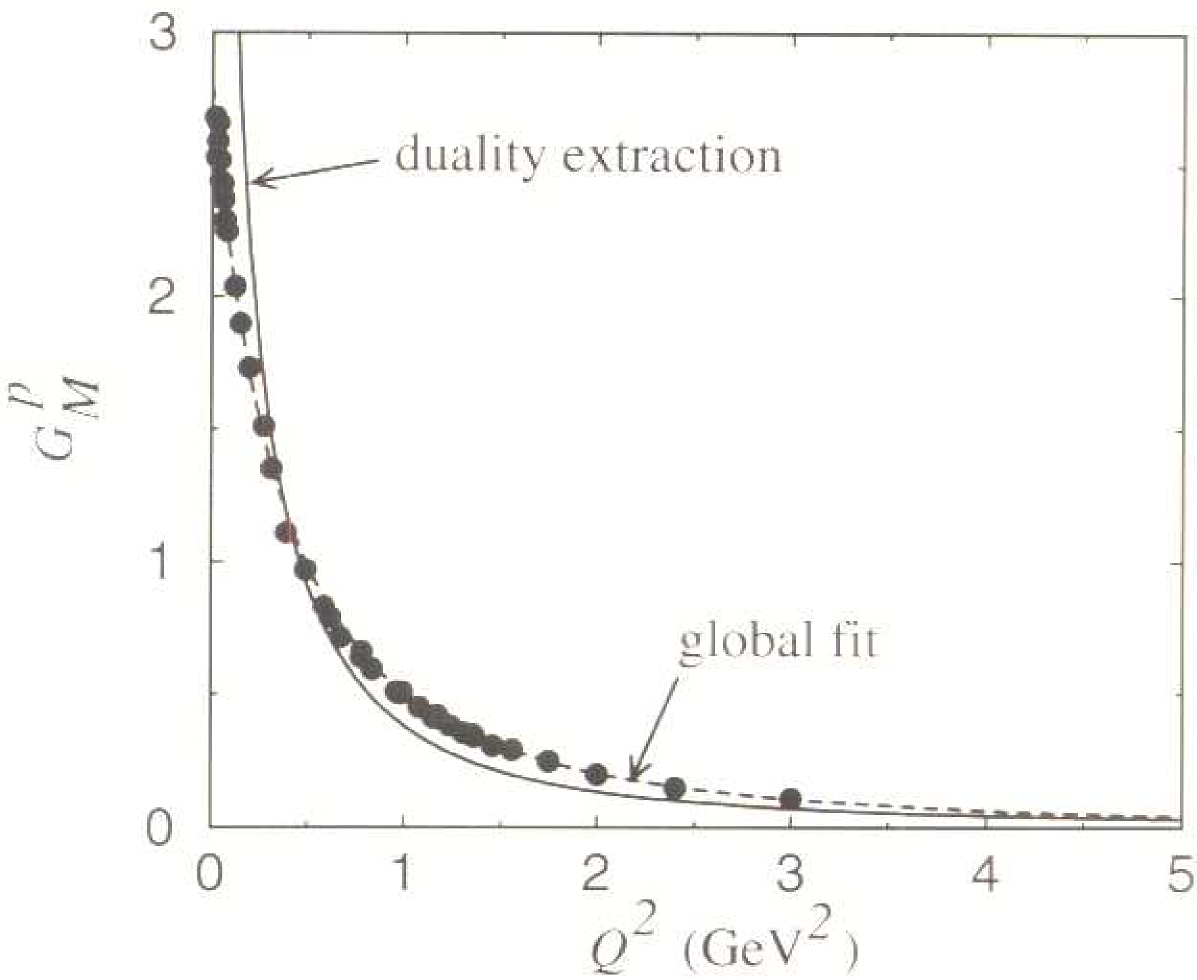
$$\int_{\xi_{th}}^{1} d\xi \; \xi^n \; g_2(\xi, Q^2) \; = \; \frac{\xi_0^{n+2}}{4 - 2\xi_0} \, \frac{\tau G_M \left(G_E - G_M\right)}{1 + \tau}$$

$$\xi = 2x/(1 + \sqrt{1 + x^2/\tau}), \qquad \tau = Q^2/4M^2$$

$\xi_{th} \rightarrow \pi$ threshold, $\xi_0 \rightarrow$ nucleon pole ($x = 1$)

