Users Group Symposium

Highlights of the First 7 Years

June 12, 2003

Structure Functions of the Nucleon:

the Resonance-Scaling Frontier

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$\boxed{\text{Outline}}$

- Introduction
  $\longrightarrow$ definitions
  $\longrightarrow$ operator product expansion (& beyond)

- Structure functions in the resonance region
  $\longrightarrow$ Bloom-Gilman duality
  $\longrightarrow$ onset of scaling
  (coherent $\longrightarrow$ incoherent transition)
  $\longrightarrow$ duality violation & higher twists
  $\longrightarrow$ transition to $Q^2 = 0$

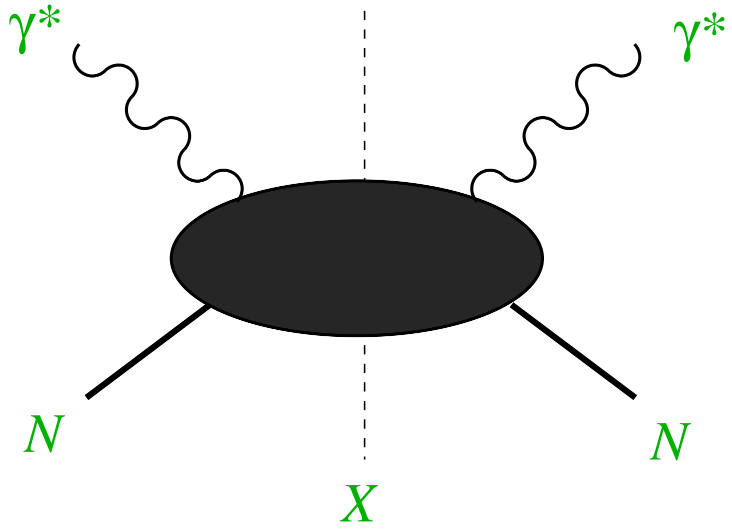
- Structure functions at high x
  $\longrightarrow$ valence quarks in the $x \to 1$ limit
  $\longrightarrow$ sea quark asymmetries
  $\longrightarrow$ transverse structure

- Structure functions on the lattice
  $\longrightarrow$ moments of parton distributions

- Conclusions & outlook

Introduction

Inclusive cross section for $eN \to eX$
$\longrightarrow$ forward Compton scattering amplitude



Hadronic tensor

$$W_{\mu\nu} = \sum_X \langle X|J_\mu(z)|N\rangle \, \langle N|J_\nu(0)|X\rangle \, \delta^4(p+q-p_X)$$
$$= \int d^4z \, e^{iq\cdot z} \, \langle N|J_\mu(z)J_\nu(0)|N\rangle$$

using completeness (sum over ALL states X)

$$\sum_X |X\rangle\langle X| = 1$$

"duality"

- Wilson Operator Product Expansion

Expand product of currents $J(z)J(0)$ in a series of (nonperturbative) local operators $\widehat{\mathcal{O}}$ and (perturbative) coefficient functions C_n

$$J(z)J(0) \;\sim\; \sum_n C_n(z^2)\; z^{\mu_1} z^{\mu_2} \ldots z^{\mu_n}\; \widehat{\mathcal{O}}_{\mu_1\mu_2\cdots\mu_n}$$

- Matrix elements of $\widehat{\mathcal{O}}_{\mu_1\mu_2\cdots\mu_n}$

$$\langle N|\widehat{\mathcal{O}}_{\mu_1\mu_2\cdots\mu_n}|N\rangle \;=\; \mathcal{A}_n(\mu^2)\; p_{\mu_1} p_{\mu_2} \cdots p_{\mu_n} \;-\; \text{traces}$$

- Moments of structure function $F(x, Q^2)$

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

$$= \sum_i \tilde{C}_n^i(Q^2)\; \mathcal{A}_n^i(Q^2/\mu^2)$$

where $\tilde{C}_n(Q^2)$ is Fourier transform of $C_n(z^2)$

- Reconstruct structure function from moments via inverse Mellin transform

- Fourier transform of $J_\mu(z) J_\nu(0)$

$\longrightarrow$ series in $\left(\frac{1}{Q^2}\right)^{d-n-2}$, where $\tau \equiv d - n$

"twist"

- Twist expansion of moments

$$
\begin{aligned}
M_n(Q^2) &= \sum_\tau \frac{A_n^{(\tau)}}{(Q^2)^{\tau-2}} \\
&= A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots
\end{aligned}
$$

- $A_n^{(2)}$ = leading twist

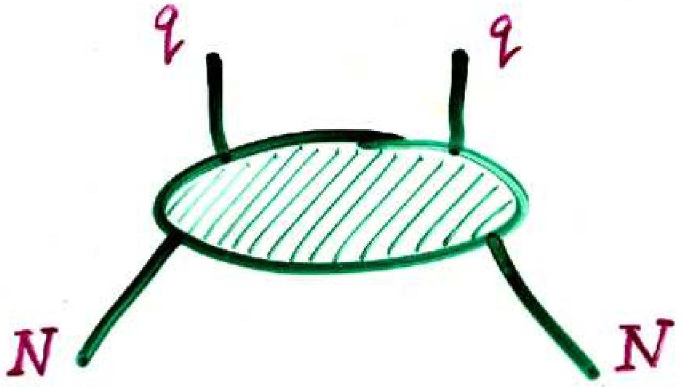
$e.g. \quad \bar{\psi}\, \gamma_\mu\, \psi$

$\longrightarrow$ *free quark scattering*

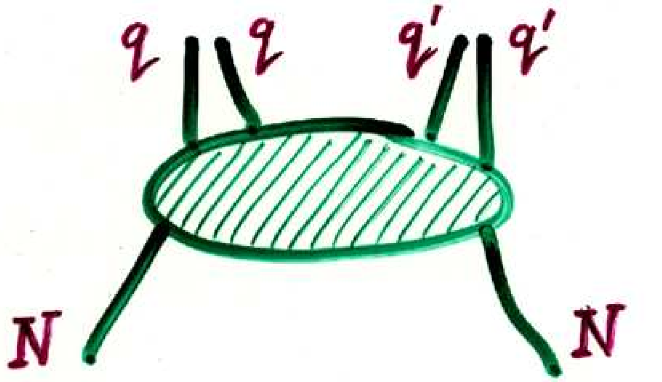
- $A_n^{(\tau>2)}$ = higher twists

$e.g.\ \tau = 4 \quad \bar{\psi}\, \gamma_\mu\, \psi\, \bar{\psi}\, \gamma_\nu\, \psi$ or $\bar{\psi}\, \tilde{G}_{\mu\nu} \gamma^\nu\, \psi$

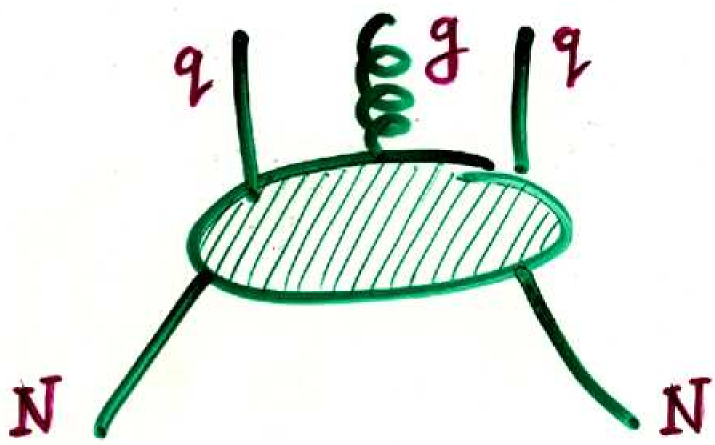
$\longrightarrow$ *multi-quark or quark-gluon correlations*



$\tau = 2$



$\tau > 2$



- Soft matrix elements $A_n^{(\tau)}$ also evolve perturbatively with Q^2

$\longrightarrow$ obey renormalization group equations
e.g. τ=2 nonsinglet

$$A_n^{(2)}(Q^2) \;=\; A_n^{(2)}(Q_0^2)\;\left(\frac{\alpha_s(Q^2)}{\alpha_s(Q_0^2)}\right)^{\gamma_n/2\beta}$$

where γ_n = anomalous dimension

- Extraction of leading twists

$\longrightarrow$ need high Q^2

$\longrightarrow$ compare data with calculated α_s dependence

- Extraction of higher twists

$\longrightarrow$ deviations from α_s dependence

$\longrightarrow$ need intermediate Q^2

Structure Functions & Resonances

- Existing JLab data mostly in the resonance region, $W \leq 2$ GeV

$\Rightarrow$ Perception: pQCD analysis is not valid in resonance region

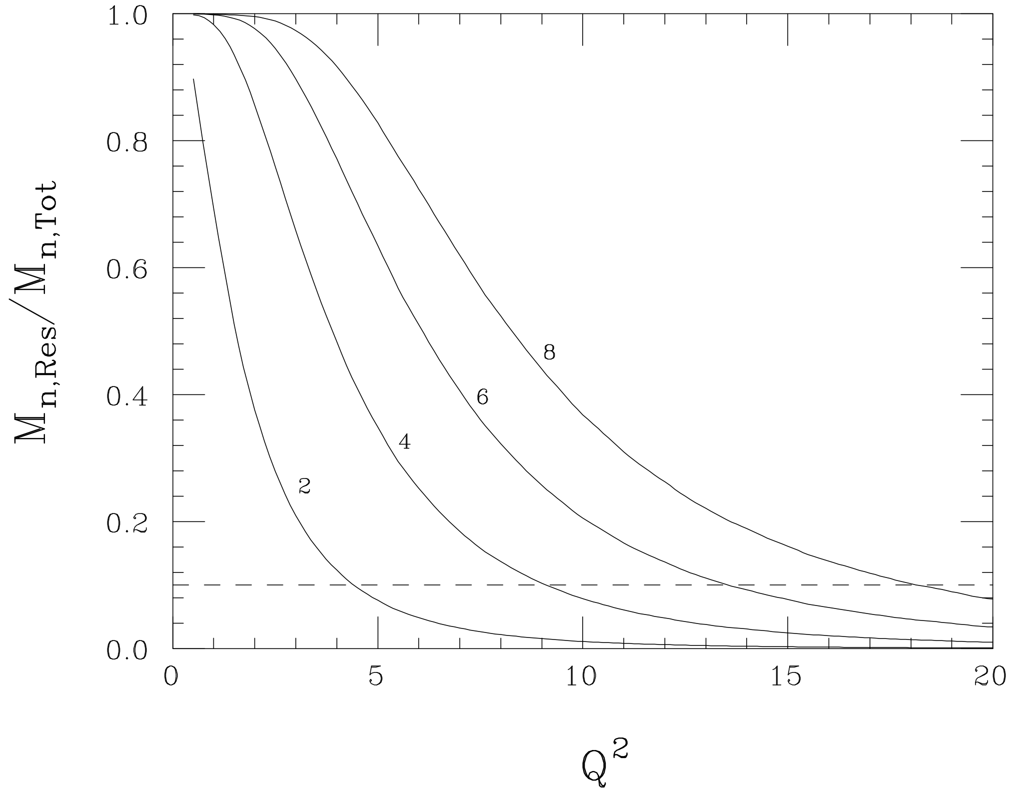
$\Rightarrow$ Fact: partonic interpretation of *moments* *DOES* include resonance region!

$\longrightarrow$ implicit role of *quark-hadron duality*

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

BUT resonances and DIS continuum conspire to produce only $\sim$ 10% higher twist contribution

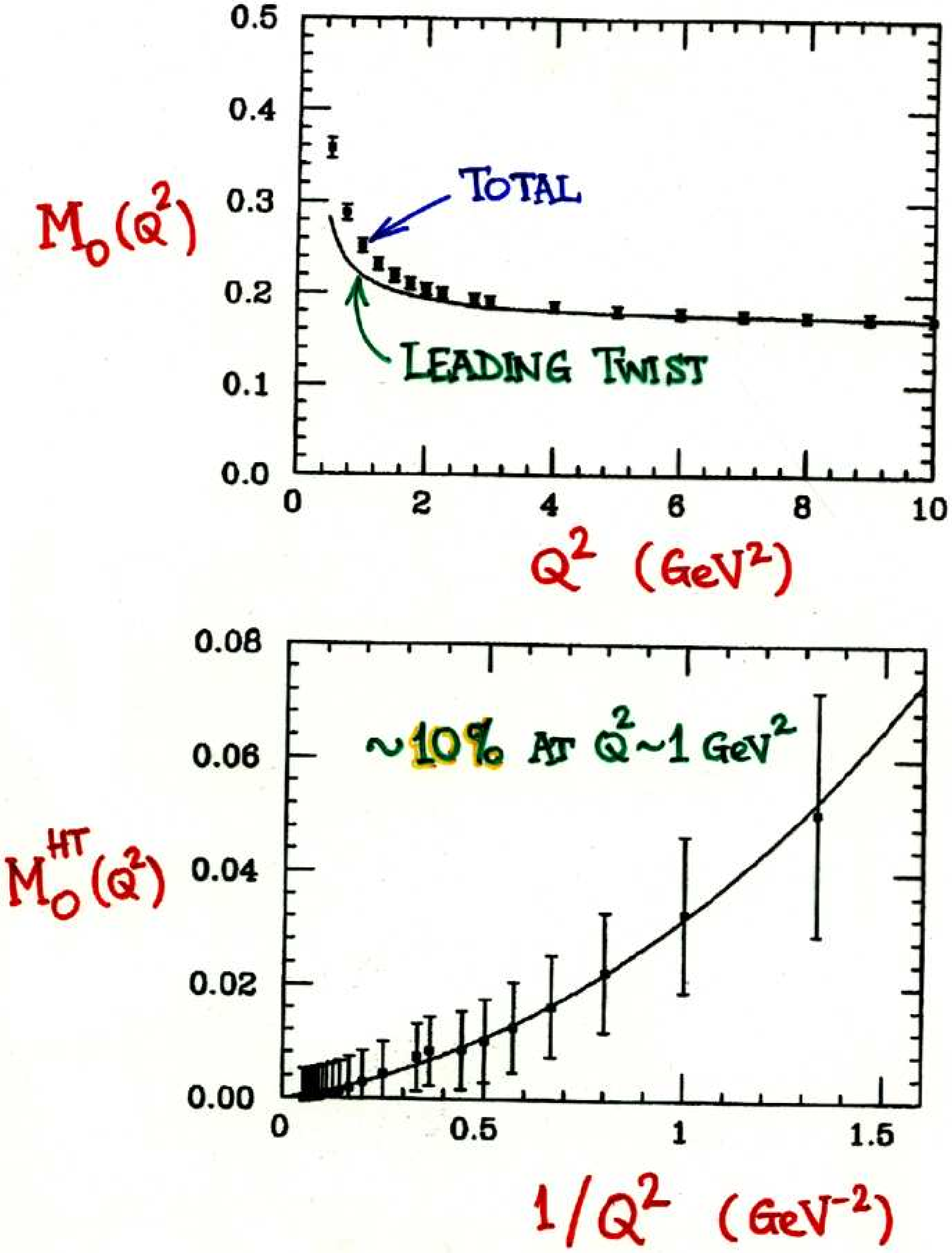
$\longrightarrow$ *Resonances are an integral part of deep inelastic structure function !*



Relative contribution of resonance region ($W < 2$ GeV) to n-th moment of F_2^p

Ji, Unrau
Phys. Rev. D 52 (1995) 72

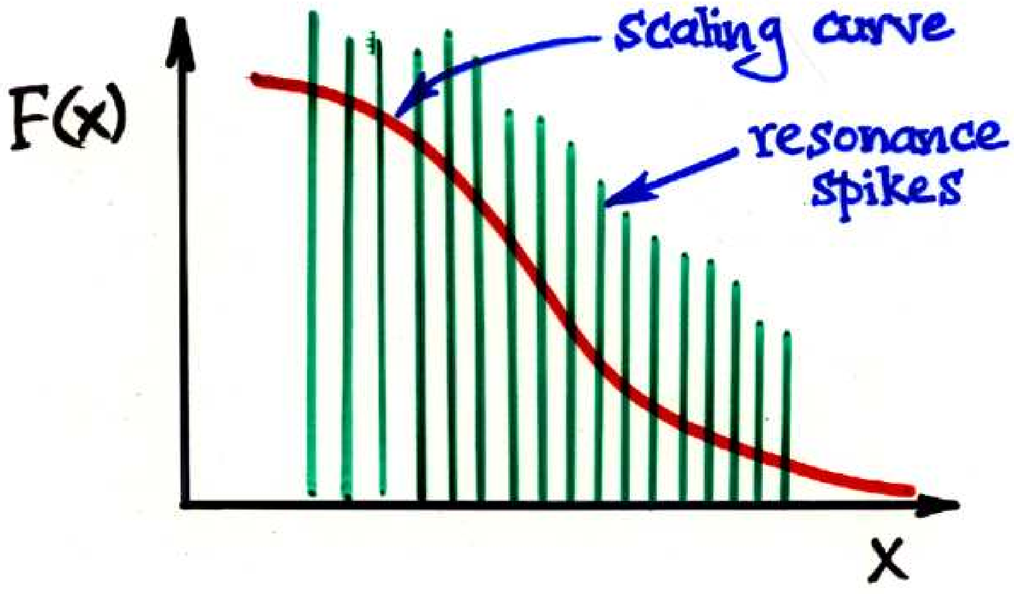
Ji, Unrau 1995



$\boxed{\text{QCD with } N_c \to \infty}$

- Hadrons as infintely narrow resonances

- Structure functions in scaling region built up *entirely* from resonances



- Distinction between "resonance" and "deep inelastic" regions is spurious!

Isgur et al.
Phys. Rev. D 64 (2001) 054005

$\boxed{\text{Quark-Hadron Duality}}$

Complementarity

between quark and hadron

descriptions of observables

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

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

Bloom-Gilman Duality

Individual resonances are
strongly Q^2 dependent

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

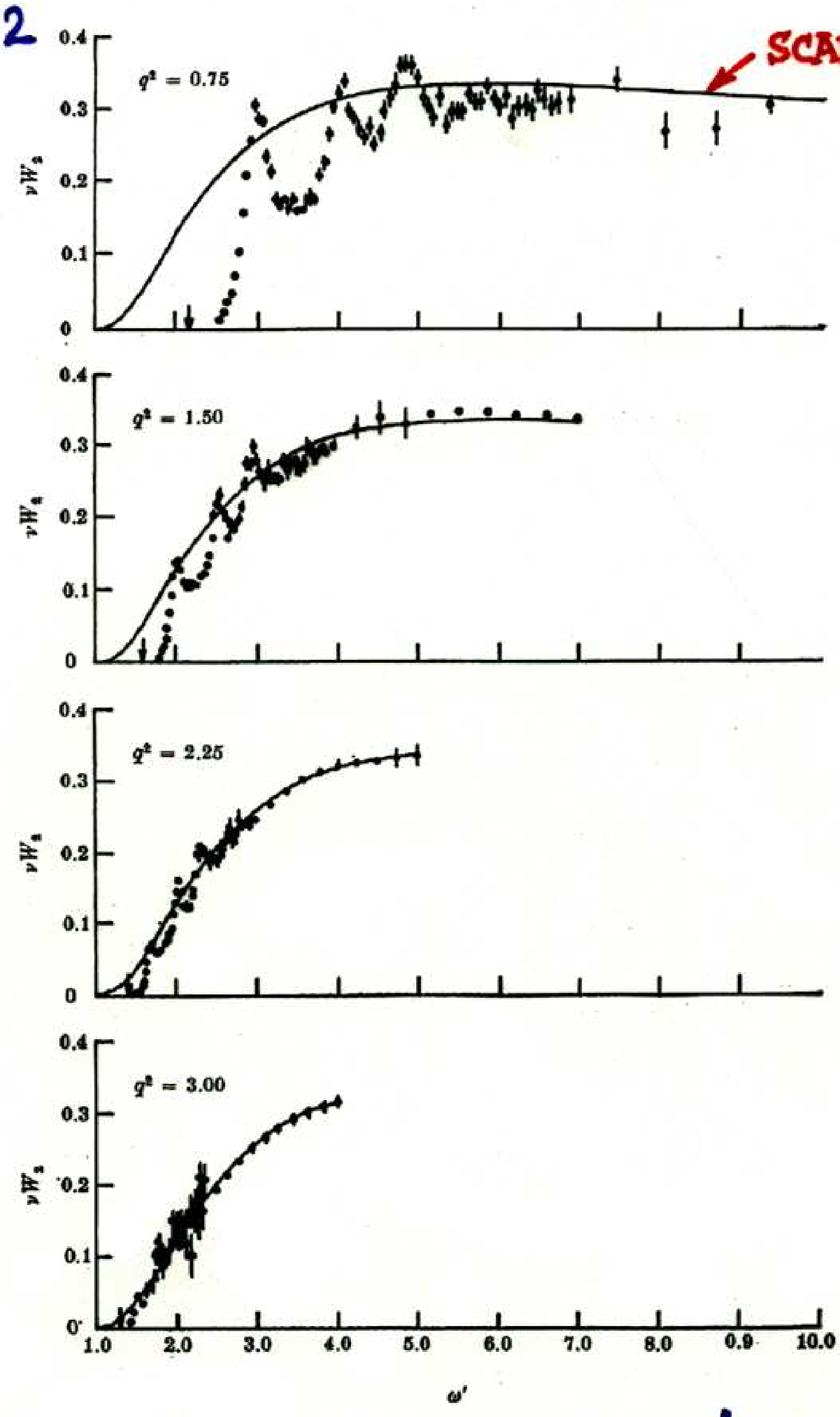
$\Rightarrow$ resembles scaling (leading twist)
structure function

(Bloom, Gilman 1970)