Extract magnetic form factor from JLab data on integral of F_2

(Niculescu et al, Phys. Rev. Lett. 85 (2000) 1186)



Proton magnetic form factor from local duality

R ratio from duality

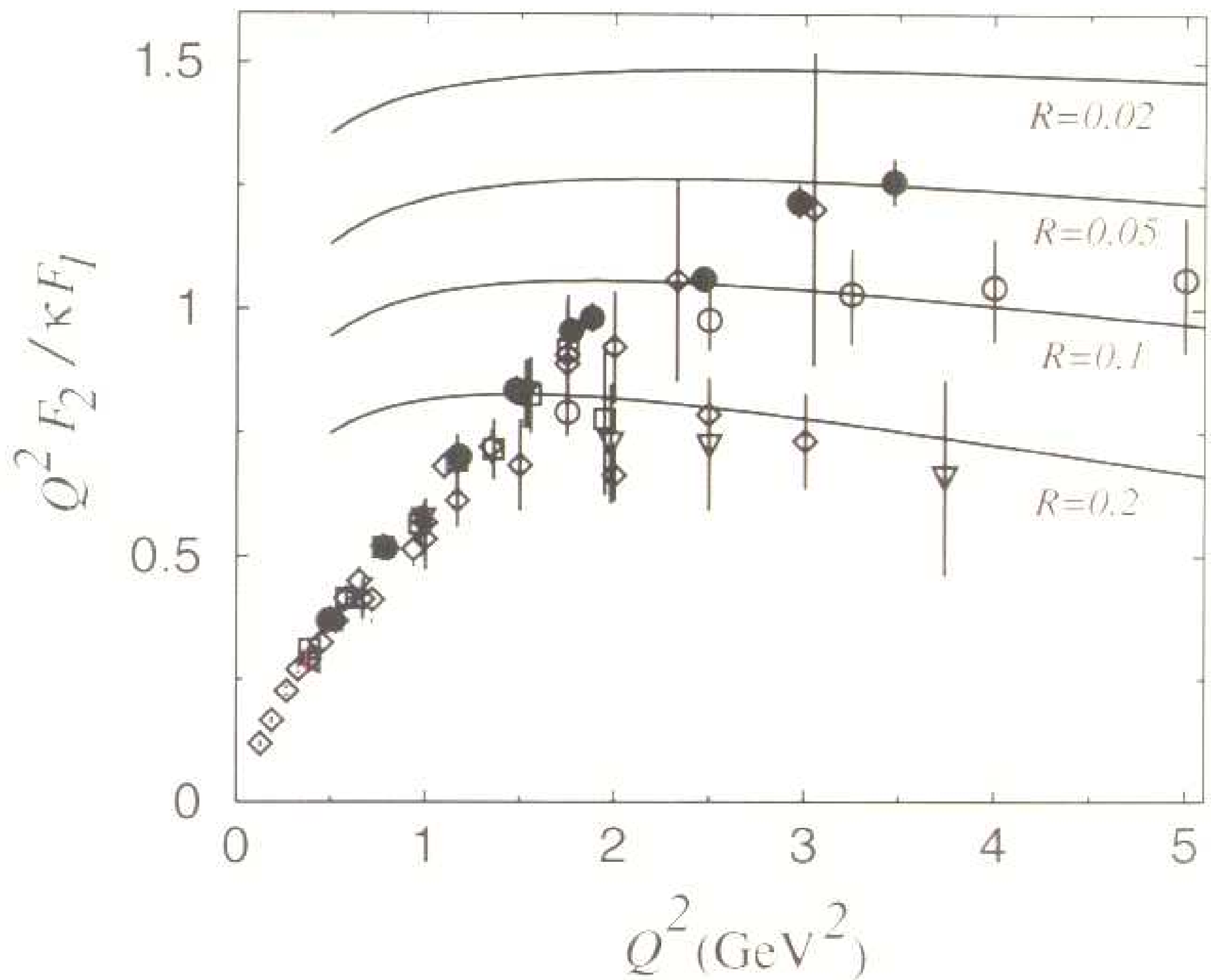
$$R = \frac{\sigma_L}{\sigma_T} = \left(1 + \frac{1}{\tau}\right)\frac{F_2(\xi, Q^2)}{2F_1(\xi, Q^2)} - 1$$

In terms of R the E/M form factor ratio is:

$$\frac{G_E}{G_M} = \sqrt{\tau R}$$

or in terms of Pauli & Dirac form factors:

$$\frac{F_2^{\mathrm{Pauli}}(Q^2)}{F_1^{\mathrm{Dirac}}(Q^2)} = \frac{(1+R)\tau - (1+\tau)\sqrt{\tau R}}{(\tau - R)\tau}$$



Duality relation between R and elastic (Pauli/Dirac) form factor ratio

Local Duality for the Pion

- charged pion form factor

  $\longleftrightarrow$ pion structure function at $x \approx 1$

$$F_\pi^2(Q^2) \approx \int_1^{\omega_t} d\omega\, F_2^\pi(\omega)$$

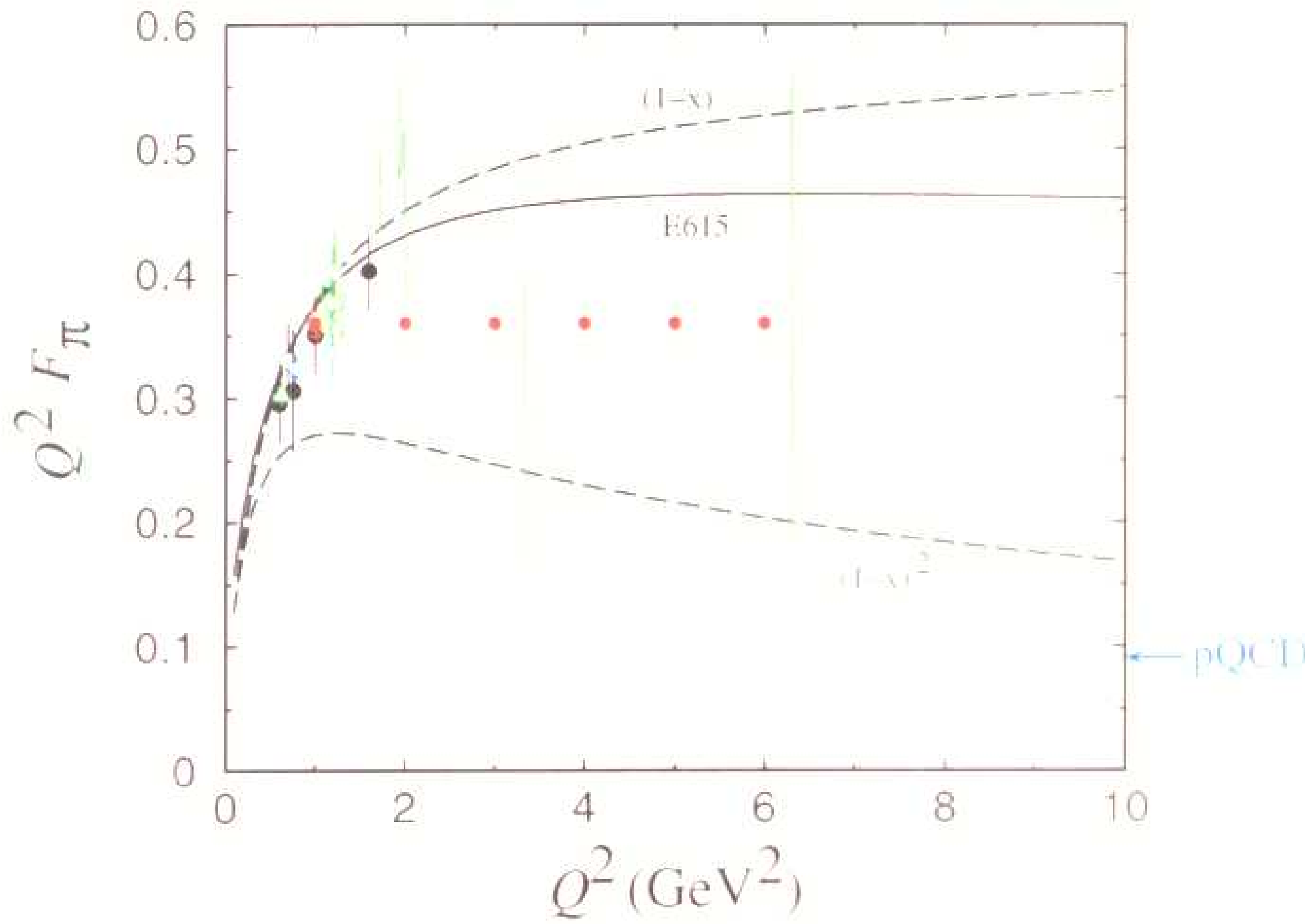
where $\omega = 1/x$, $\omega_t = 1 + (W_t^2 - m_\pi^2)/Q^2$