BLOOM - GILMAN 1970

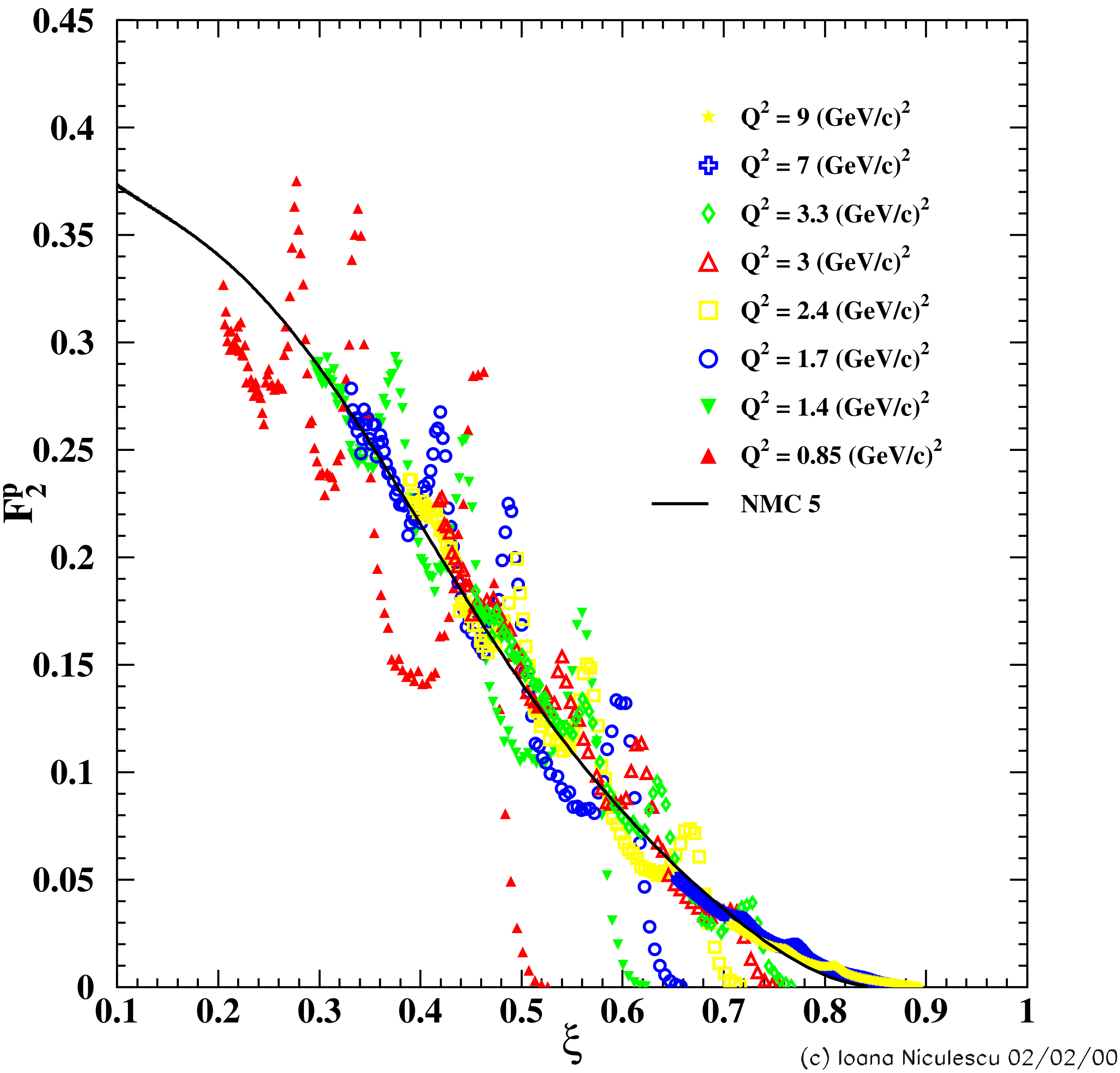
F_2^p

SCALING CURVE



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

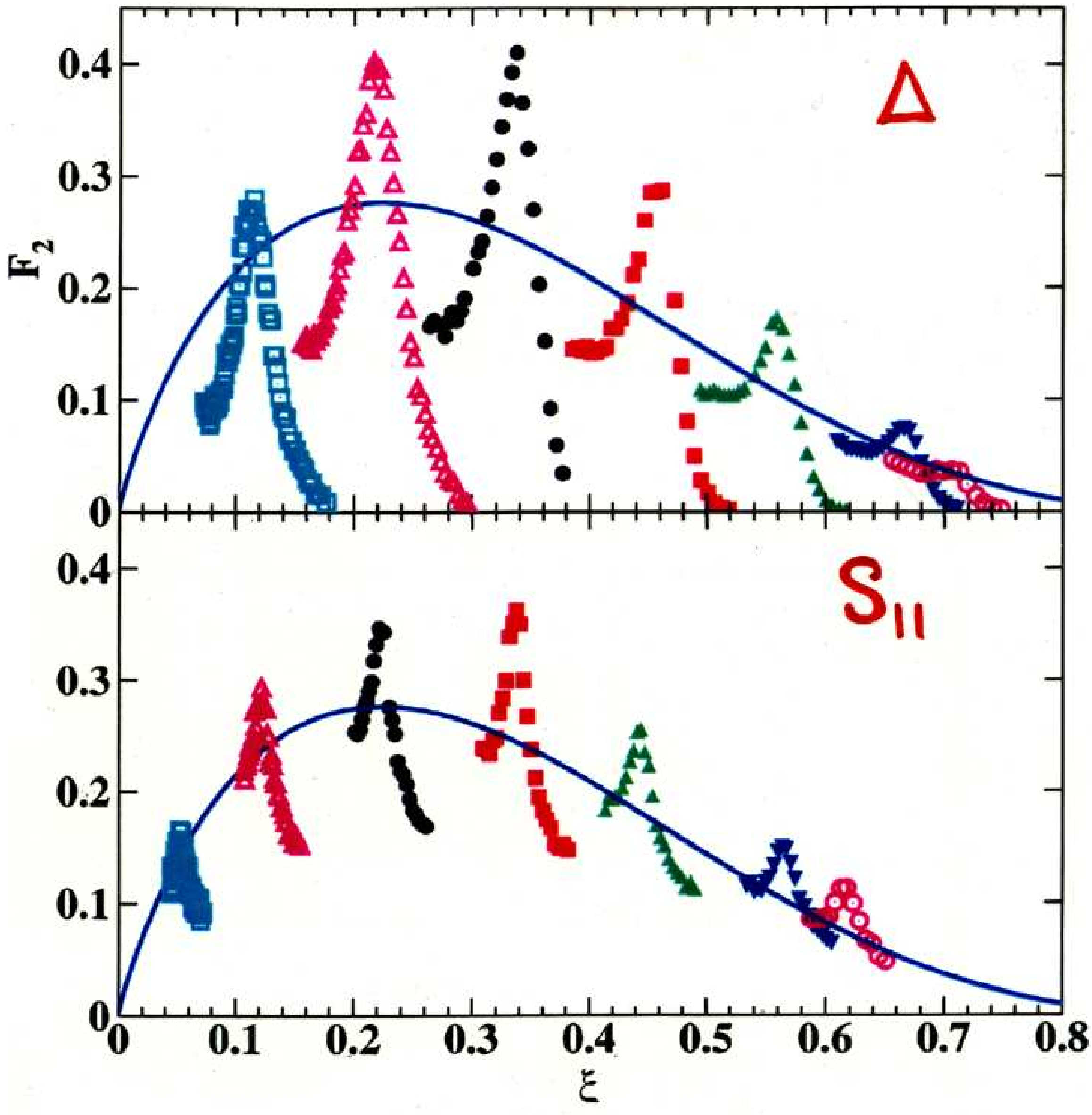
Niculescu et al.
Phys. Rev. Lett. 85 (2000) 1182, 1186



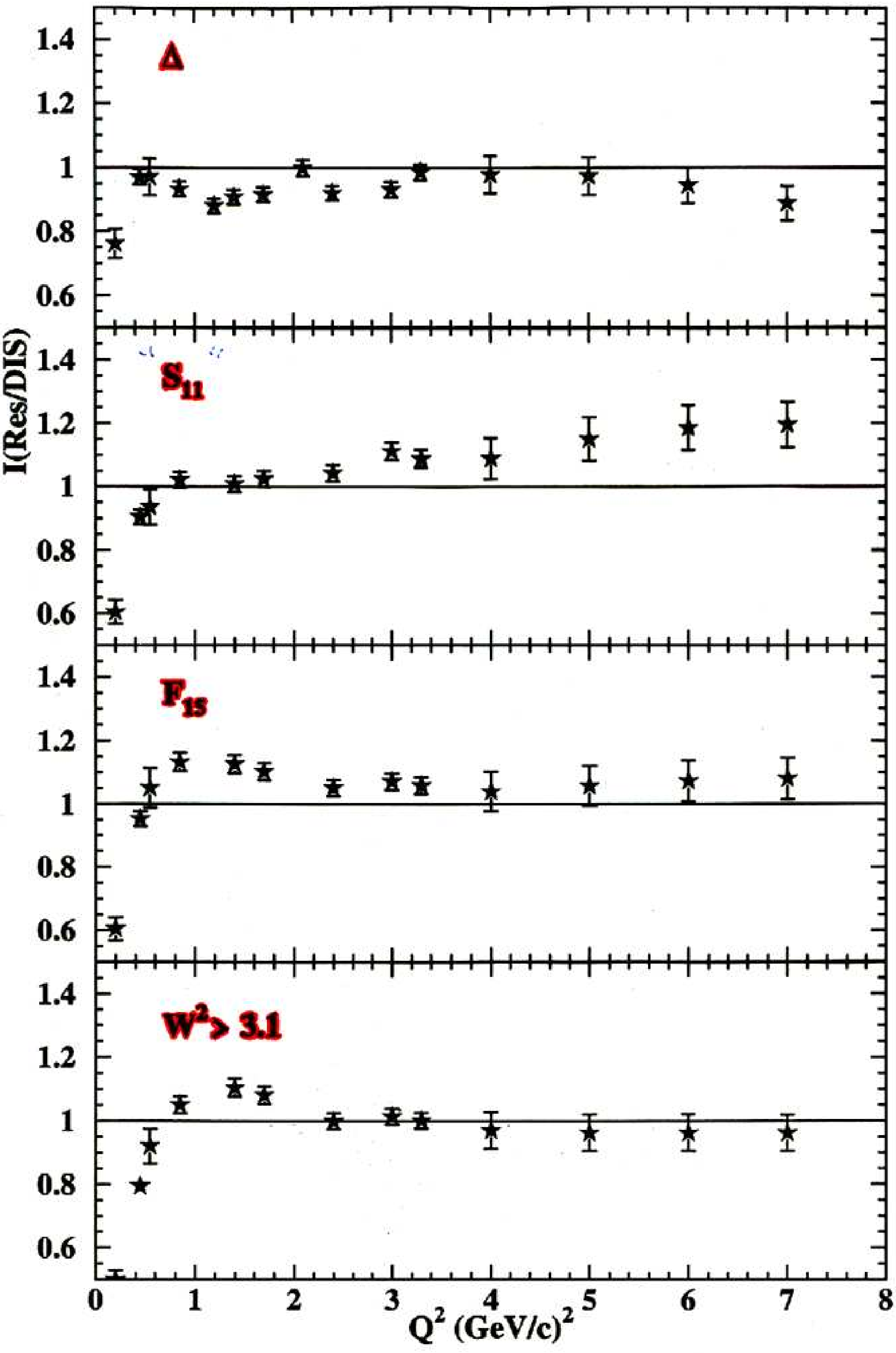
$$\xi = 2x/(1+\sqrt{1+4x^2M^2/Q^2})$$

Nachtmann scaling variable

LOCAL DUALITY

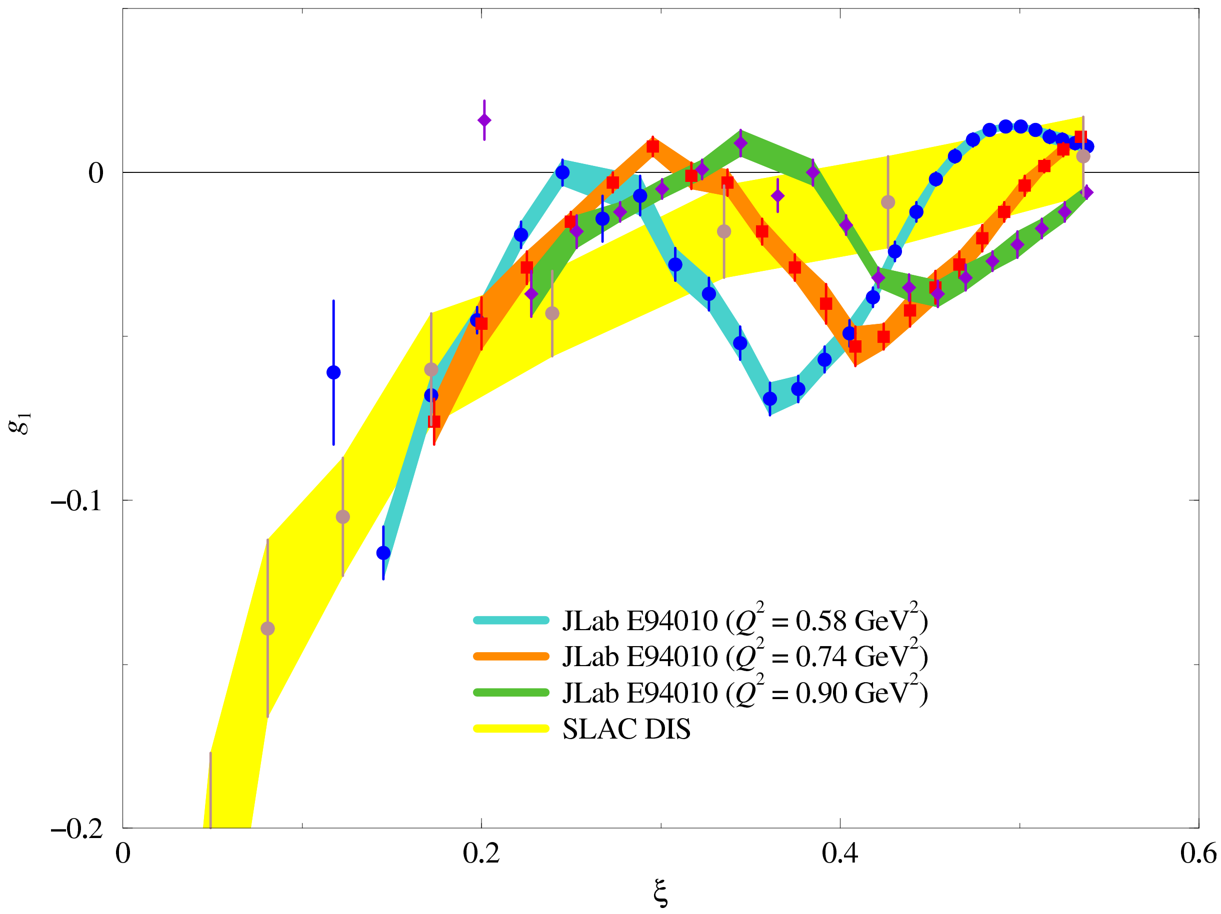


$$\xi = 2x \Big/ \left(1 + \sqrt{1 + 4x^2M^2/Q^2}\right)$$



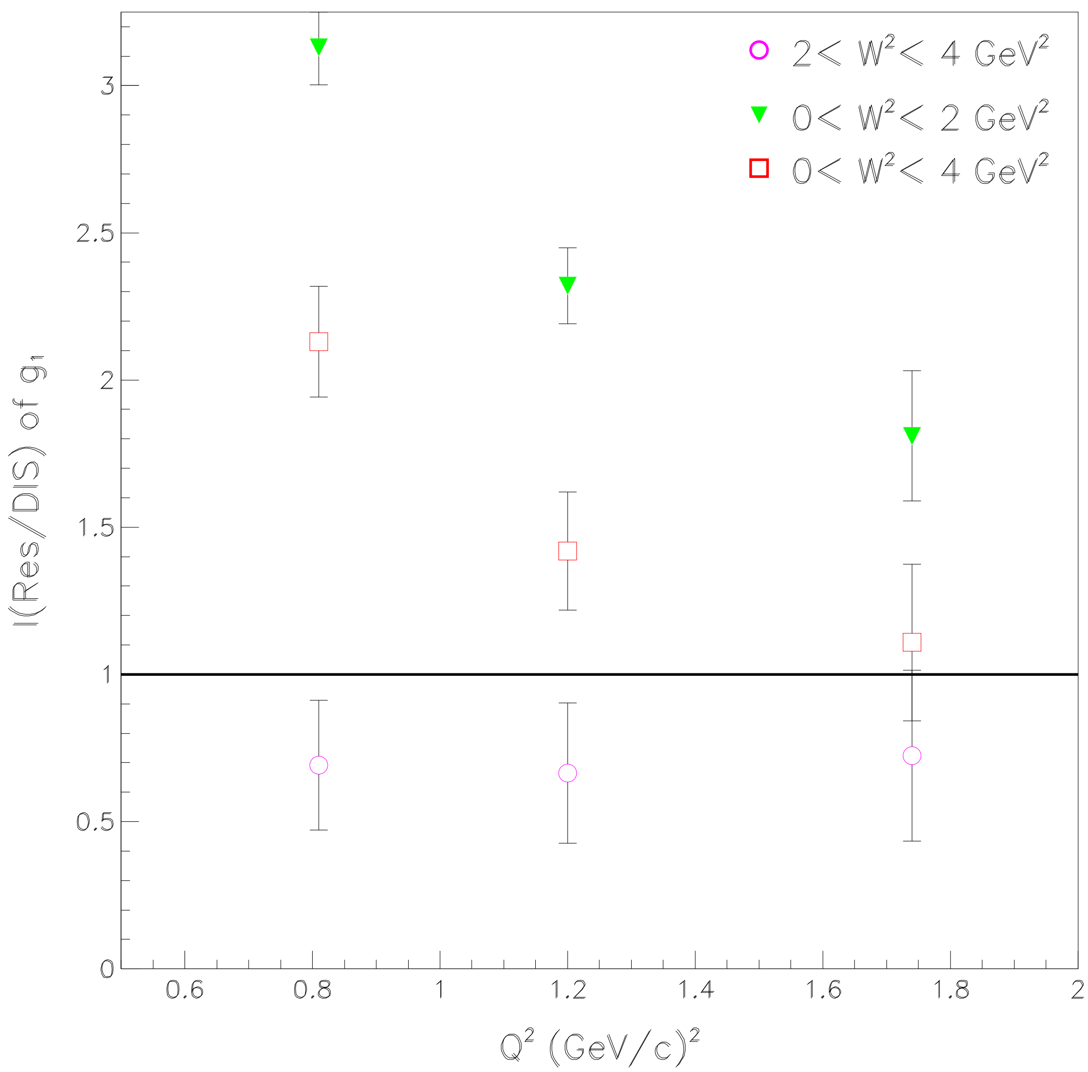
Δ
S_{11}
F_{15}
$W^2 > 3.1$
I(Res/DIS)
Q^2 (GeV/c)^2

Hall A preliminary



Duality in the neutron (^{3}He) g_1 structure function

Hall C preliminary



Relative contribution to g_1^p integral from low-W region

Bloom-Gilman Duality & the OPE

Twist expansion $\longrightarrow$ moments of structure function in powers of $1/Q^2$

$$
\begin{aligned}
M_n(Q^2) &= \int_0^1 dx\; x^{n-2}\; F_2(x,Q^2) \\
&= A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots
\end{aligned}
$$

If moment $M_n(Q^2) \approx$ independent of Q^2

$\longrightarrow$ higher twist terms $A_n^{(\tau>2)}$ intrinsically small or cancel

Duality $\Leftrightarrow$ *suppression of higher twists*

De Rujula, Georgi, Politzer

Ann. Phys. 103 (1975) 315

Duality and the OPE

- OPE allows one to *systematically* identify and interpret duality in terms of *size of higher twists*

BUT!

- Does not *explain* size of high twists, nor how resonances interfere *constructively* or *destructively*

- Need insight from nonperturbative QCD to understand *origin of duality*

  $\longrightarrow$ *either* calculate leading & higher twist matrix elements on the lattice

  $\longrightarrow$ *or* use models of QCD

What are higher twists good for, anyway?

Noise or signal?