Moffat, Snell, 1971
Mahapatra, 1978

- compare with pion structure function measured in πN Drell-Yan production (NA10 @ CERN, E615 @ FNAL)

- shed light on $x_\pi \to 1$ controversy!

Pion Form Factor, pQCD and Duality



Pion form factor at large Q^2 related to
pion structure function at $x \to 1$
via quark-hadron duality

Drell, Yan, West 1970
Moffat, Snell 1971

- Additional suppression due to quark–hadron helicity mismatch

$$\Delta S_z = |S_z^{\text{quark}} - S_z^{\text{hadron}}|$$

$$q(x) \;\sim\; (1-x)^{2N-1+2\Delta S_z}$$

- For spinless pion, $N = 1$, $\Delta S_z = 1/2$

$$F_2^\pi \sim (1-x)^2$$

- Drell-Yan data consistently harder

$$F_2^\pi\Big|_{exp} \sim (1-x)^p$$

$p = 1.25 - 1.30$ (E615 @ FNAL)
$0.96 - 1.12$ (NA10 @ CERN)
1.17 (NA3 @ CERN)

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"

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

$$\Downarrow$$

"Fragmentation Duality"

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

Duality in Semi-inclusive Scattering

- Factorization of interaction and production vertices $\longrightarrow$

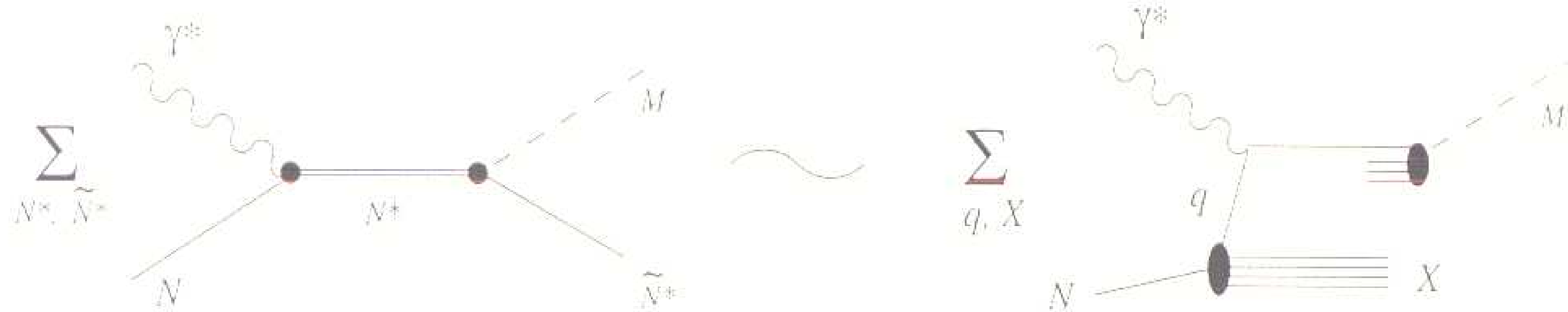
$$\frac{d^3\sigma}{dx\,dz\,dQ^2} \sim \sum_q e_q^2\, q(x, Q^2)\, D_q(z, Q^2)$$

- Duality for fragmentation functions?

  $\longrightarrow$ *How do resonances build up semi-inclusive scaling curve?*

- Essential for flavor and spin separation

DUALITY IN MESON PRODUCTION



$$\sum_{N^*, \tilde{N}^*} F_{\gamma N \to N^*}(Q^2, W^2) \; \mathcal{D}_{N^* \to \tilde{N}^* M}(W^2, \tilde{W}^2) \qquad \sum_q e_q^2 \, q(x) \, D_{q \to M}(z)$$

TRANSITION FORM FACTOR

DECAY AMPLITUDE

Duality in Semi-Inclusive π Production

Non-relativistic quark model predictions for production amplitude

$$F(\gamma N \to \pi X) = \sum_{W'=56,70} F(\gamma N \to \pi W')$$

Relative strengths for different channels given by SU(6) couplings

Close, Isgur (2001)

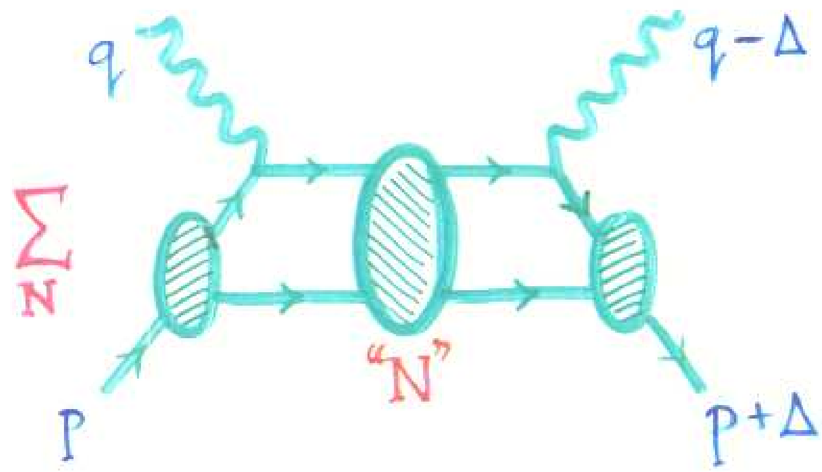
W'	$\gamma p \to \pi^+$	$\gamma p \to \pi^-$	$\gamma n \to \pi^+$	$\gamma n \to \pi^-$
$56; 8$	100	0	0	25
$56; 10$	32	24	96	8
$70;^2 8$	64	0	0	16
$70;^4 8$	16	0	0	4
$70; 10$	4	3	12	1
$TOTAL$	216	27	108	54

Duality in DVCS

Toy model: two quarks in harmonic oscillator potential (Close, Zhao 2002)

GPD given by sum over (infinitely narrow) resonances:

$$H(\nu, q, \Delta, t) \sim \sum_{N=0}^{\infty} (e_1 \pm e_2)^2 \, \delta(\nu + E_0 - E_N) \times F_{0N}(\vec{q}) \, F_{N0}(\vec{q} - \vec{\Delta})$$



In limit $Q^2 \to \infty$, GPD becomes smooth (scaling) function!