First moment of proton g_1 structure function

$$\Gamma_1(Q^2) = \int_0^1 dx\ g_1(x, Q^2)$$

$$= \mu_2 + \frac{\mu_4}{Q^2} + \frac{\mu_6}{Q^4} + \cdots$$

$\longrightarrow$ leading twist ($\tau = 2$)

$$\mu_2 = \frac{1}{12} g_A + \frac{1}{36} g_8 + \frac{1}{9} \Delta\Sigma$$

$\longrightarrow$ higher twist

$$\mu_4 = \frac{1}{9} M^2 \ (a_2 + 4d_2 + 4f_2)$$

$a_2 \to$ target mass correction

d_2, f_2 related to *color polarizabilities*

Color polarizabilities

Twist-3 and 4 matrix elements from components of dual field strength tensor

$$8\ d_2\ S^\mu \ = \ \langle N|(\vec{j}_a \times \vec{E}_a)^\mu \ + \ 2 j_a^0 B_a^\mu |N\rangle$$

$$2\ f_2\ S^\mu \ = \ \langle N|(\vec{j}_a \times \vec{E}_a)^\mu \ - \ j_a^0 B_a^\mu |N\rangle$$

quark current $j_a^\alpha = -g\bar{\psi}\gamma^\alpha t_a \psi$

E_a^μ and B_a^μ color electric and magnetic fields

- Color electric and magnetic polarizabilities

$$\chi_E\ S^\mu \ \equiv \ \langle N|(\vec{j}_a \times \vec{E}_a)^\mu |N\rangle$$

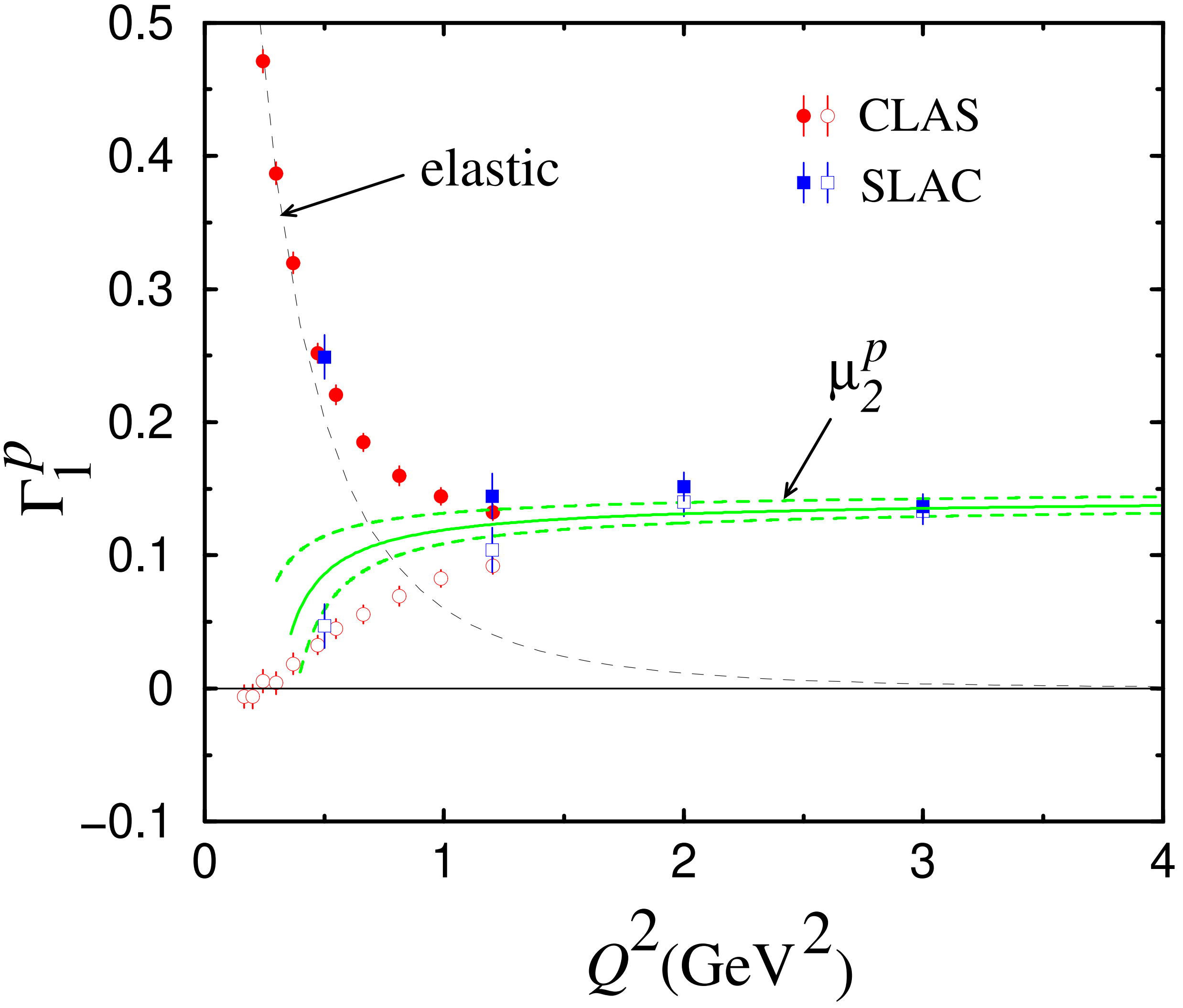
$$\chi_B\ S^\mu \ \equiv \ \langle N| j_a^0\ B_a^\mu |N\rangle$$

- In terms of d_2 and f_2

$$\chi_E \ = \ \frac{2}{3}(4 d_2 \ + \ 2 f_2)$$

$$\chi_B \ = \ \frac{2}{3}(4 d_2 \ - \ f_2)$$

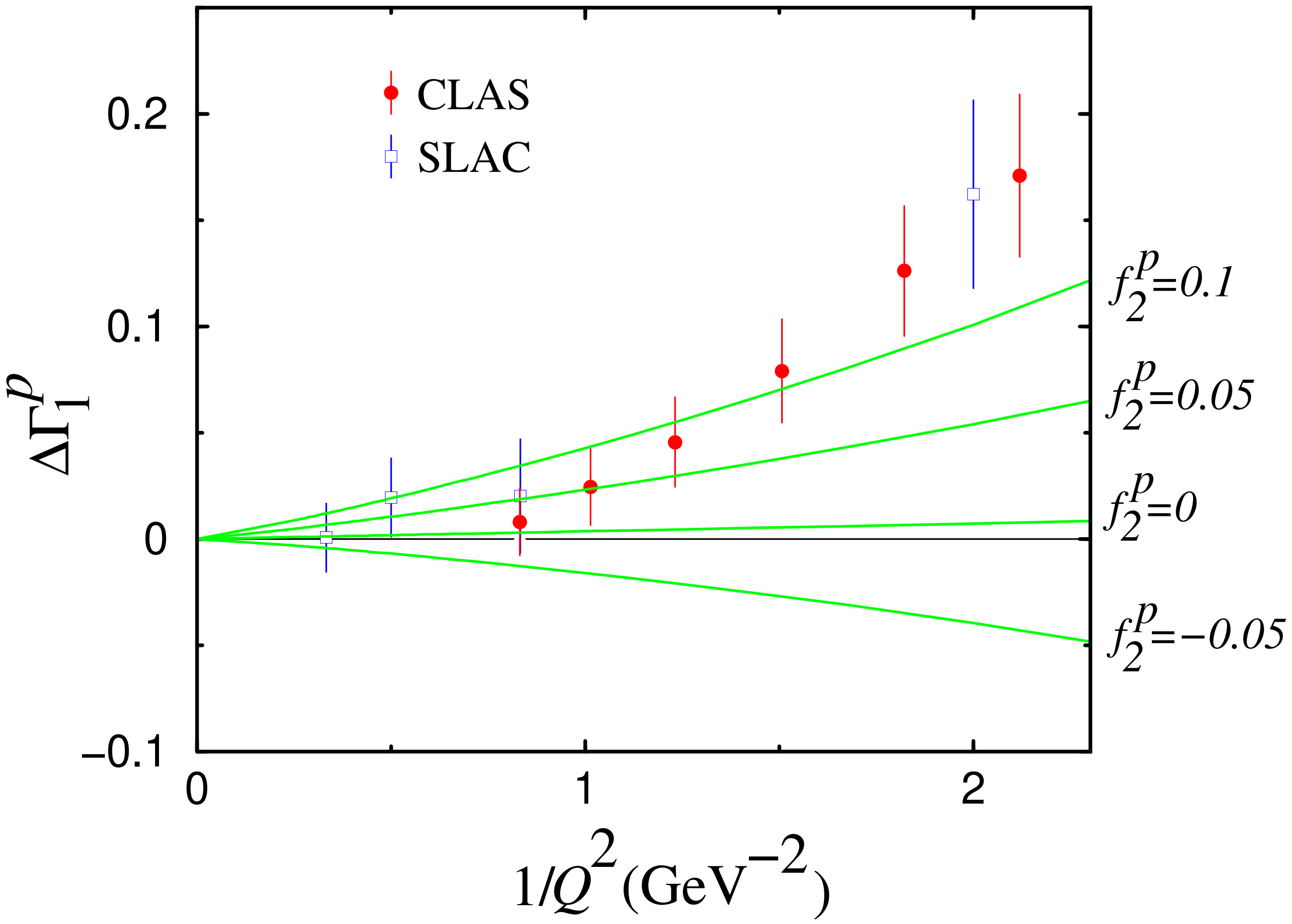
Mankiewicz, Schafer *et al.*; Balitsky, Braun *et al.* 1995 *preliminary*



open symbols ⟶ inelastic only

filled symbols ⟶ inelastic + elastic

Higher twist contribution $\Delta\Gamma_1^p \equiv \Gamma_1^p - \mu_2^p$



Preliminary results: $f_2 = 0.05(5)$

$\Rightarrow \quad \chi_E \approx 0.08, \quad \chi_B \approx -0.02$

Color magnetic field antiparallel to proton spin?

$\boxed{\textbf{Transition to } Q^2 = 0}$

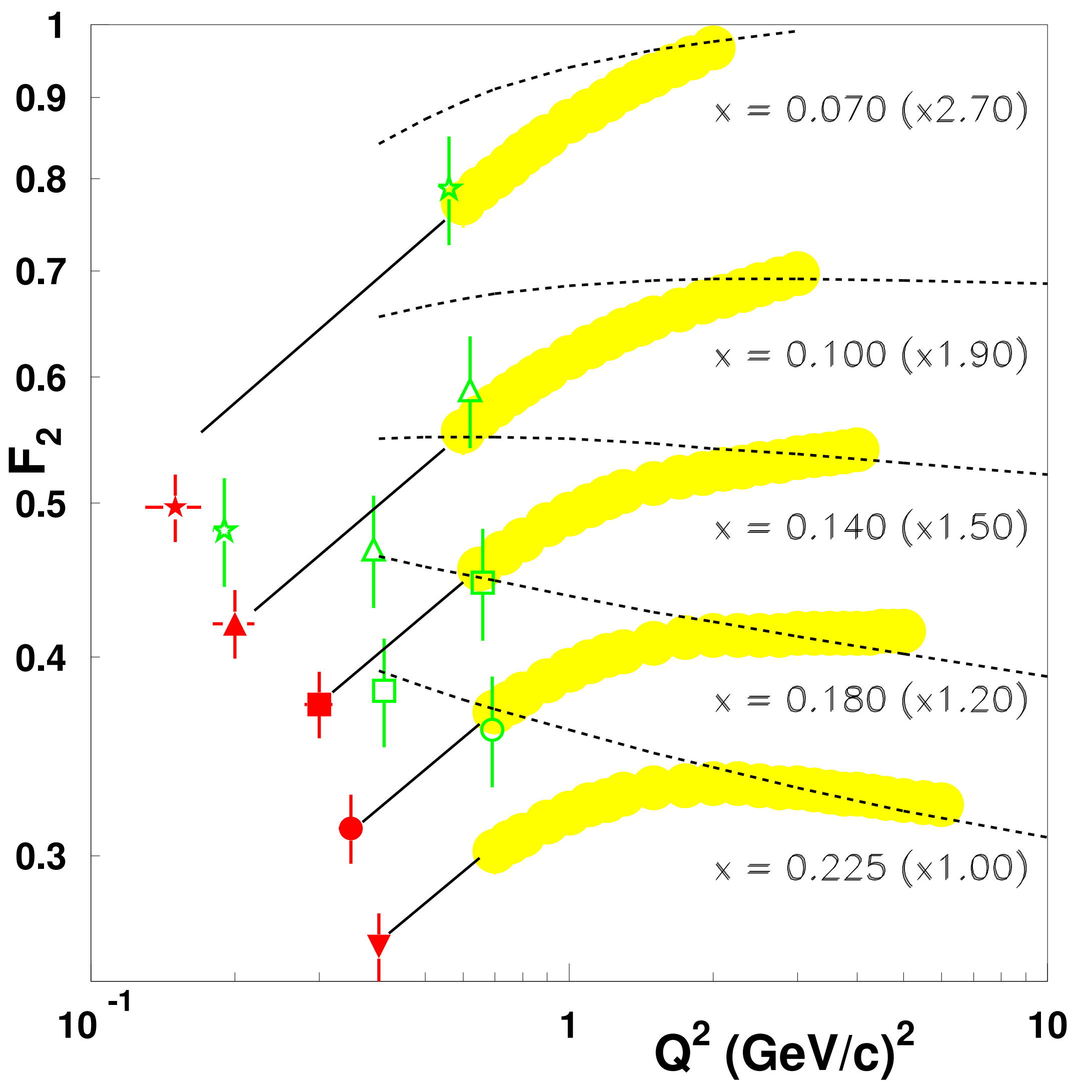
- In $Q^2 \to 0$ limit, total photoabsorption cross section $\sigma^{\gamma N} \sim F_2/Q^2$
  $\longrightarrow$ from gauge invariance, since real photoabsorption cross section is finite,

$$F_2 \ \sim \ Q^2 \qquad \text{as} \qquad Q^2 \to 0$$

- Similarly, longitudinal cross section $\sim Q^4$
  $\longrightarrow$ ratio $R = \sigma_L/\sigma_T$ behaves as

$$R \ \sim \ Q^2 \qquad \text{as} \qquad Q^2 \to 0$$

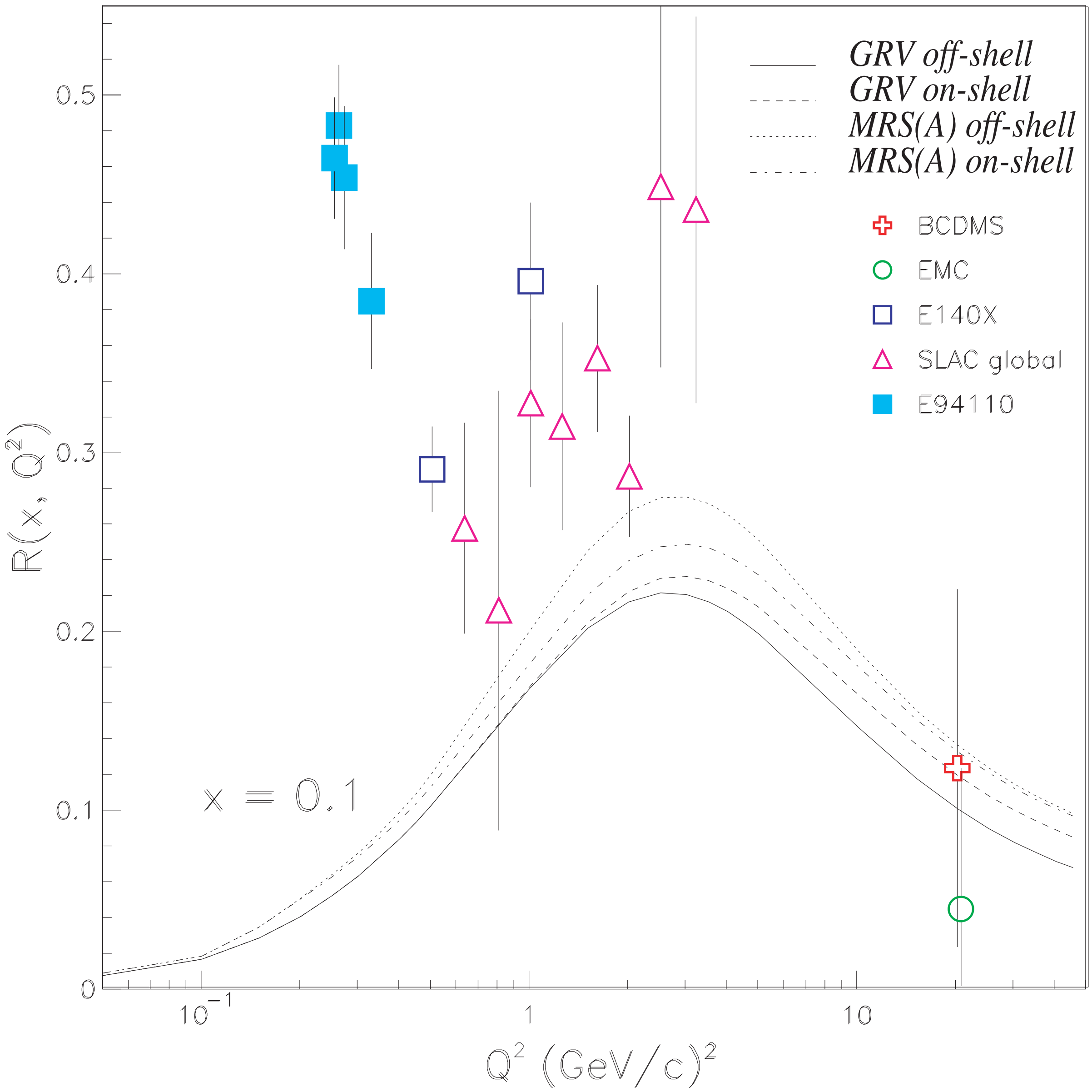
- Models linking high Q^2 limit with VMD-type low Q^2 behavior, constrained by gauge invariance
  $\longrightarrow$ fail to reproduce observed Q^2 dependence down to $Q^2 \sim 0.3$ GeV^2
  $\longrightarrow$ hints at nontrivial dynamics (beyond OPE or gauge invariance) still to be uncovered...



Q^2 dependence of proton F_2 structure function

solid lines $\longrightarrow$ $F_2 \sim Q^{0.5}$

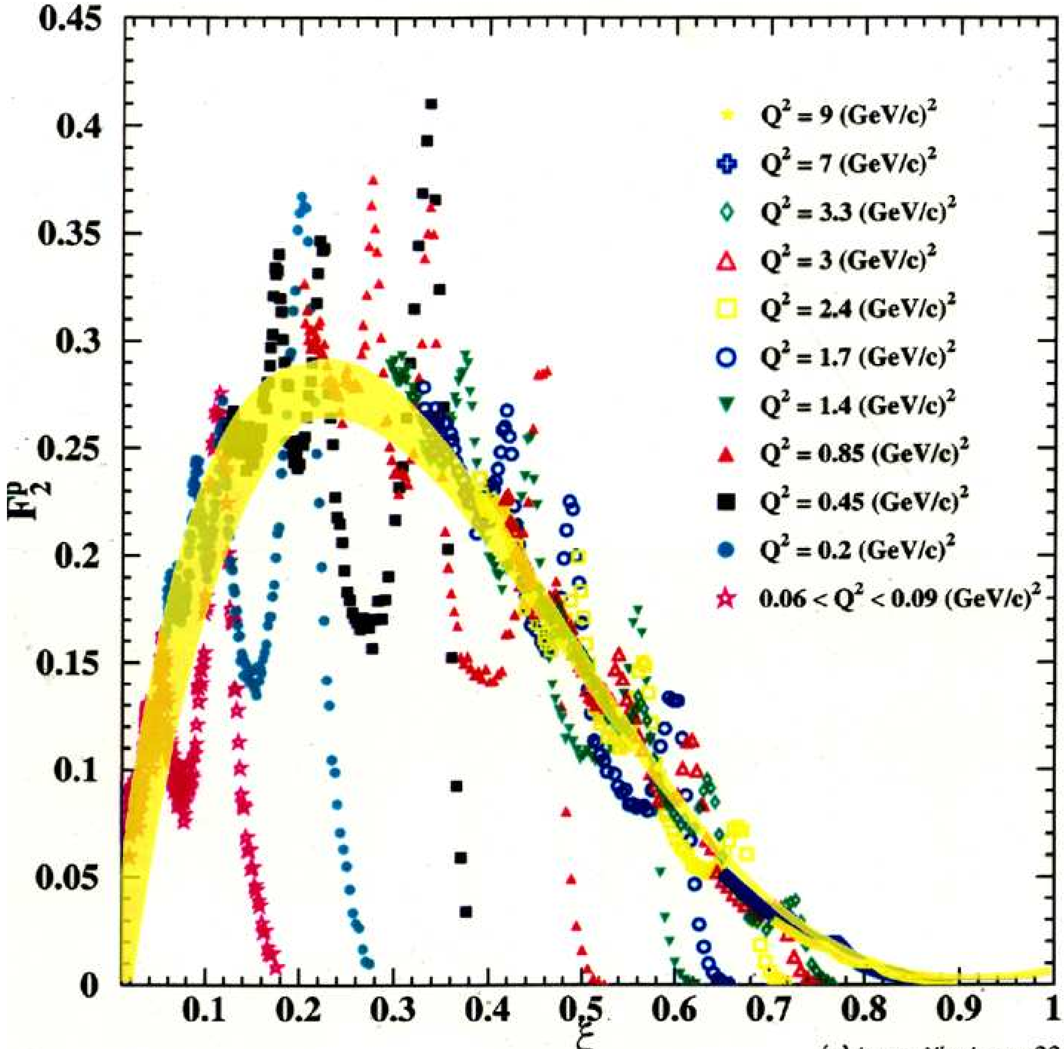
Niculescu et al., *Phys. Rev. Lett.* 85 (2000) 1192



Q^2 dependence of proton $R = \sigma_L/\sigma_T$ ratio

Models based on pQCD fits modified by VMD-like low Q^2 behavior (Badelek, Kwiecinski, Stasto 1997) underestimate low Q^2 data

NICULESCU ET AL. PRL 85 (2000) 1182



(c) Ioana Niculescu 02/02/00

Regge theory $\longrightarrow$ $\sigma_{tot} \sim s^{\alpha(0)-1}$ at large s

$\alpha(0) =$ intercept of Regge trajectory

For $\gamma^* N$ scattering, structure function

$$F_2 \;\sim\; x^{1-\alpha(0)} \qquad [x \sim 1/s]$$

$\longrightarrow$ valence (non-diffractive Reggeon exchange)

$\Rightarrow$ *dual to resonances*

$$F_2^{(\mathrm{val})} \;\sim\; x^{1/2}$$

$\longrightarrow$ sea (diffractive Pomeron exchange)

$\Rightarrow$ *dual to background*

$$F_2^{(\mathrm{sea})} \sim x^0$$

"Two-component duality"
Harari, Freund 1968

$\boxed{\textbf{Inclusive–Exclusive Relation}}$

- Form factors $\longrightarrow$ coherent scattering

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

- Structure functions $\longrightarrow$ incoherent scattering

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

- Difference $\longrightarrow$ higher-twist interference term

$$\sum_{i \neq j} \; e_i \; e_j$$

Basic problem:

How does the square of sums

become a sum of squares?

$\boxed{\text{Pedagogical Model}}$

Two quarks bound in a harmonic oscillator potential $\longrightarrow$ *exactly solvable spectrum*

Greenberg (1993), Ioffe et al. (1993), Gurvitz (1995),
Pace, Salme, Rinat (1998), Close & Isgur (2001),
Isgur, Jeschonnek, WM, Van Orden (2001),
Paris & Pandharipande (2001), Harrington (2002)

- Structure function given by sum of squares of transition form factors

$$F(\nu, \mathbf{q}^2) \sim \sum_n \left| \mathcal{F}_{0,n}(\mathbf{q}^2) \right|^2 \delta(E_n - E_0 - \nu)$$

- Charge operator $\sum_i e_i \exp(i\vec{q} \cdot \vec{r}_i)$ excites

even partial waves with amplitude $\propto (e_1 + e_2)^2$
odd partial waves with amplitude $\propto (e_1 - e_2)^2$

- Resulting structure function

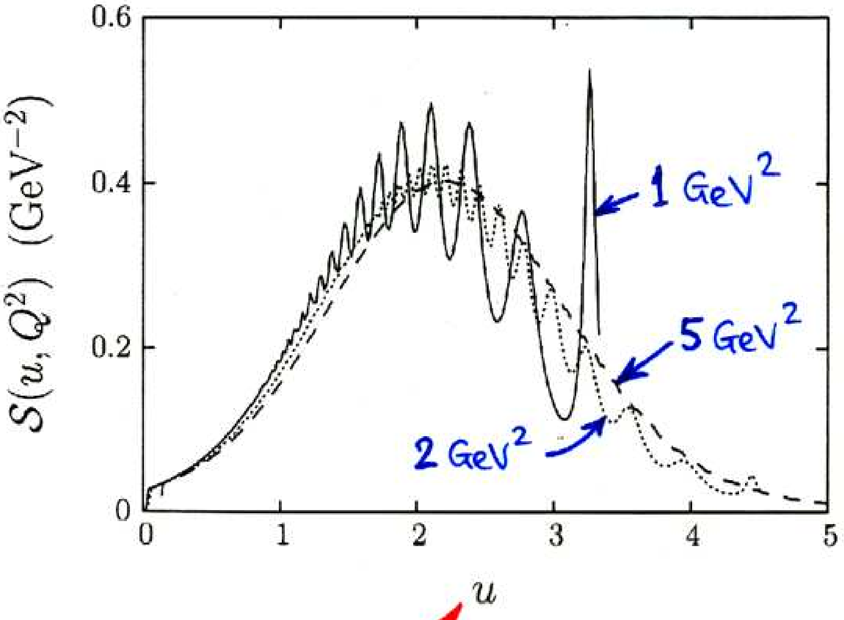
$$F(\nu, \mathbf{q}^2) \sim \sum_n \left\{ (e_1 + e_2)^2 \mathcal{F}^2_{0,2n} + (e_1 - e_2)^2 \mathcal{F}^2_{0,2n+1} \right\}$$

- If states degenerate, cross terms $(\sim e_1 e_2)$ cancel when averaged over nearby even and odd parity states

Minimum condition for duality:

$\longrightarrow$ *at least one complete set of* <u>*even*</u> *and* <u>*odd*</u> *parity resonances must be summed over*

Close, Isgur (2001)



"Rescaled" scaling variable

$$u \equiv \frac{M}{m_q} x$$

STRUCTURE FUNCTION

$$S \equiv |\vec{q}|\, W = \sqrt{\nu^2 + Q^2}\; W$$

Isgur, Jeschonnek, WM, Van Orden
Phys. Rev. **D64** (2001) 054005

Duality in SU(6) Quark Model

- Duality in quark model realized through cancellations between resonances in symmetric ($L^P = 0^+$) **56** and antisymmetric ($L^P = 1^-$) **70** representations of SU(6)

- Relative $N \to N^*$ transition probabilities

	56		**70**			
$Repr^n.$	$^2\mathbf{8}$	$^4\mathbf{10}$	$^2\mathbf{8}$	$^4\mathbf{8}$	$^2\mathbf{10}$	sum
F_2^p	9	8	9	0	1	27
F_2^n	4	8	1	4	1	18
g_1^p	9	−4	9	0	1	15
g_1^n	4	−4	1	−2	1	0

$\boxed{\text{Parton Model Relations}}$

$$R^{np} = \frac{F_2^n}{F_2^p} = \frac{u + 4d}{4u + d} \to \frac{2}{3}$$

$$A_1^p = \frac{g_1^p}{F_1^p} = \frac{4\Delta u + \Delta d}{4u + d} \to \frac{5}{9}$$

$$A_1^n = \frac{g_1^n}{F_1^n} = \frac{4\Delta d + \Delta u}{4d + u} \to 0$$

Proton Wave Function

in

Non-Relativistic Quark Model

$$
\begin{aligned}
p\uparrow \;=\; & -\frac{1}{3}\, d\uparrow (uu)_1 - \frac{\sqrt{2}}{3}\, d\downarrow (uu)_1 \\
& + \frac{\sqrt{2}}{6}\, u\uparrow (ud)_1 - \frac{1}{3}\, u\downarrow (ud)_1 \\
& + \frac{1}{\sqrt{2}}\, u\uparrow (ud)_0
\end{aligned}
$$

- Summing over all resonances in 56 and **70** multiplets

$$\Rightarrow \qquad R^{np} = \frac{F_2^n}{F_2^p} = \frac{2}{3}$$

$$A_1^p = \frac{g_1^p}{F_1^p} = \frac{5}{9}$$

$$A_1^n = \frac{g_1^n}{F_1^n} = 0$$

$\longrightarrow$ *as in quark-parton model* !!

- Expect duality to appear earlier for F_1^p than F_1^n

- Earlier onset for g_1^n than g_1^p
  $\longrightarrow$ cancellations within multiplets for g_1^n
  $\longrightarrow$ for $A_1^n \neq 0$ SU(6) must be broken *within* each multiplet, not just *between* the **56** and **70**

SU(6) Breaking

- SU(6) results may be valid at $x \sim \frac{m_Q}{m_N} \sim \frac{1}{3}$

  but are *badly broken* at $x \sim 1$

- Because of kinematics, $x \to 1$ behavior of structure functions related to large Q^2 behavior of (transition) form factors

$\longrightarrow$ Drell-Yan-West relation

$$G(Q^2) \sim \left(\frac{1}{Q^2}\right)^n \quad \Leftrightarrow \quad F(x) \sim (1-x)^{2n-1}$$

$\longrightarrow$ resonance contributions to structure function slide along scaling curve to larger x with increasing Q^2

$\longrightarrow$ which resonances are needed to describe structure functions at $x \sim 1$?

- If characteristic Q^2 dependence of Δ excitation is due to spin dependence

  $\longrightarrow$ can be realized by suppression of $S = 3/2$ states

  $\longrightarrow$ duality satisfied by $S = 1/2$ and $S = 3/2$ contributions separately

  $\longrightarrow$ $R^{np} \to 6/19$ with $A_1^N \to 1$

- If $N - \Delta$ mass splitting attributed to suppression of symmetric part of wave function

  $\longrightarrow$ suppression of d quark relative to u $d/u \to 0$ ($R^{np} \to 1/4$)

  $\longrightarrow$ polarization asymmetries $A_1^N \to 1$ with $\Delta u/u = 1$ but $\Delta d/d = -1/3$

Isgur, *Phys. Rev.* D 59 (1999) 034013

- At high Q^2, γ^* interacts predominantly with quark of same helicity as hadron

  $\longrightarrow$ $\sigma_{3/2}$ cross section expected to be suppressed relative to $\sigma_{1/2}$

  $\longrightarrow$ $R^{np} \to 3/7$, $A_1^N \to 1$ as in $pQCD$ $parton\text{-}level\ calculation$!

Farrar & Jackson
Phys. Rev. Lett. 35 (1975) 1416

- Scenarios can be tested by comparing with

  $\longrightarrow$ structure function data at large x

  $\longrightarrow$ Q^2 dependence of $N \to N^*$ transition form factors

R. FEYNMAN 1972
F. CLOSE 1973

N − Δ MASS SPLITTING

→ $(qq)_{S=1}$ CONFIGURATION HEAVIER THAN $(qq)_{S=0}$

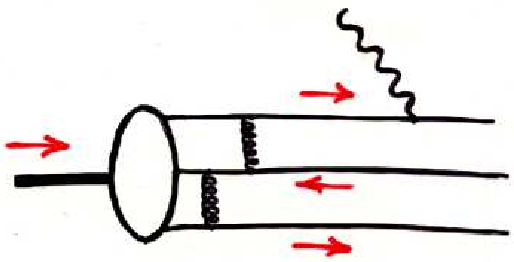
$(qq)_{S=0}$ DOMINANT IN $x \to 1$ LIMIT

→ $d/u \to 0$

$F_2^n / F_2^p \to 1/4$

FARRAR / JACKSON 1975

PERTURBATIVE GLUON EXCHANGE



$\lambda_{quark} = \lambda_{hadron}$

$\twoheadrightarrow$ $q\uparrow \gg q\downarrow$ AT $x \sim 1$

$$\boxed{(qq)_{S_z=0} \text{ DOMINANT IN } x \to 1 \text{ LIMIT}}$$

$\twoheadrightarrow$ $d/u \to 1/5$

$F_2^n / F_2^p \to 3/7$

Predictions for F_2^n/F_2^p at $x \to 1$

- SU(6) symmetry:

$$\frac{F_2^n}{F_2^p} = \frac{2}{3} \qquad \frac{d}{u} = \frac{1}{2}$$

- Broken SU(6) via scalar diquark dominance (d quark suppression):

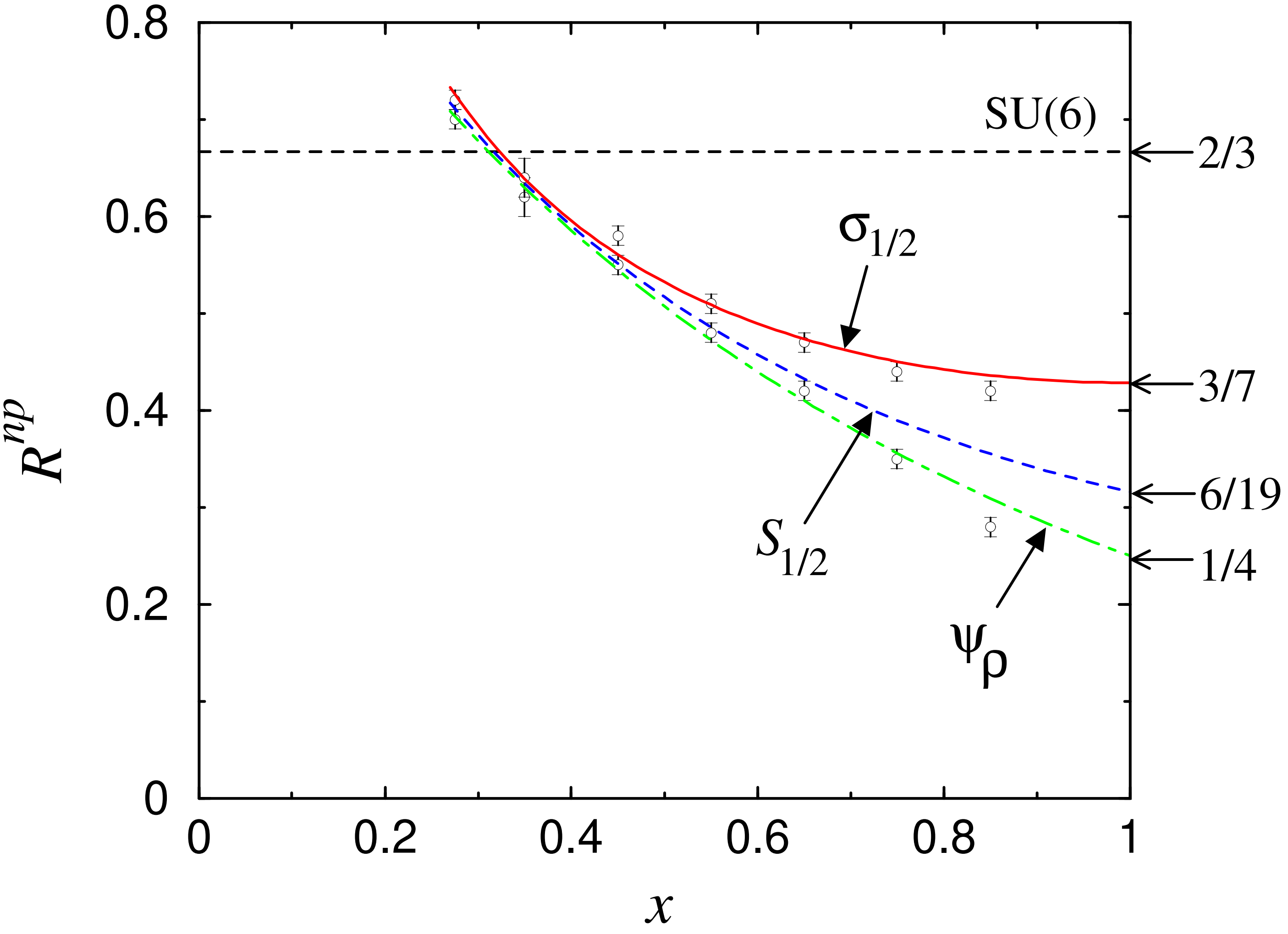
$$\frac{F_2^n}{F_2^p} \longrightarrow \frac{1}{4} \qquad \frac{d}{u} \longrightarrow 0$$

- Broken SU(6) via helicity flip suppression:

$$\frac{F_2^n}{F_2^p} \longrightarrow \frac{3}{7} \qquad \frac{d}{u} \longrightarrow \frac{1}{5}$$

- Local quark-hadron duality:

$$\frac{F_2^n}{F_2^p} \longrightarrow \frac{d(G_M^n)^2/dQ^2}{d(G_M^p)^2/dQ^2} \approx \frac{4}{9}$$

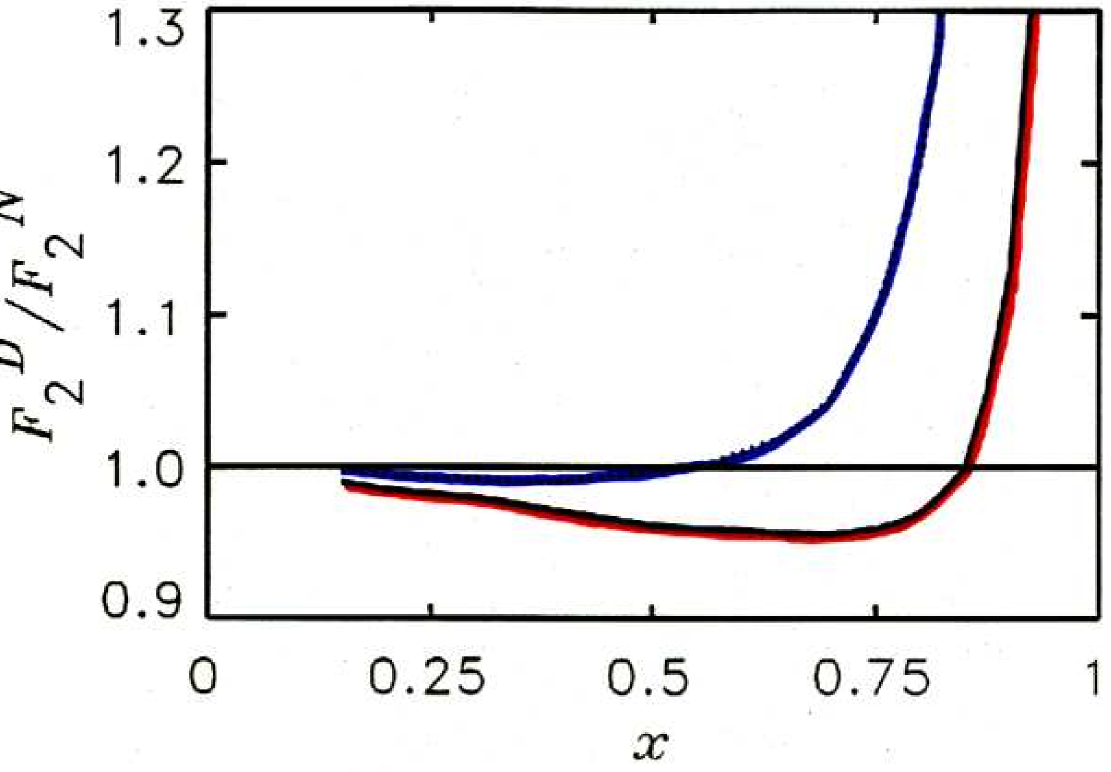


Ratio R^{np} of unpolarized n to p

structure functions from duality

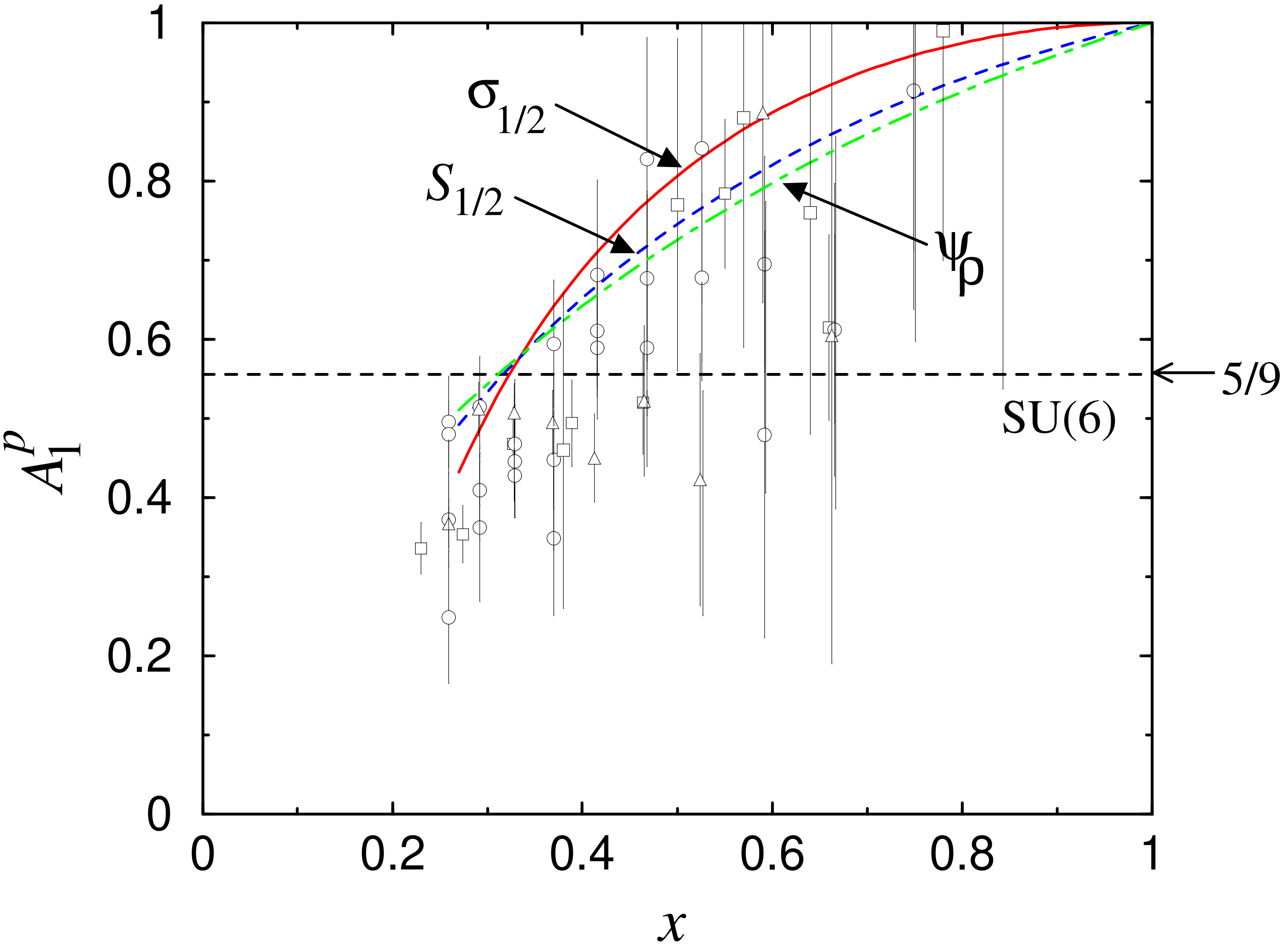
Close, WM
Phys. Rev. C (2003), `hep-ph/0302013`

WM, THOMAS 1996



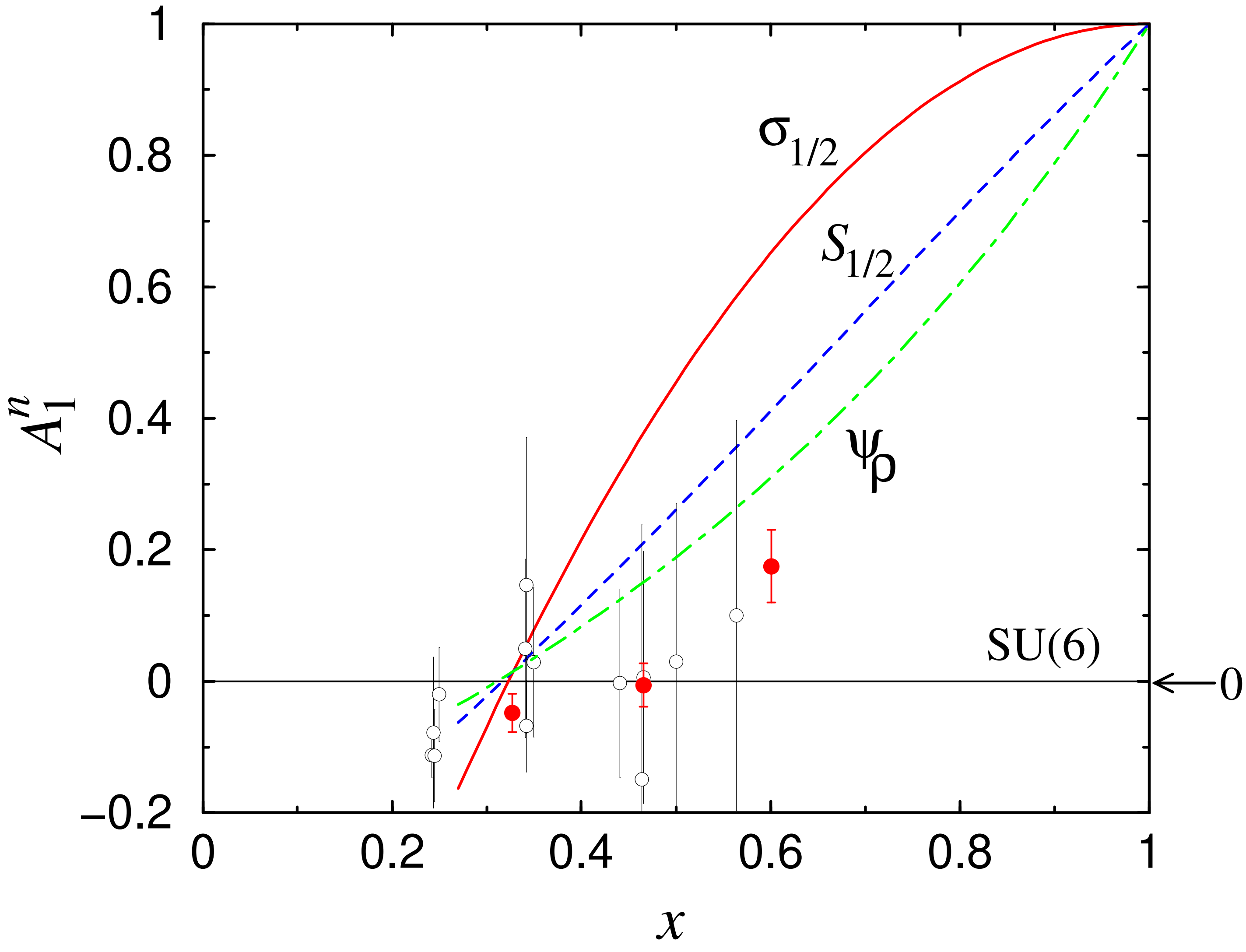
— FERMI MOTION

— FERMI MOTION + EMC EFFECT



Proton polarization asymmetry A_1^p

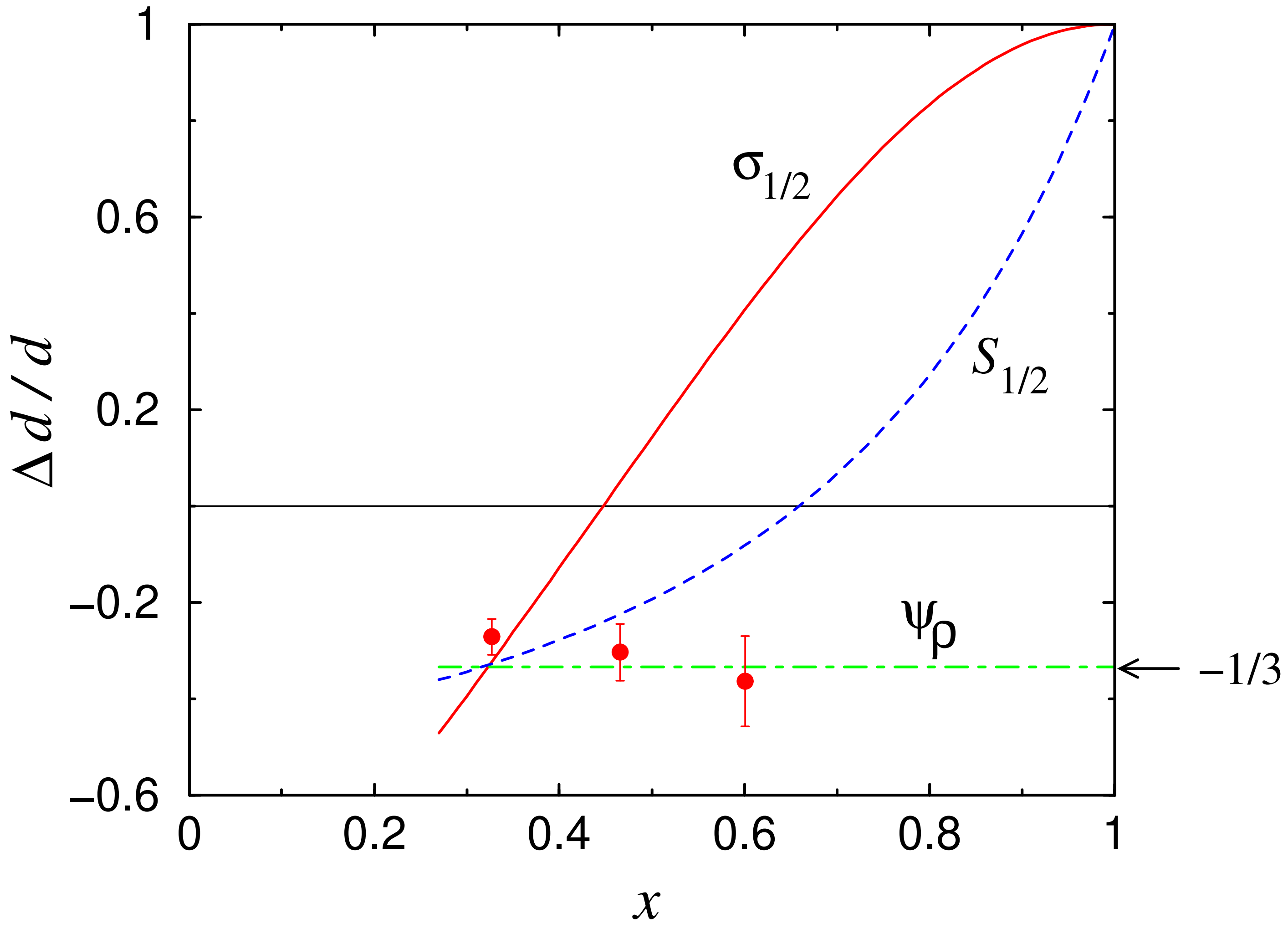
Close, WM
Phys. Rev. C (2003), `hep-ph/0302013`