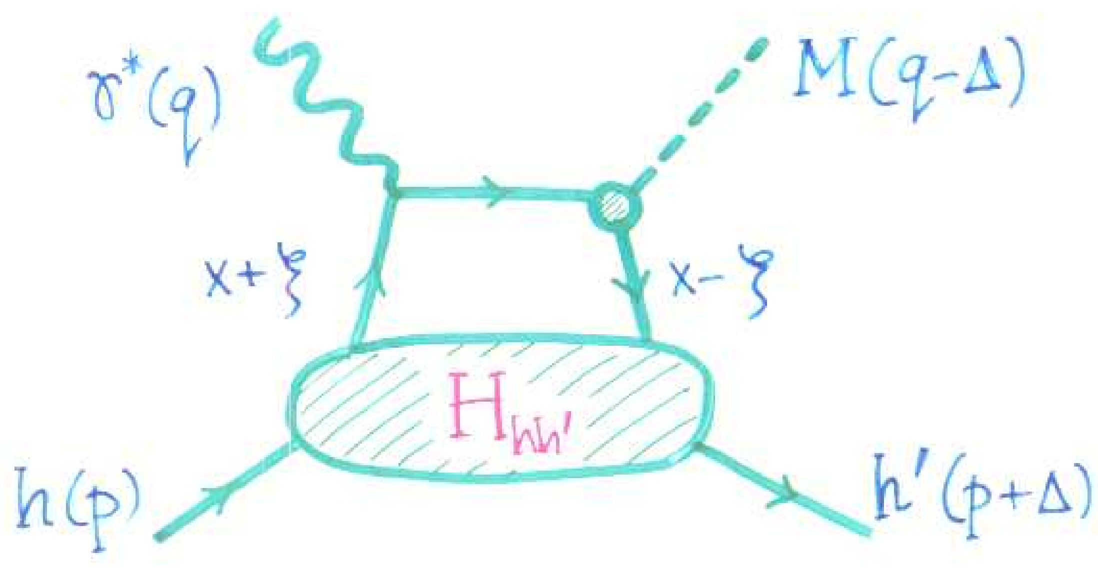
$$H(x, \xi, t) = (e_1^2 + e_2^2) \frac{(x - \xi)(x + \xi)}{x^2} \, q(x) \, F_1(t)$$

Generalized Parton Distributions

Unifying framework for correlating vast array of observables: *elastic form factors, transition form factors, exclusive meson production, DVCS, RCS, DIS structure functions, ...*

$$\longrightarrow H_{hh'}(x,\xi,t) \sim \sum_X \psi(h(p) \to q((x+\xi)p) + X)$$

$$\times\, \psi^*(h'(p') \to q((x-\xi)p') + X)$$



- Powerful tool for studying pre-asymptotic regime

- Moments:

$$\longrightarrow \int dx\ H_{hh'}(x,\xi,t) = F_{hh'}(t)$$

elastic & transition form factors

$$\longrightarrow \int dx\ x\,(H_{hh}(x,\xi,t=0) + E_{hh}(x,\xi,t=0)) = \frac{1}{2}J_h^q$$

total angular momentum of quarks

- Forward limit:

$$\longrightarrow H_{hh}(x,\xi=0,t=0) = q_h(x)$$

deep-inelastic parton distributions

- Forces us to confront models of QCD with broad range of data

Nuclear Medium Dependence

- Fermi motion of nucleons in nucleus
  $\longrightarrow$ duality/scaling should set in earlier

  Arrington et al. 2001

- Earlier onset of duality/scaling for meson production?
  $\longrightarrow$ precocious factorization?

  Eides et al. 1999

  (c.f. HERMES data)

  $\longrightarrow$ nuclear filtering of configurations with large quark separation?

  Ralston, Pire et al. 2000

  $\longrightarrow$ color transparency a necessary
  — but not sufficient —
  condition for factorization
  (& access to nuclear GPD's)

  Strikman 2000

- Color transparency should be seen eventually also in $A(e, e'p)$
  $\longrightarrow$ pQCD prediction (if there exist point like configurations in nucleus)
  $\longrightarrow$ scale of onset unknown