Neutron polarization asymmetry A_1^n

Close, WM
Phys. Rev. C (2003), `hep-ph/0302013`

$$\frac{\Delta d}{d} = -\frac{1}{15} A_1^p \left(1 + \frac{4u}{d}\right) + \frac{4}{15} A_1^n \left(4 + \frac{u}{d}\right)$$



Close, WM

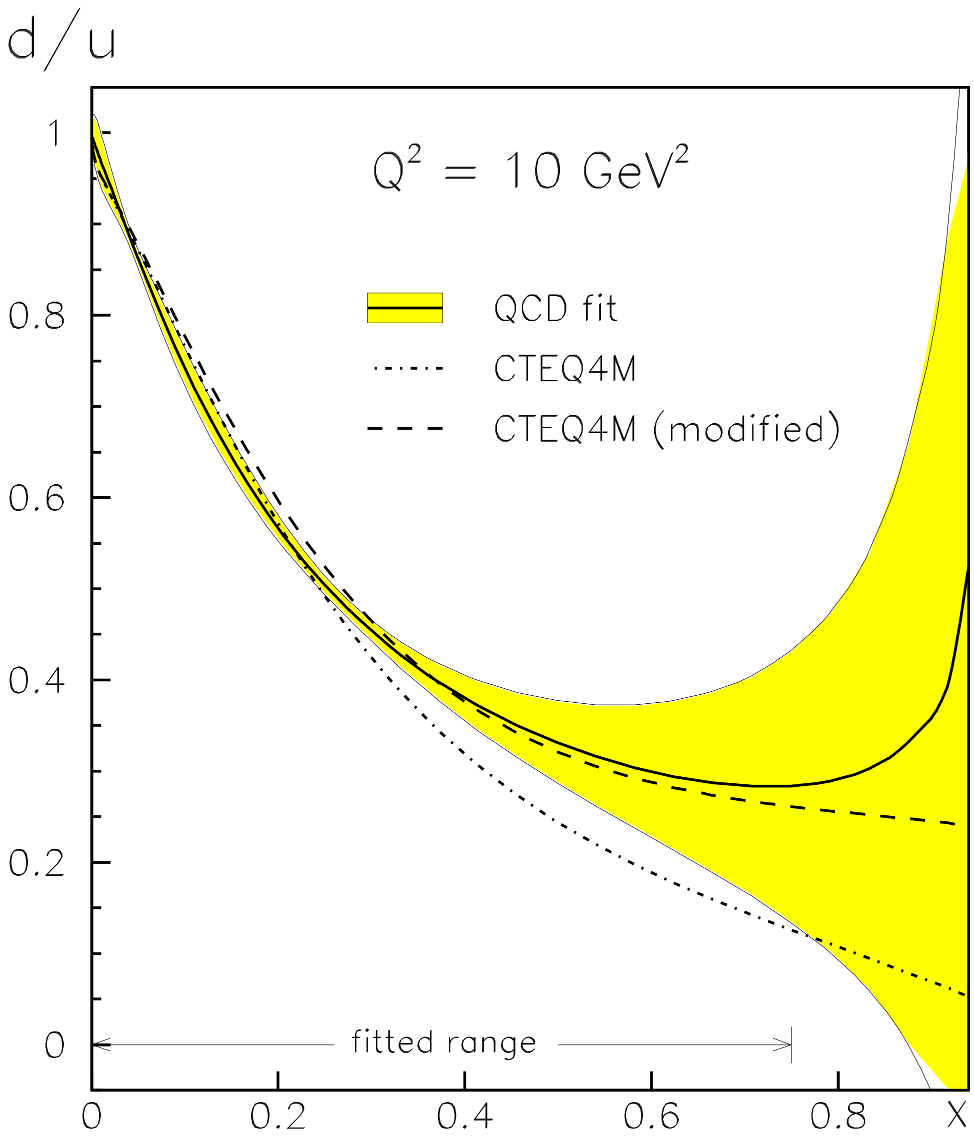
Phys. Rev. C (2003), `hep-ph/0302013`

$\boxed{\textbf{Large-}x \textbf{ is vital in particle physics!}}$

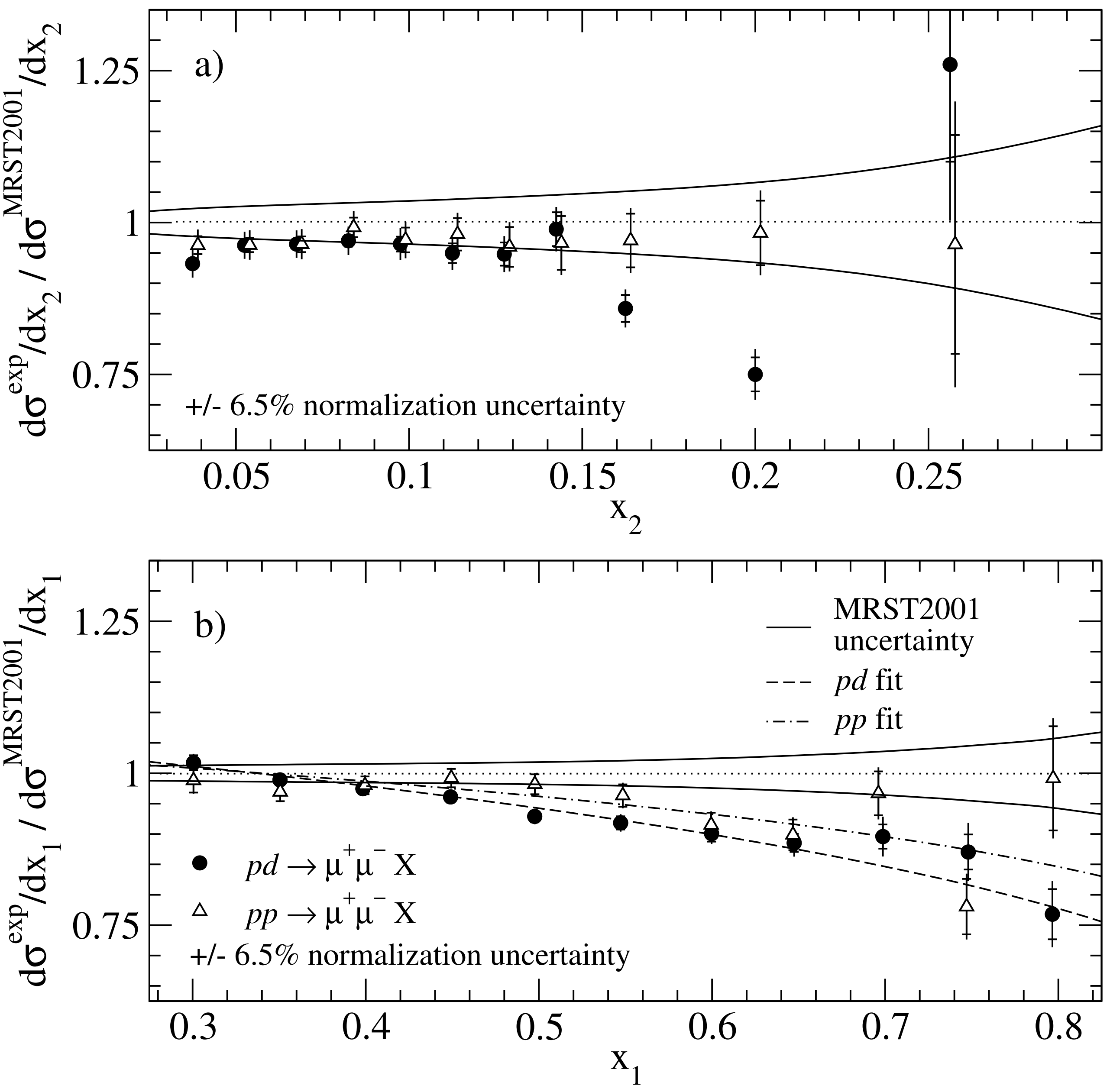
- Parton distributions at large x are input into simulations of hadronic backgrounds at colliders
  $\longrightarrow$ under Q^2 evolution, high x at low Q^2
  $\Rightarrow$ low x at high Q^2
  $\longrightarrow$ small uncertainties $amplified$

- $HERA$ "anomaly" (1998):
  excess of neutral & charged current events at $Q^2 > 10,000$ GeV^2
  $\longrightarrow$ $leptoquarks$!
  $\longrightarrow$ ... or $\sim$ 0.5% larger $u(x)$ at $x \sim 0.9$?

- $NuTeV$ "anomaly" (2002):
  3-σ deviation of $\sin^2\theta_W$ from Standard Model value
  $\longrightarrow$ $physics\ beyond\ Standard\ Model$!
  $\longrightarrow$ ... or poorly known sea quarks
  at large x?



Uncertainty in d/u ratio in the proton



$u(x)$ overestimated?

FNAL E866, `hep-ex/0302019`

Tagged Neutron Structure Function

- Measure structure function of nearly on-shell neutron by detecting *slow spectator proton* in semi-inclusive $e\ d \to e\ p_s\ X$ reaction

Frankfurt, Strikman (1981); Simula (1996);

WM, Sargsian, Strikman (1997)

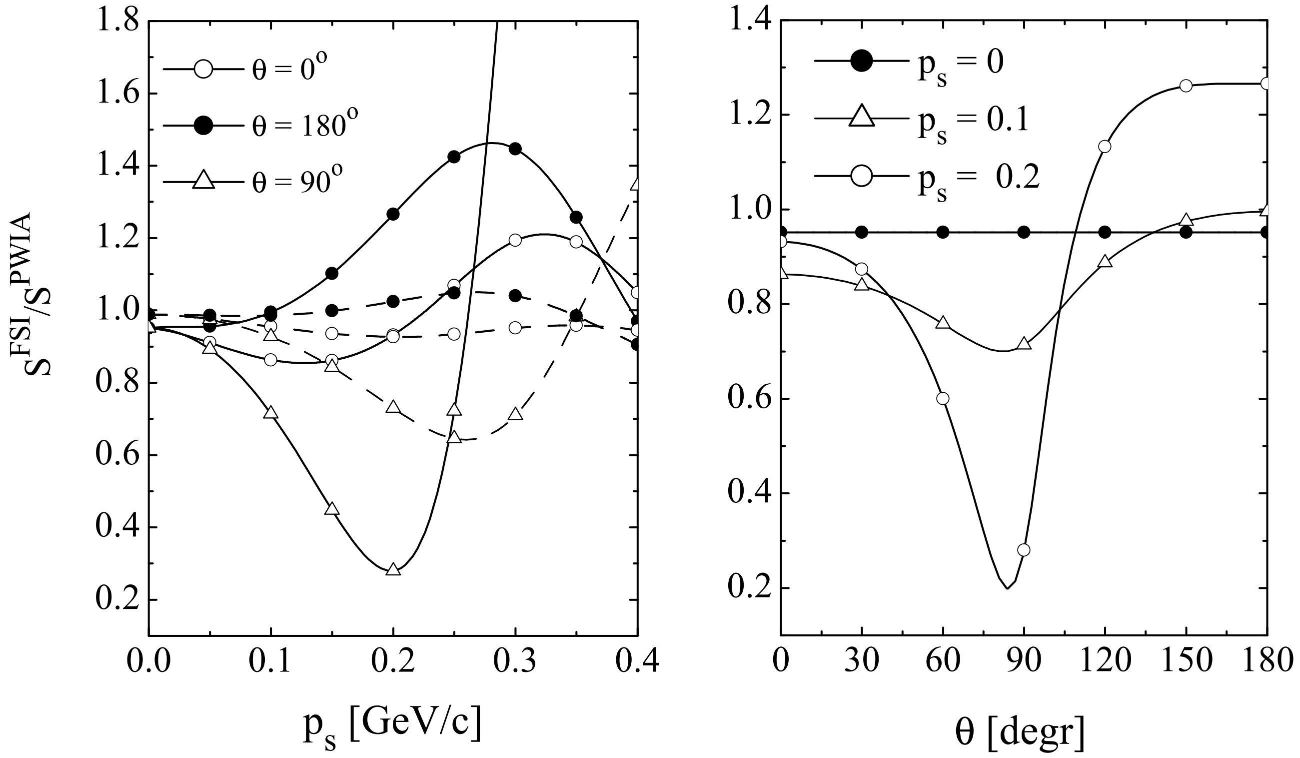
- Low momentum proton
$\longrightarrow$ minimize off-shell extrapolation
$\longrightarrow$ "BoNuS" kinematics: $p_s \sim$ 70 MeV
$\Rightarrow$ neutron $\sim$ 10 MeV off-shell

- Backward angles
$\longrightarrow$ target fragmentation suppressed

- Main nuclear correction from rescatting of spectator proton with neutron remnants
$\longrightarrow$ minimized for $p_s \to$ 0 and $\theta \to 180°$

WM, Sargsian, Strikman (1996)

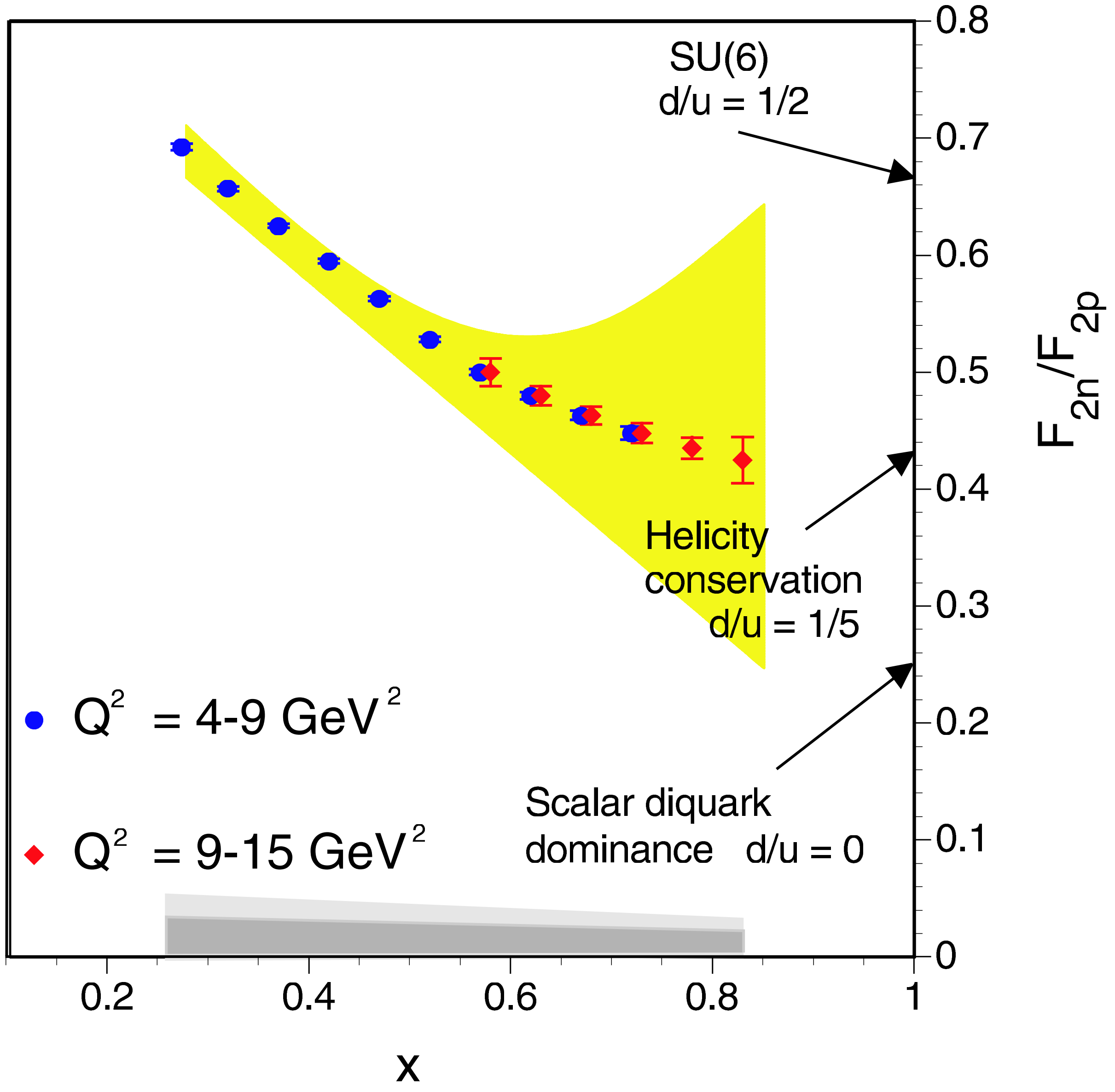
Ciofi degli Atti, Kopeliovich (2003)



Momentum and angular dependence of rescattering (final state interactions) of spectator proton with neutron remnants

(left panel: solid — $\sigma_{eff}(t, Q^2)$, dashed — $\sigma_{eff} = 20$ mb)

Ciofi degli Atti, Kopeliovich
Eur. Phys. J. A17 (2003) 133



Projectged errors for tagged neutron structure function measurement with CLAS^{++}

$\boxed{\textbf{Extract } F_2^n \textbf{ from } F_2^{^3He}/F_2^{^3H}}$

EMC ratios for $A = 3$ mirror nuclei

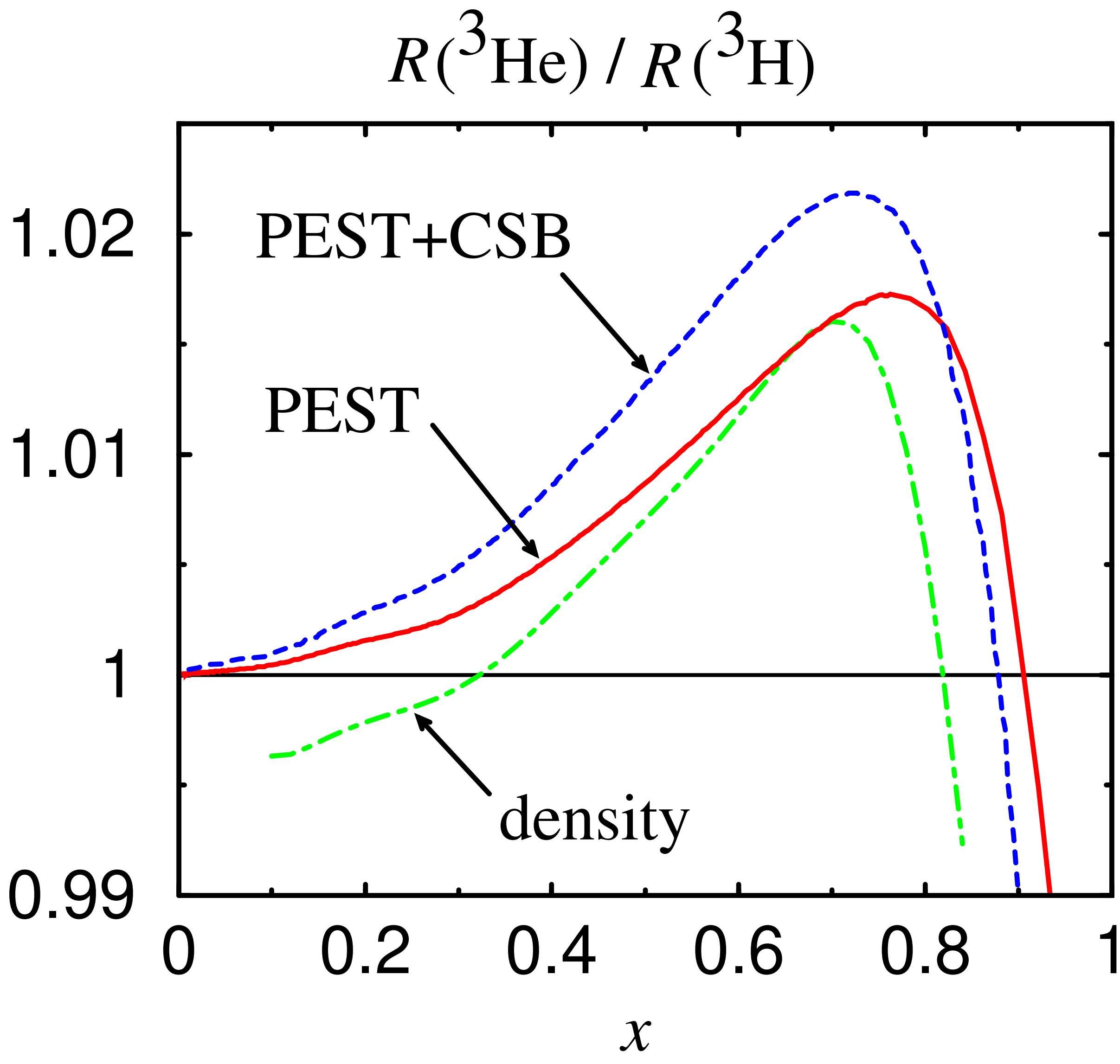
$$R(^3He) \;=\; \frac{F_2^{^3He}}{2F_2^p + F_2^n}$$

$$R(^3H) \;=\; \frac{F_2^{^3H}}{F_2^p + 2F_2^n}$$

Extract n/p ratio from measured $^3He/^3H$ ratio

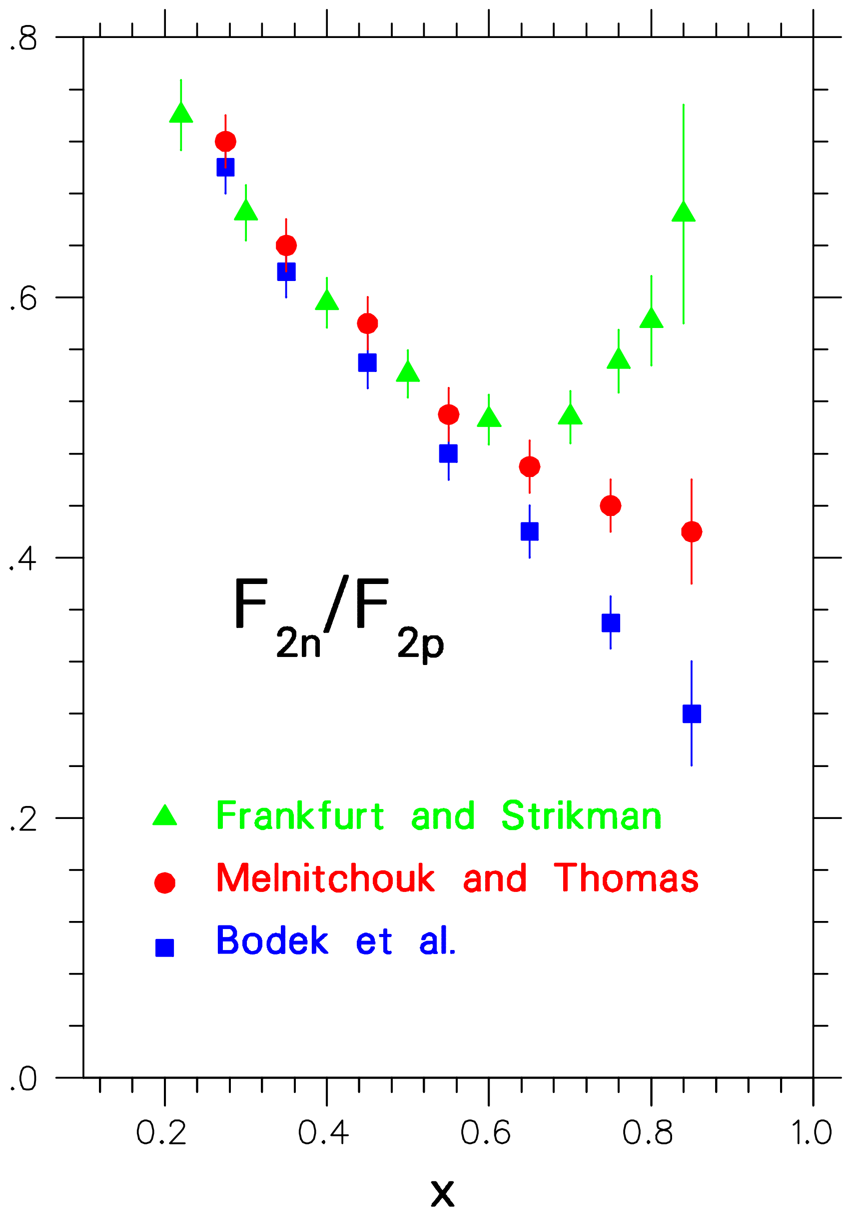
$$\frac{F_2^n}{F_2^p} \;=\; \frac{2\mathcal{R} - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - \mathcal{R}}$$

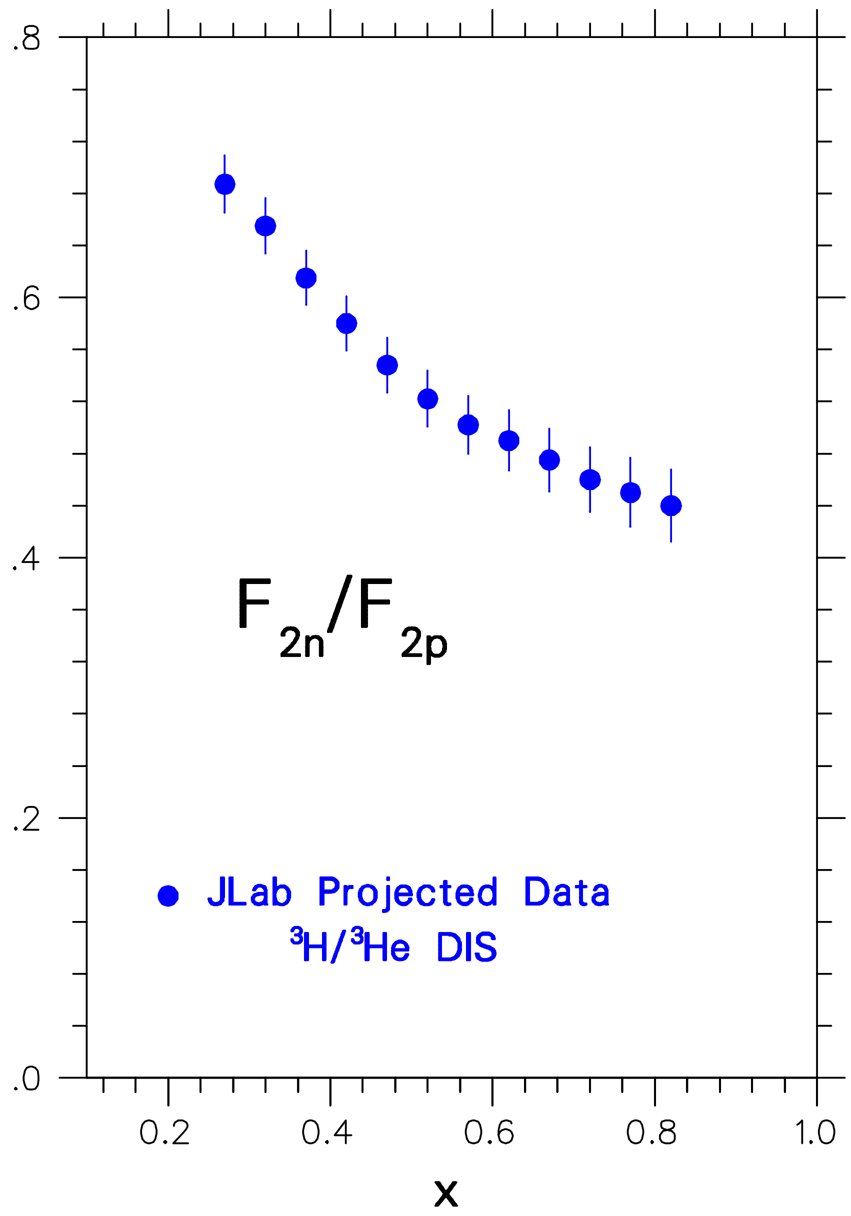
where $\mathcal{R} = R(^3He)/R(^3H)$



Nuclear model dependence of ratio of
^{3}He and ^{3}H EMC ratios

Afnan et al.
Phys. Lett. B 493 (2000) 36


.8
.6
.4
.2
.0
0.2
0.4
0.6
0.8
1.0
x
F_{2n}/F_{2p}
Frankfurt and Strikman
Melnitchouk and Thomas
Bodek et al.


.8
.6
.4
.2
.0
0.2
0.4
0.6
0.8
1.0
x
F_{2n}/F_{2p}
JLab Projected Data
$^3H/^3He$ DIS

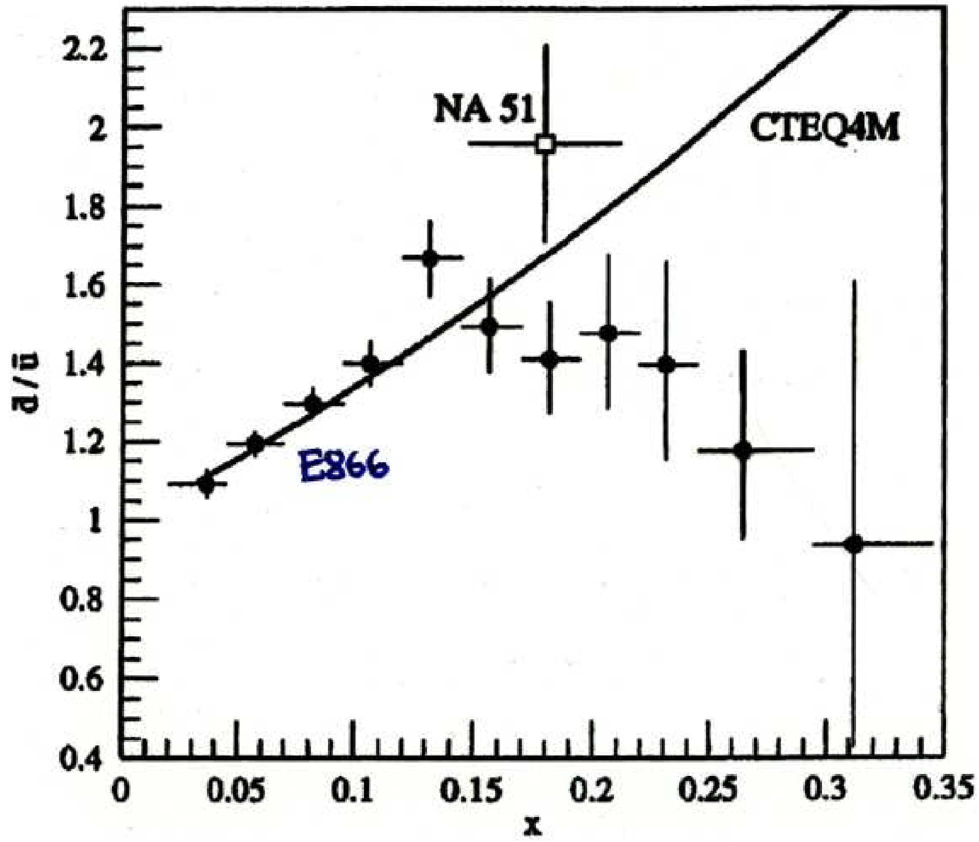
Flavor Asymmetry $\bar{d} - \bar{u}$

- Large $\bar{d} - \bar{u}$ asymmetry in proton observed in DIS (NMC) and Drell-Yan (CERN NA51 & FNAL E855) experiments

- Evidence for role of dynamical chiral symmetry breaking at high energies
  $\longrightarrow$ pion cloud of nucleon

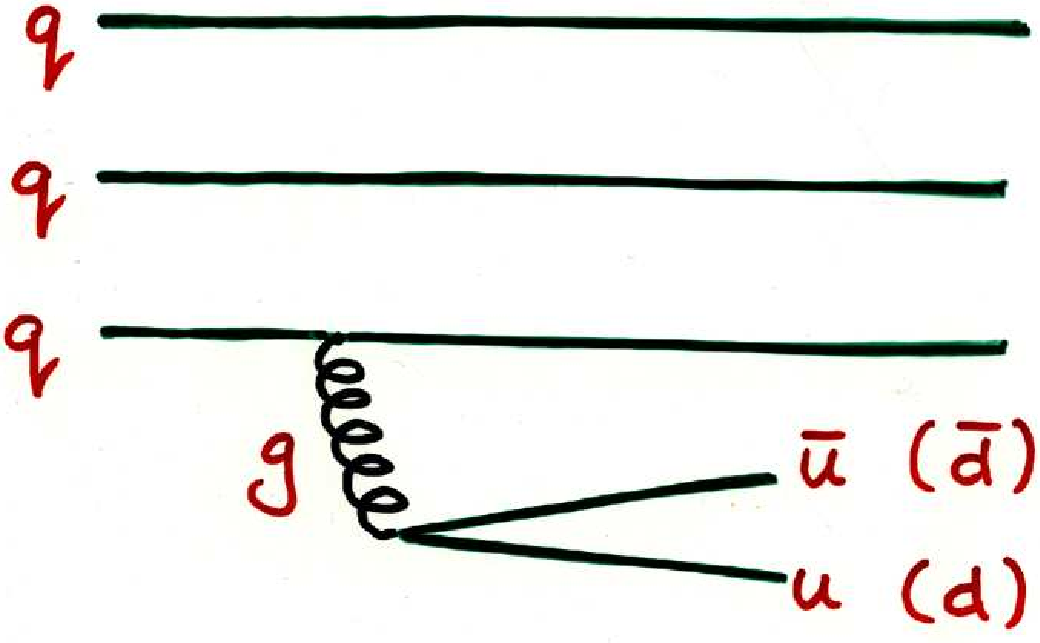
- Trend of $\bar{d}/\bar{u}$ at large x poses serious challenge to theoretical models
  $\longrightarrow$ although large errors for $x \geq 0.25$
  $\longrightarrow$ can significantly improve in semi-inclusive DIS at JLab

HAWKER ET AL. PRL 80 (1998) 3715



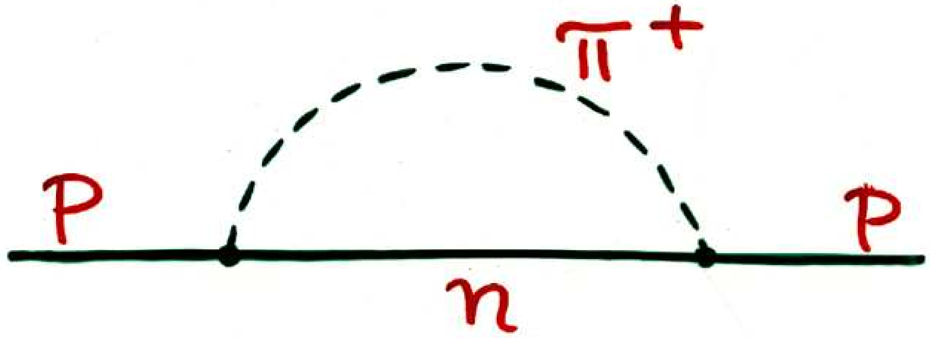
$$\frac{\sigma^{pd}}{2\sigma^{pp}}\bigg|_{x_1 \gg x_2} \approx \frac{1}{2}\,\frac{\left(1+\frac{1}{4}\frac{d_1}{u_1}\right)}{\left(1+\frac{1}{4}\frac{d_1}{u_1}\frac{\bar{d}_2}{\bar{u}_2}\right)}\left(1+\frac{\bar{d}_2}{\bar{u}_2}\right)$$

NAIVELY EXPECT SYMMETRIC SEA



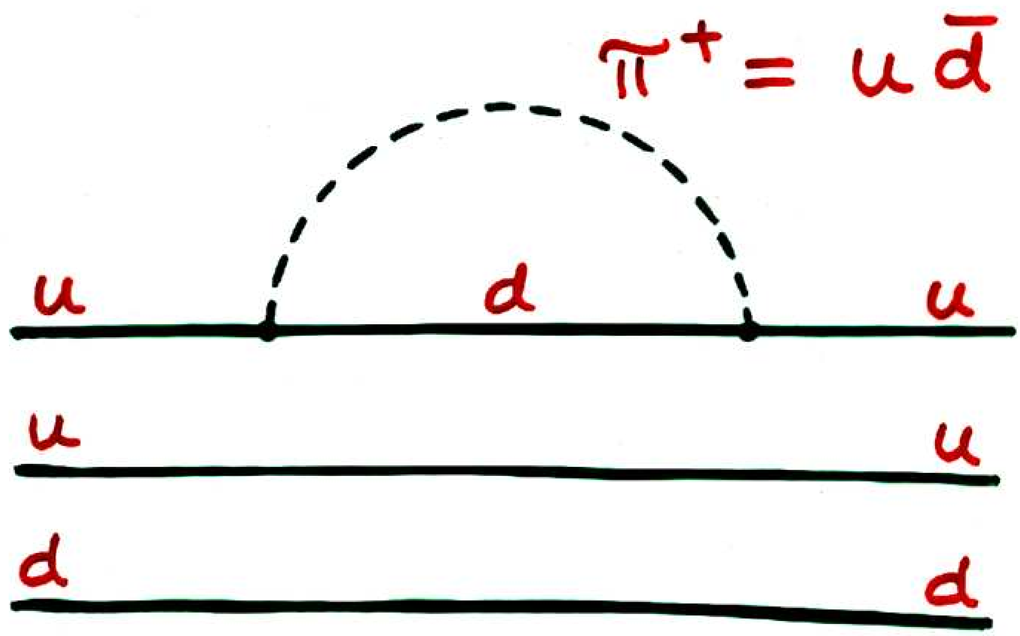
$$\bar{d} = \bar{u}$$

PION CLOUD

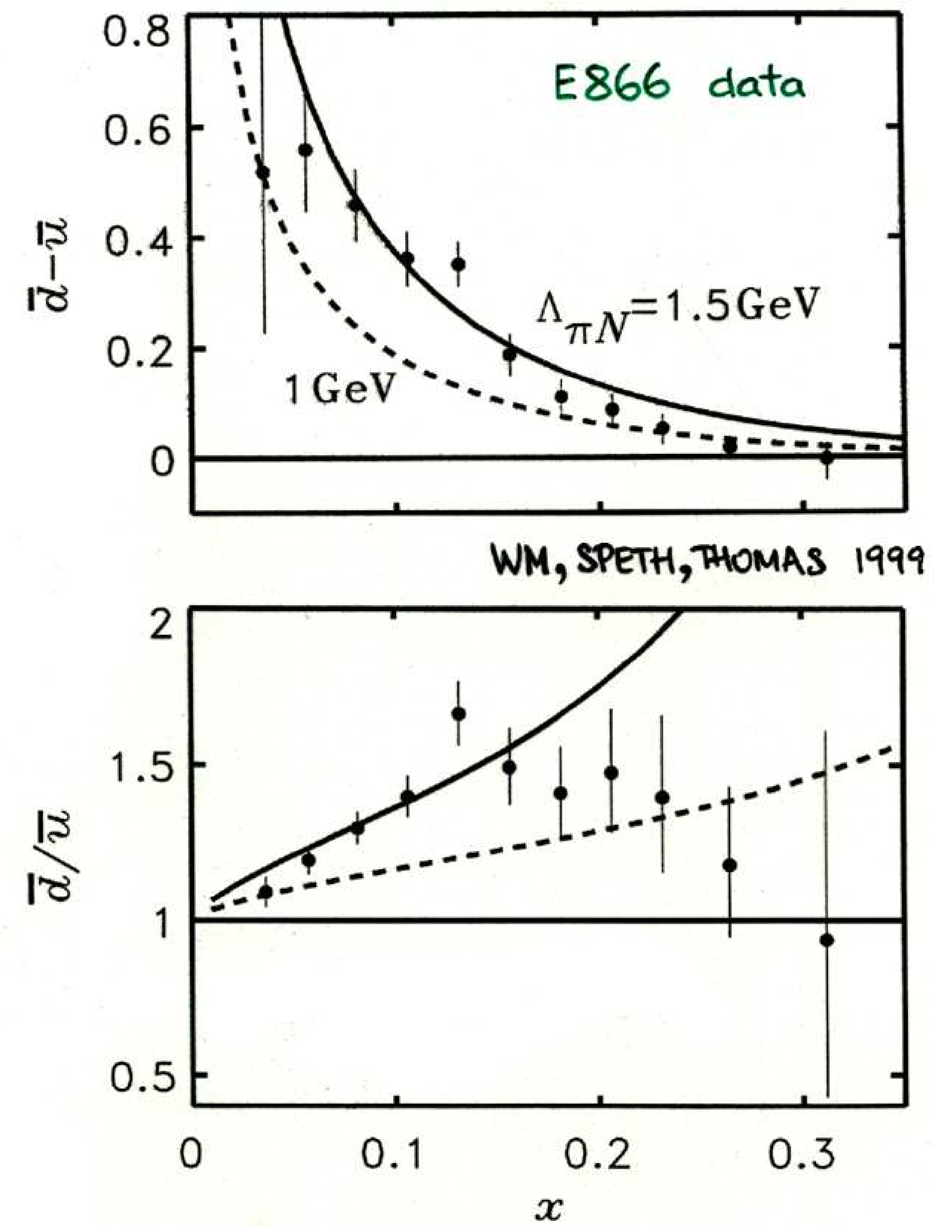


SOME OF THE TIME
A PROTON CAN EXIST
AS NEUTRON PLUS
VIRTUAL PION

AT THE QUARK LEVEL



EFFECT OF "πN CLOUD"



Semi-Inclusive DIS

Assuming factorization of quark scattering and $q \to h$ fragmentation, differential cross section in parton model is