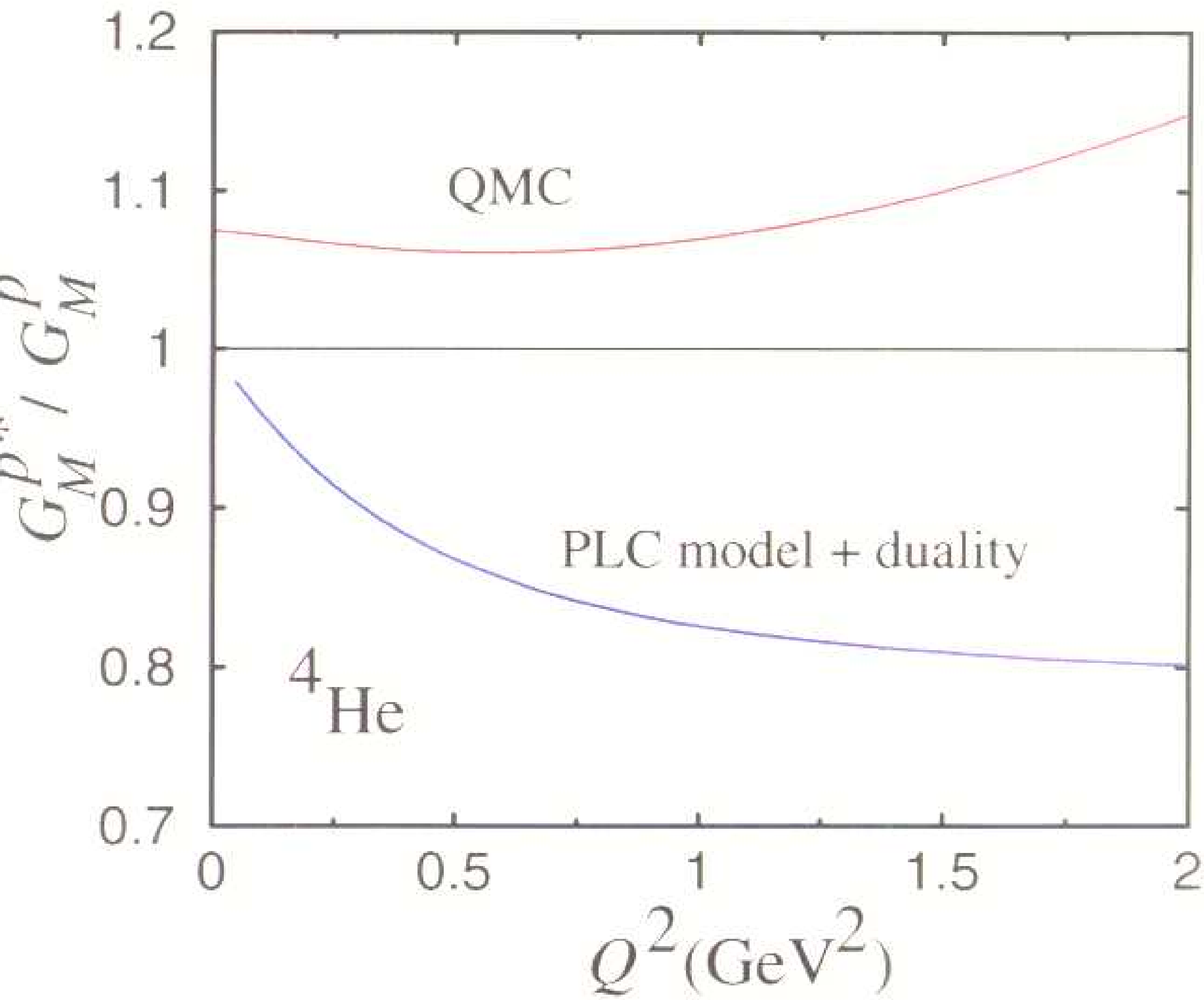
- Evidence for PLC's in other observables?
  $\longrightarrow$ nuclear EMC effect: deformation of intrinsic nucleon structure function

  Frankfurt, Strikman 1988

  WM, Sargsian, Strikman 1996

  $\longrightarrow$ use local duality to relate to medium modification of form factors in $A(\vec{e}, e'\vec{p})$