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

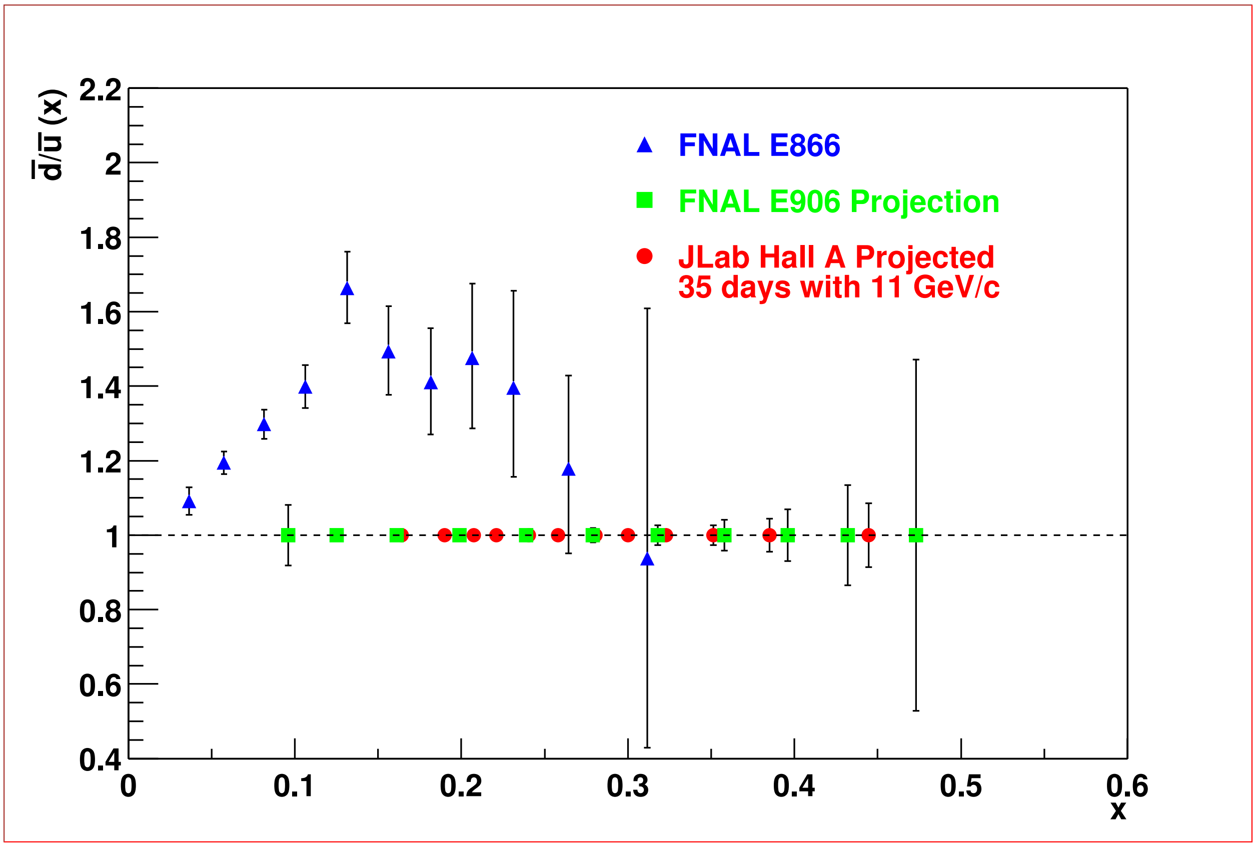
- Hadron h provides tag of scattered quark flavor (in current fragmentation region)
  $\longrightarrow$ at large z primary fragmentation is $u \to \pi^+$, $d \to \pi^-$

- Assume isospin and charge conjugation invariance of fragmentation functions

$$\longrightarrow D^+ \equiv \underbrace{D_u^{\pi^+}}_{favored} = D_{\bar{d}}^{\pi^+} = D_{\bar{u}}^{\pi^-} = D_d^{\pi^-}$$

$$\longrightarrow D^- \equiv \underbrace{D_u^{\pi^-}}_{unfavored} = D_{\bar{d}}^{\pi^-} = D_{\bar{u}}^{\pi^+} = D_d^{\pi^+}$$

$\longrightarrow$ ratio $D^-/D^+ \to 0$ as $z \to 1$



Flavor asymmetry $\bar{d} - \bar{u}$ *with semi-inclusive DIS in Hall A at 12 GeV JLab*

Polarized Asymmetry $\Delta\bar{u} - \Delta\bar{d}$

- Pauli Exclusion Principle (antisymmetrization) also gives $\bar{d} > \bar{u}$

- Experimental asymmetry a combination of pion cloud + Pauli blocking effects?

- Pion cloud

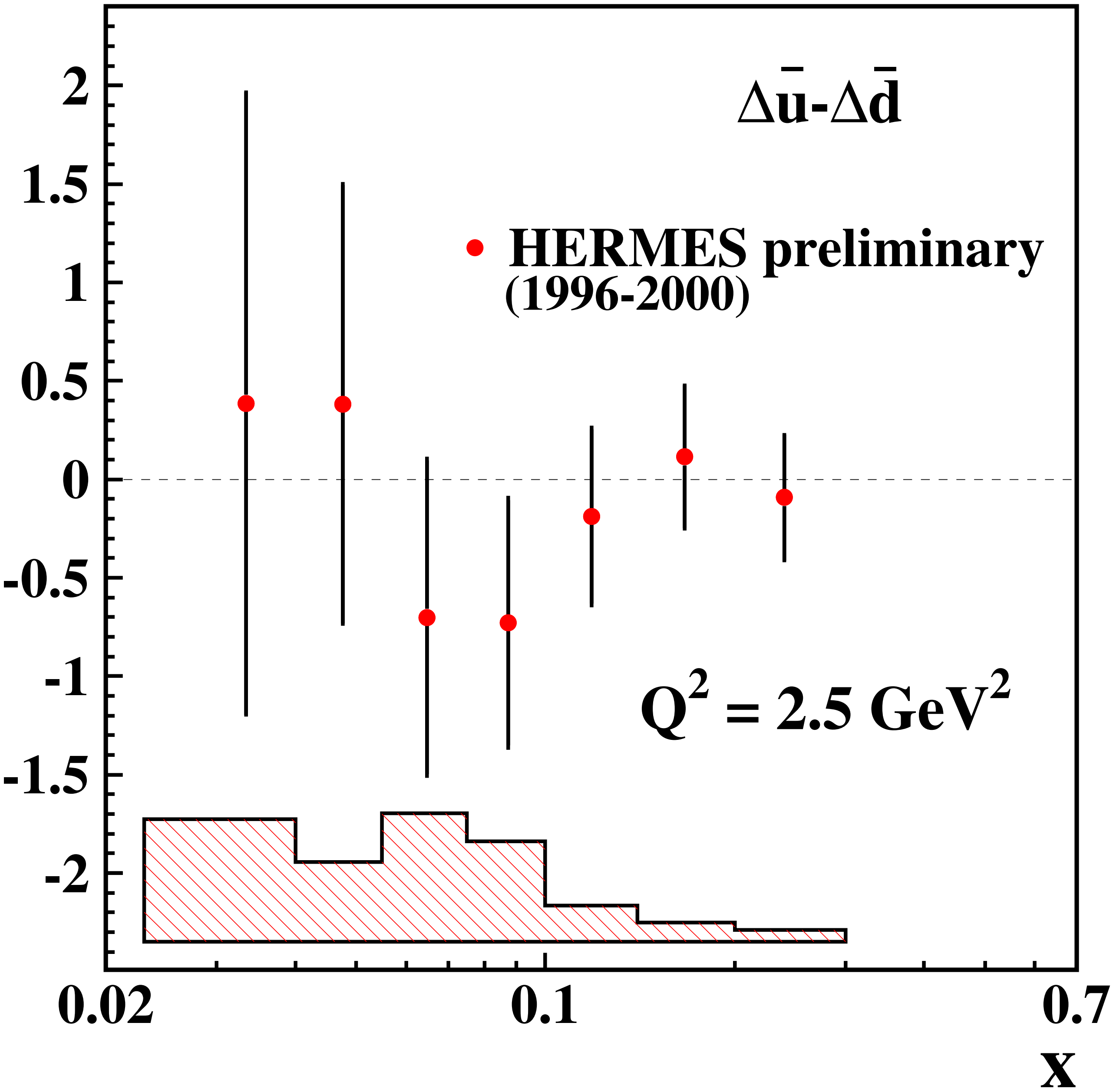
  $$\longrightarrow \Delta\bar{u} \approx \Delta\bar{d} \approx 0$$

- Pauli blocking

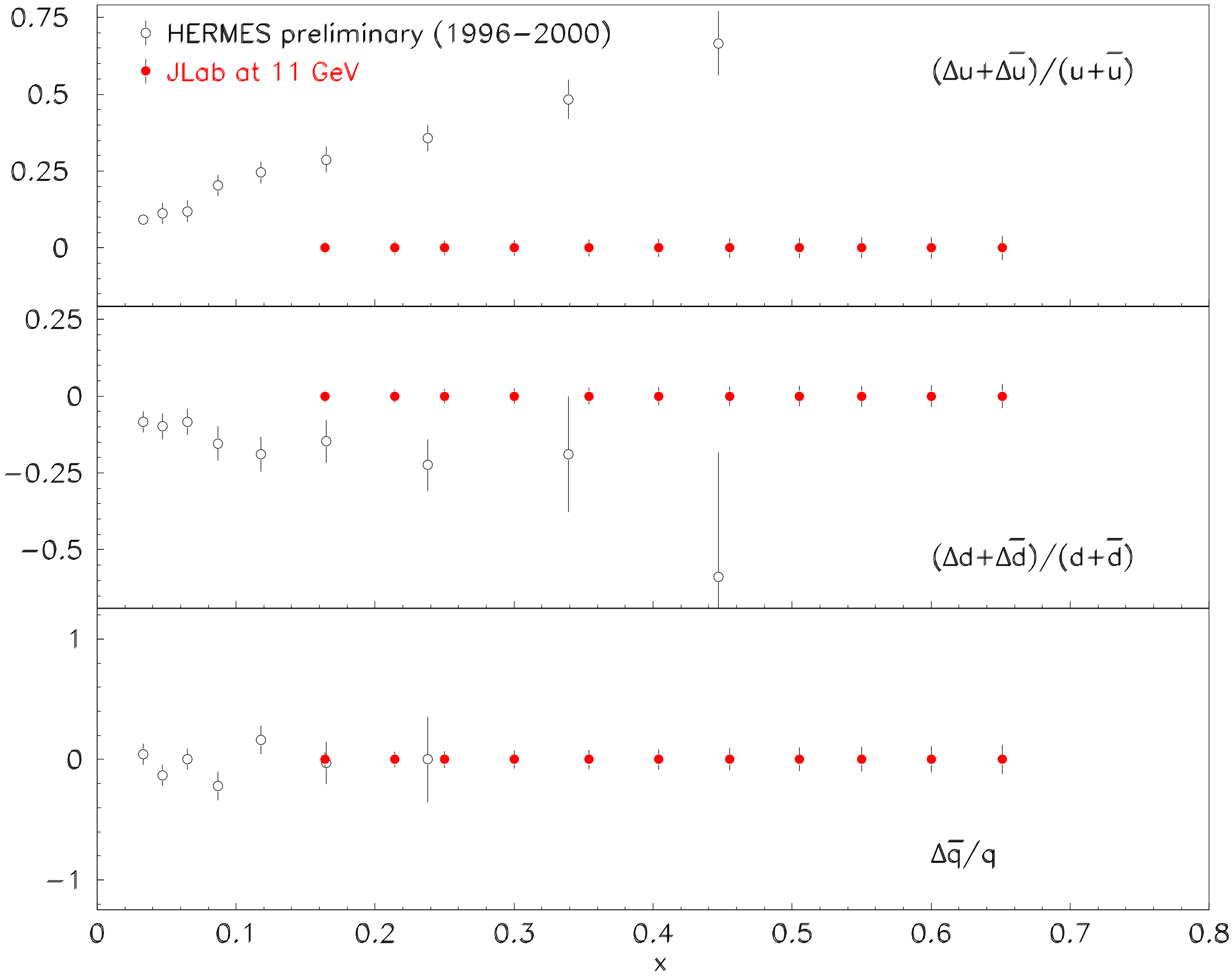
  $$\longrightarrow \Delta\bar{u} - \Delta\bar{d} \ \sim \ \frac{5}{3}\,(\bar{d} - \bar{u})$$

  (e.g. chiral soliton model)

- Disentangle origin of unpolarized and polarized asymmetries in nucleon sea via semi-inclusive DIS



Spin dependent flavor asymmetry of the proton sea



Projected errors for semi-inclusive polarization ratios for Hall A at 12 GeV

Transverse Structure

- Transversity distribution $\delta q(x)$

$\longrightarrow$ transversely polarized quarks in a transversely polarized nucleon

Ralston, Soper (1979)

$\longrightarrow$ twist-2

$\longrightarrow$ in nonrelativistic limit $\delta q \to \Delta q$

$\longrightarrow$ valence-like (no transverse gluon δG)

$\longrightarrow$ chiral-odd $\Rightarrow$ need ≥ 2 hadrons

e.g. semi-inclusive DIS, $eN \to e\pi X$

- Transverse momentum dependent distributions

$\longrightarrow$ $q(x) = \int d^2k_\perp \; q^\perp(x, k_\perp)$

$\longrightarrow$ final state interactions at leading twist !

Brodsky, Hwang, Schmid (2001)

$\longrightarrow$ implies T-odd "Sivers" function $f_{1T}^\perp(x, k_\perp)$

Collins (2002)

$\longrightarrow$ measure in spin-azimuthal asymmetries

δq is *similar* to q, Δq

- leading twist (not $1/Q^2$ suppressed)

- has simple parton model interpretation

- is "big"
  $\longrightarrow$ in SU(6) quark model $\delta q = \Delta q$

- calculable in lattice QCD

δq is *<u>different</u>* from q, Δq

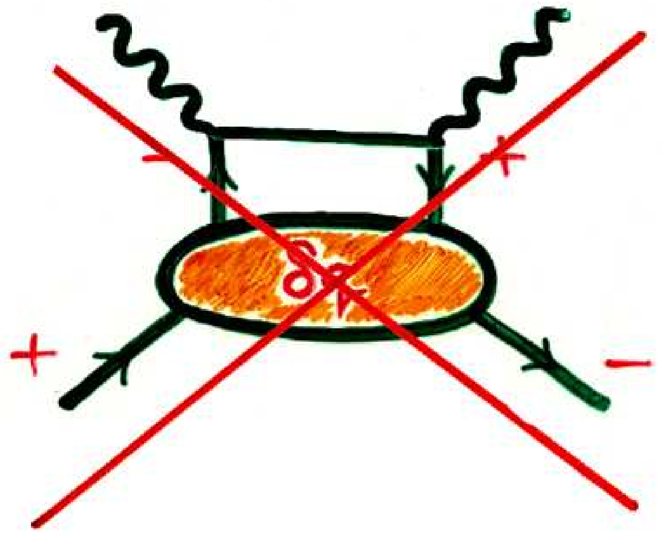
- chiral odd — requires chirality (helicity) flip
  $\longrightarrow$ cannot be measured in inclusive DIS

- has no "transverse gluon" counterpart
  $\longrightarrow q \longleftrightarrow G \;, \quad \Delta q \longleftrightarrow \Delta G$

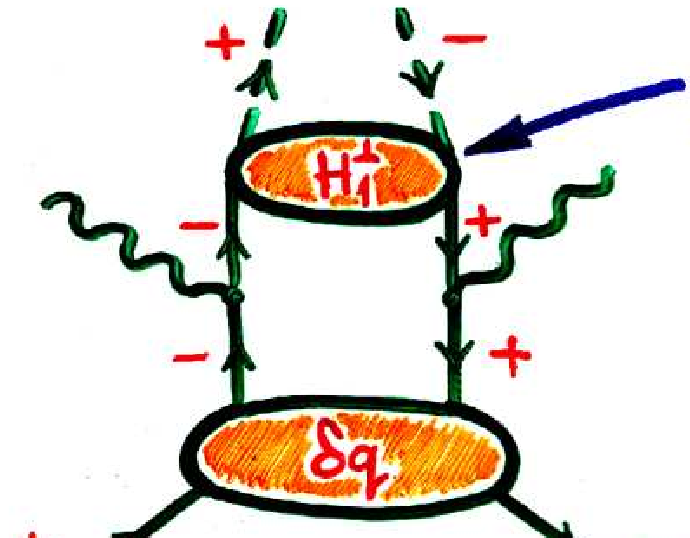
  but $\delta q \longleftrightarrow \cancel{\delta G}$

- does not couple to gluons
  $\longrightarrow$ valence-like (evolves as non-singlet)

- no empirical information!



chiral odd



chiral odd
fragmentation
function
(Collins)

Transversity in semi-inclusive DIS

δq can be extracted from transverse single spin asymmetry in semi-inclusive DIS

$$A_{UT} = \frac{d\sigma(\vec{S}_\perp) - d\sigma(-\vec{S}_\perp)}{d\sigma(\vec{S}_\perp) + d\sigma(-\vec{S}_\perp)}$$
$$\propto \sin(\phi_h + \phi_{S_\perp}) \frac{\sum_q e_q^2 \ \delta q(x) \ H_{1q}^\perp(z)}{\sum_q e_q^2 \ q(x) \ D_q(z)}$$

- chiral-odd fragmentation function $H_1^\perp$
  $\longrightarrow$ quark fragmentation to pion in a superposition of $L = 0$ and 1 states
  (Collins)

- $H_1^\perp$ also T-odd
  $\longrightarrow$ requires final state interactions
  $\longrightarrow$ existence of T-odd effects disputed
  (Jaffe et al.)

- FSI interactions recently shown to exist at leading twist

  (Brodsky, Hwang, Schmid)

  $\longrightarrow$ provides existence proof of T-odd distributions

- initial state interactions can also give rise to T-odd distribution functions

  (Anselmino et al.)

- implies existence of "Sivers" asymmetry

  ($k_\perp$ quark distribution with azimuthal asymmetry)

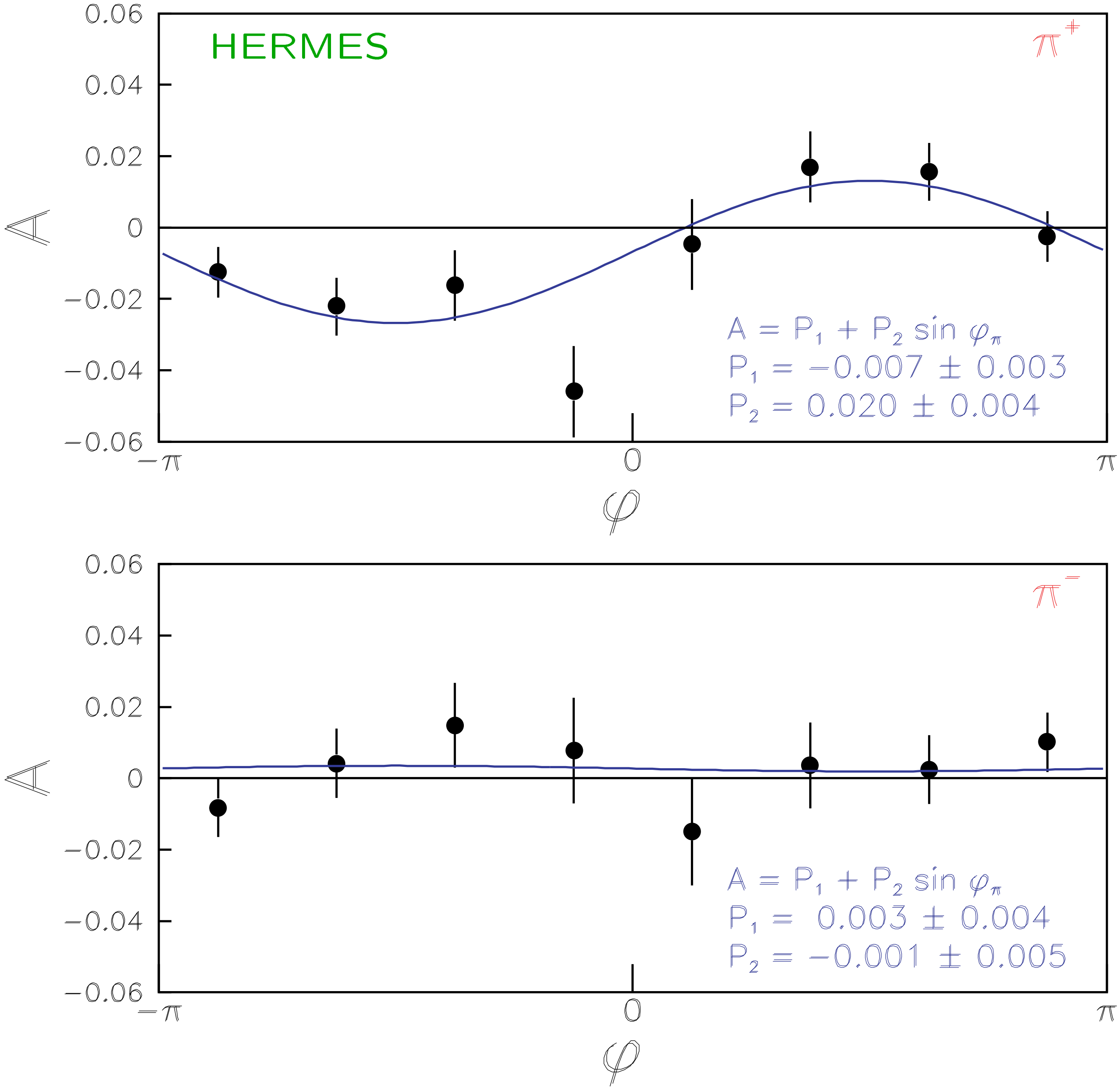
  but with opposite sign in Drell-Yan and DIS

  (Collins)

  $\longrightarrow$ $f_{1T}^{\perp}(x,k_\perp)\Big|_{DIS} = -\, f_{1T}^{\perp}(x,k_\perp)\Big|_{DY}$

  $\longrightarrow$ violates universality of parton densities

Azimuthal asymmetries



- Azimuthal $\sin\phi$ asymmetry observed with longatudinally polarized target at HERMES