  WM, Tsushima, Thomas 2001



Ratio of in-medium to free proton magnetic form factors

WM, Tsushima, Thomas
nucl-th/0110071

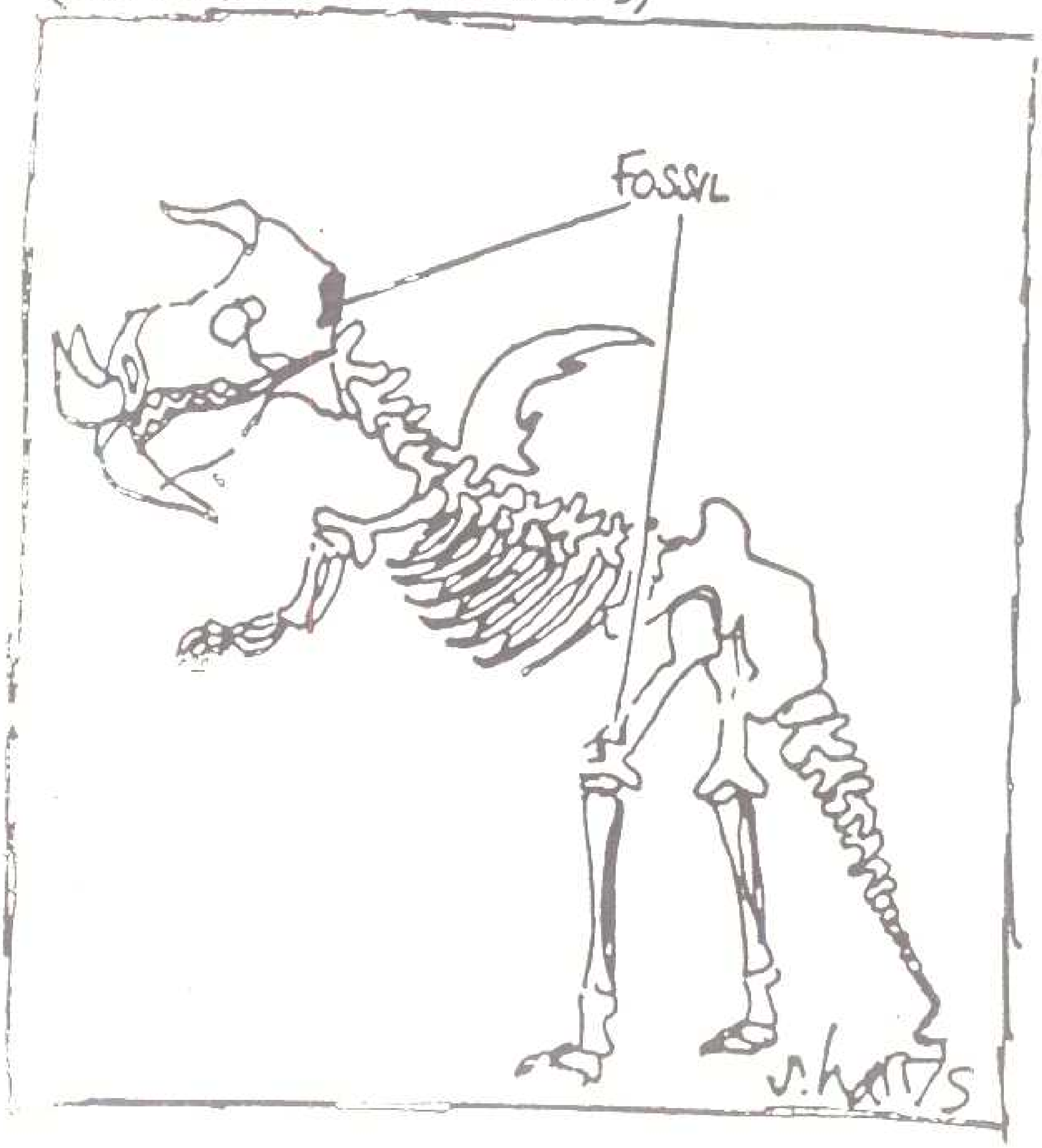
Synopsis

- Understanding strongly interacting matter requires detailed knowledge of *basic building blocks* of hadrons and nuclei $\longrightarrow$ quark & gluon wave functions

- Reconstructing structure of matter from quarks & gluons requires measurement of wide range of observables over broad kinematic regions

- Hall C @ 12 GeV, with HMS-SHMS (high $\mathcal{L}$, small θ, high $\vec{p}$) will uniquely determine critical inputs for solving the puzzle

SKELETON OF NEWLY DISCOVERED DINOSAUR SPECIES
RECONSTRUCTED FROM TWO FOSSILS
(DISPUTED BY SOME EXPERTS)



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