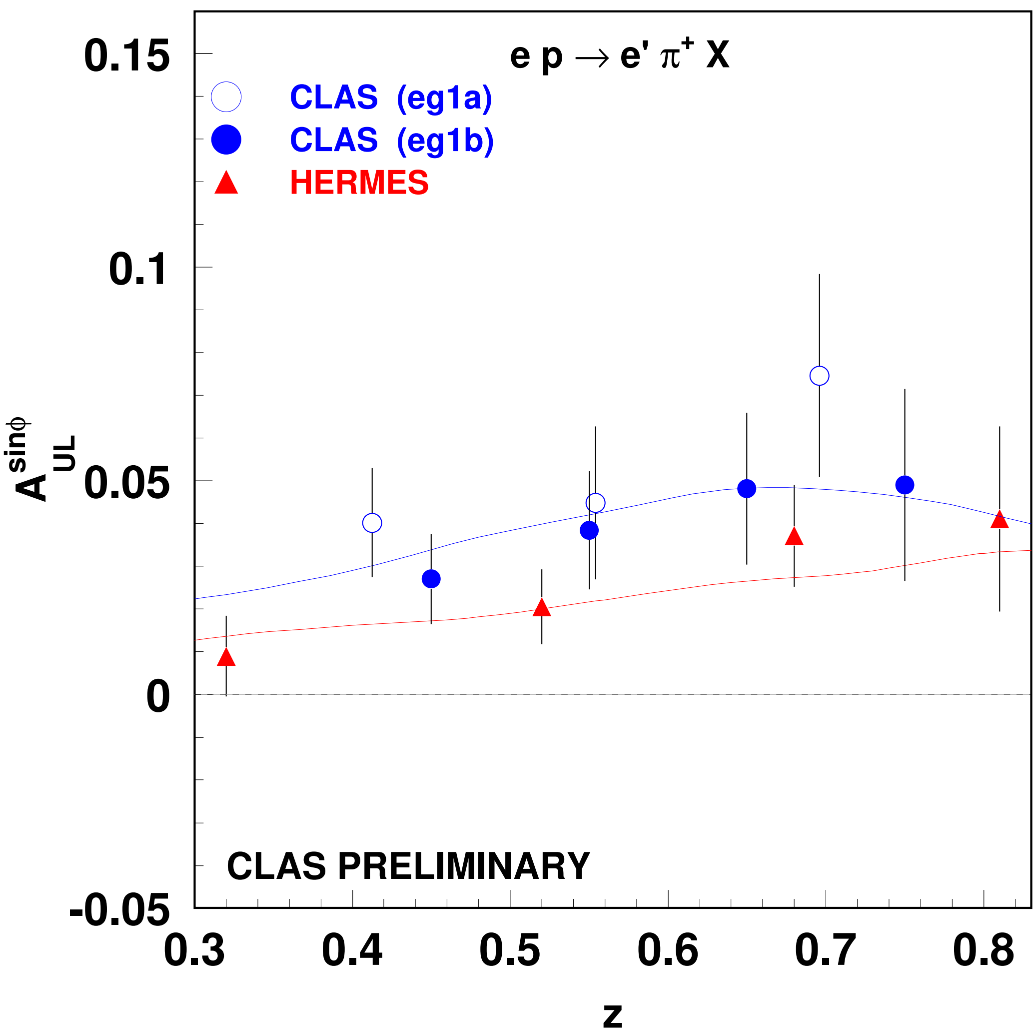
- Origin could be transversity δq, or twist-3 chiral odd distribution function h_L

$$\sigma_{UL}^{\sin\phi} \propto A\, S_L\, h_L(x)\, H_1^{\perp}(z) + B\, S_T\, \delta q(x)\, H_1^{\perp}(z)$$

- Non-zero asymmetry suggests existence of Collins fragmentation function $H_1^{\perp}$

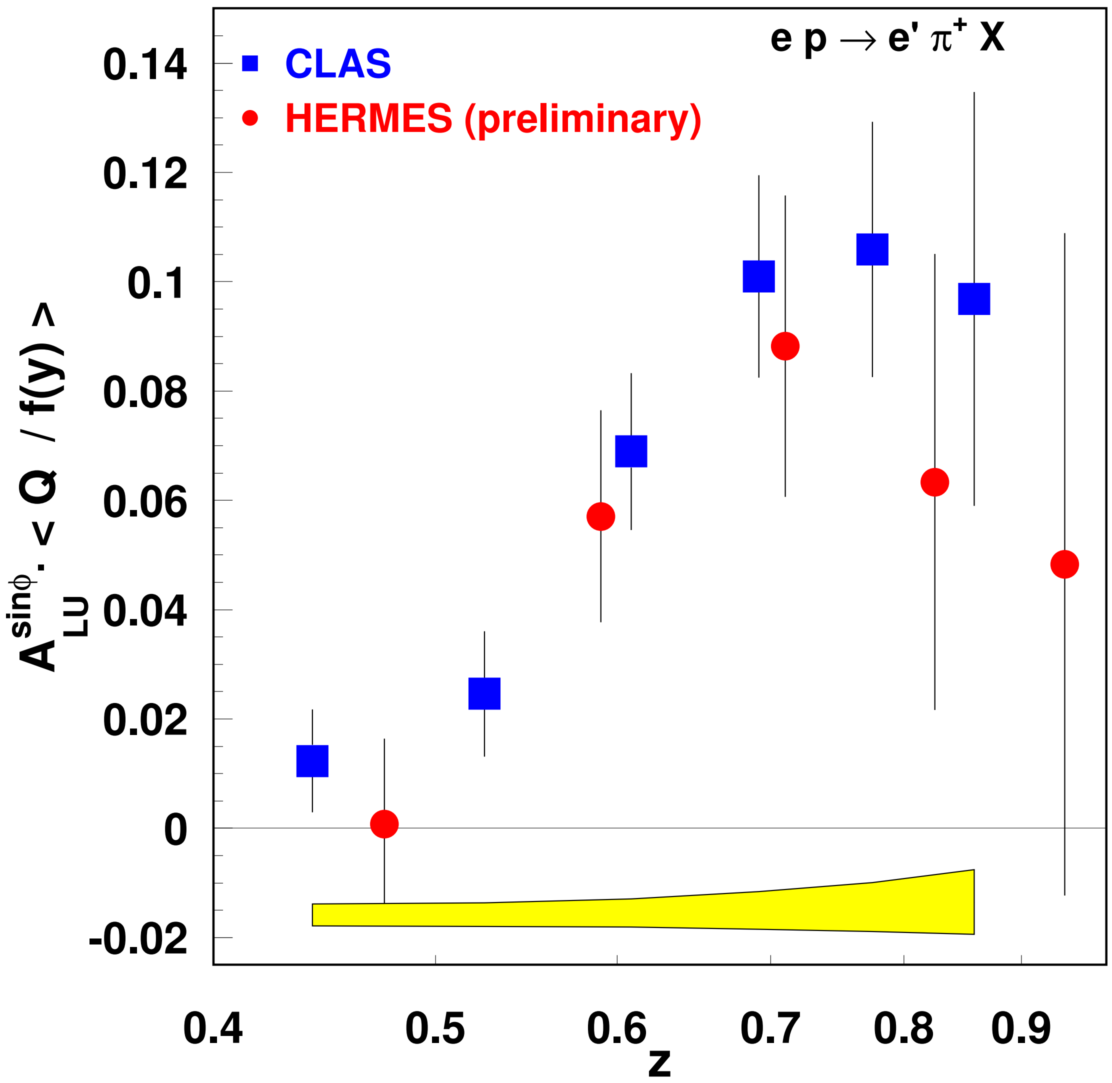
$$\sigma_{UL}^{\sin\phi} \propto A\, S_L\, h_L(x)\, H_1^{\perp}(z) + B\, S_T\, \delta q(x)\, H_1^{\perp}(z)$$

$$+\, C\; S_T\; f_{1T}^{\perp}(x)\; D(z)$$



H. Avakian, L. Elouadrhiri

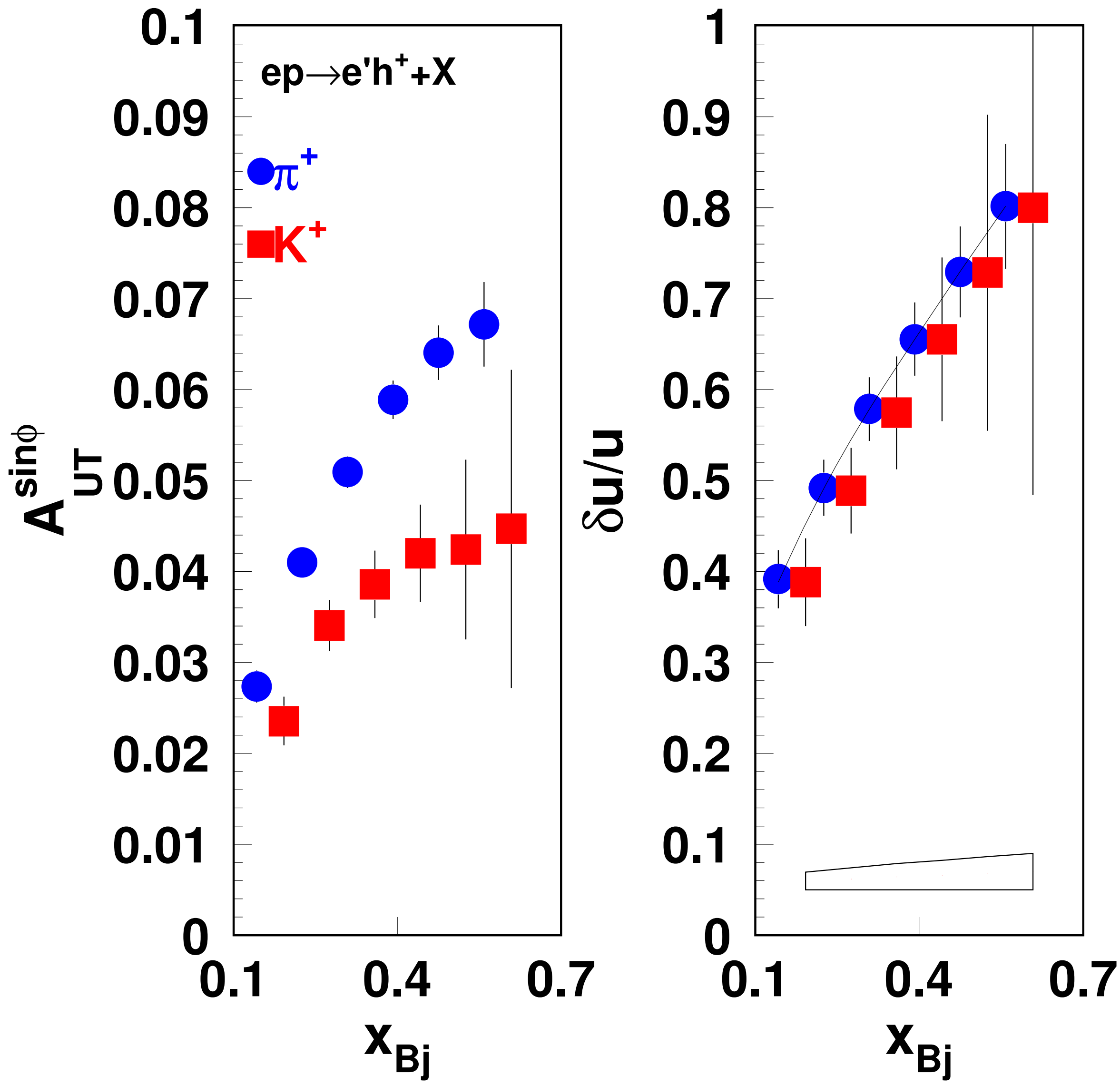
$$\sigma_{LU}^{\sin\phi} \propto e(x)\, H_1^{\perp}(z) + \text{photon Sivers effect}$$



H. Avakian, L. Elouadrhiri

$$\sigma_{UT}^{\sin\phi} \propto A\ \sin(\phi_h - \phi_{S_\perp})\ \delta q(x)\ H_1^\perp(z)$$

$$+\ B\ \sin(\phi_h + \phi_{S_\perp})\ f_{1T}^\perp(x)\ D(z)$$



Projected errors with CLAS++ (H. Avakian)

A Plethora of Functions

distribution functions		chirality even	odd
twist 2	U	q	$h_1^\perp$
	L	Δq	$h_{1L}^\perp$
	T	$f_{1T}^\perp \quad g_{1T}$	$\delta q \quad h_{1T}^\perp$
twist 3	U	$f^\perp$	e
	L	$g_L^\perp$	h_L
	T	$g_T \quad g_T^\perp$	$h_T \quad h_T^\perp$

"Son, if I could remember the names of all these ~~particles~~ functions, I would have become a botanist!" E. Fermi

$\boxed{\text{Structure Functions in Lattice QCD}}$

On lattice (Euclidean space) cannot calculate x-distribution $\longrightarrow$ only *moments*

$$\langle x^n \rangle \;=\; \int_0^1 dx\; x^n \left(q(x) + (-1)^{n+1}\; \bar{q}(x) \right)$$

$\langle x^n \rangle \longrightarrow$ matrix elements of $\tau = 2$ operators

$$\langle x^n \rangle\; p_{\mu_1} \cdots p_{\mu_{n+1}} \;=\; \langle N |\; \mathcal{O}_{\{\mu_1 \cdots \mu_{n+1}\}} | N \rangle$$

where

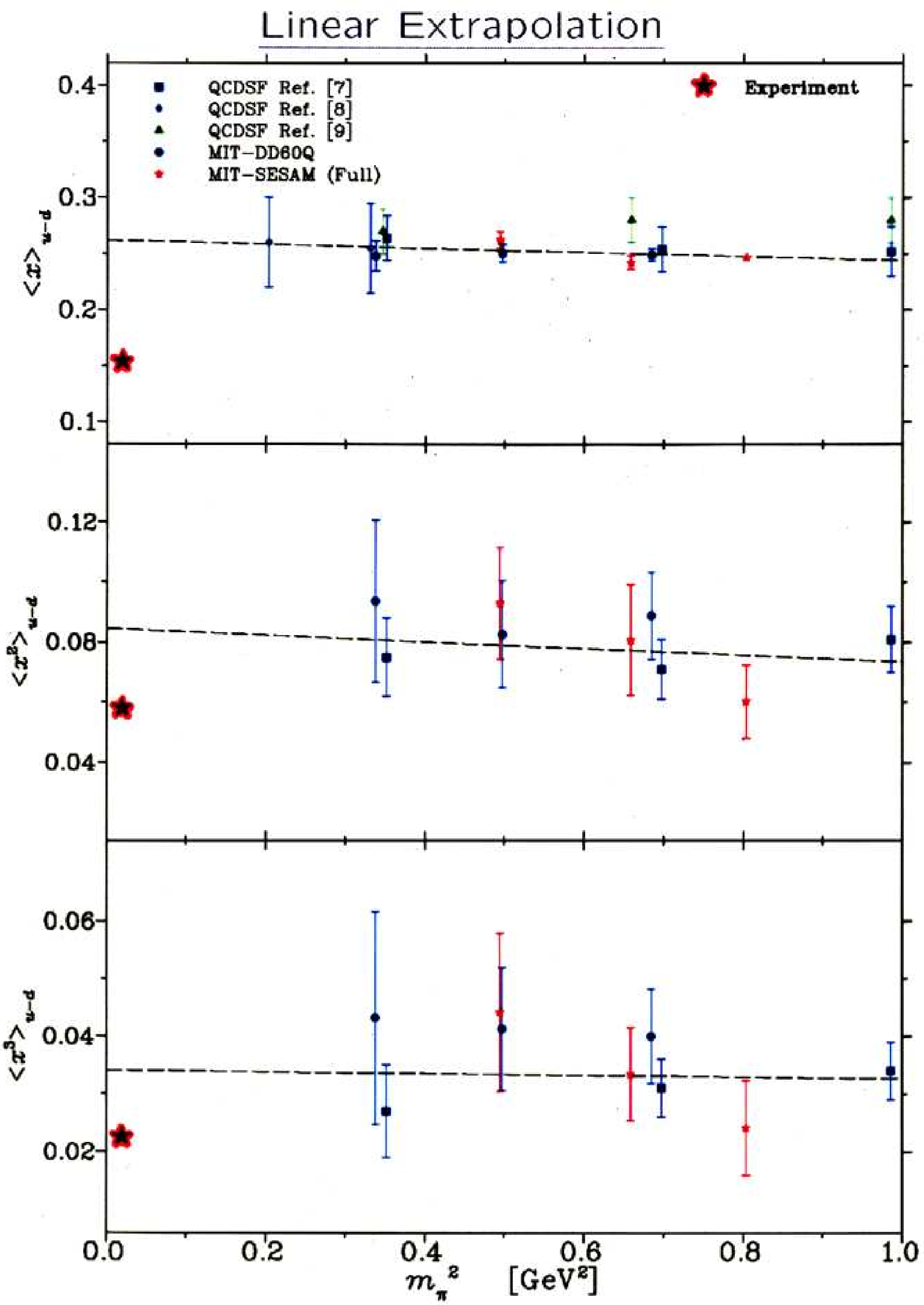
$$\mathcal{O}_{\{\mu_1 \cdots \mu_{n+1}\}} \;=\; \overline{\psi}\; \gamma_{\{\mu_1} \overleftrightarrow{D}_{\mu_2} \cdots \overleftrightarrow{D}_{\mu_{n+1}\}}\; \psi$$

Recent developments:

- first large-scale quenched simulations
  (QCDSF, 1996-7)

- first unquenched simulations
  (MIT, 2000)

- connection with phenomenology via chiral extrapolation
  (JLab-Adelaide-MIT, 2001)



Linear Extrapolation
QCDSF Ref. [7]
QCDSF Ref. [8]
QCDSF Ref. [9]
MIT-DD60Q
MIT-SESAM (Full)
Experiment
0.4
0.3
0.2
0.1
$\langle x \rangle_{u-d}$
0.12
0.08
0.04
$\langle x^2 \rangle_{u-d}$
0.06
0.04
0.02
$\langle x^3 \rangle_{u-d}$
0.0
0.2
0.4
0.6
0.8
1.0
m_π^2 [GeV^2]

$\boxed{\text{Chiral Symmetry and QCD}}$

- In limit $m_q \to 0$, QCD has exact *chiral* SU(N$_f$)$_L$×SU(N$_f$)$_R$ symmetry

- Spontaneous breaking of chiral symmetry

$\longrightarrow$ appearance of pseudoscalar Goldstone bosons (π, K)

- Pions play important role at small $m_\pi^2 \sim m_q$

$\longrightarrow$ expand observables in powers of m_π (e.g. χPT)

- Pion loops in χPT generate non-polynomial terms which are *non-analytic* in m_q (odd powers of m_π or log m_π)

- Coefficients of non-analytic terms are model-independent

  $\longrightarrow$ given in terms of g_A and f_π

- Lattice calculations employ $m_q > 30$ MeV

$\longrightarrow$ need to extrapolate to physical m_q

- m_q dependence of observables

$\longrightarrow$ constrained by χPT in $m_q \to 0$ limit
Note: expansion may not converge
at large m_π!

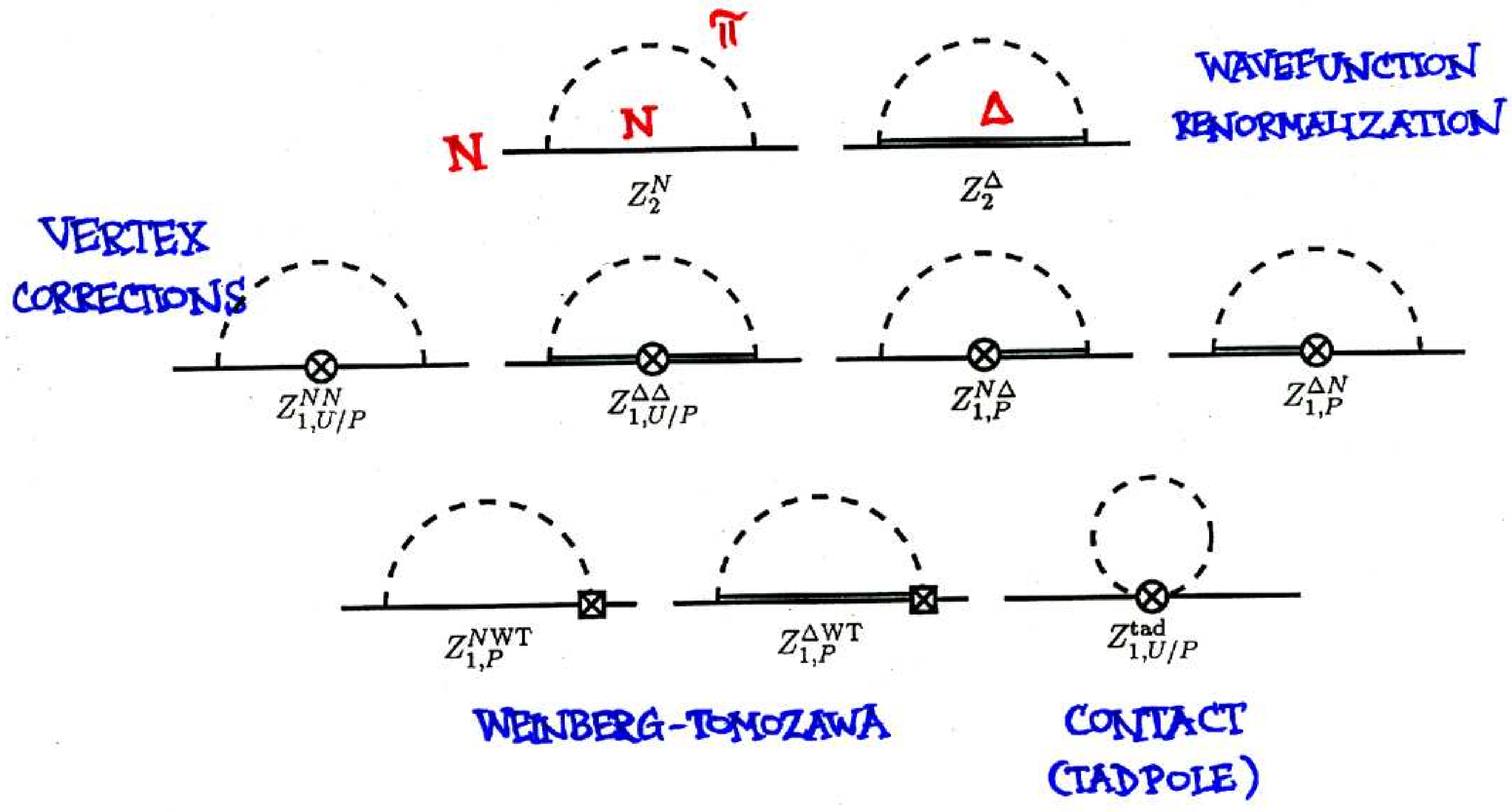
$\longrightarrow$ constrained by heavy quark effective
theory in $m_q \to \infty$ limit

- Physics picture — source of π field is a complex system of quarks and gluons with finite size, Λ

$\longrightarrow$ for $m_\pi > \Lambda$ π loops suppressed,
hadron observables smooth in m_q
("constituent quark-like" behavior)

$\longrightarrow$ for $m_\pi < \Lambda$ rapid non-linear variation

$\longrightarrow$ transition occurs at $m_\pi \sim 500$ MeV


N
N
π
Δ
WAVEFUNCTION
RENORMALIZATION
Z_2^N
Z_2^Δ
VERTEX
CORRECTIONS
$Z_{1,U/P}^{NN}$
$Z_{1,U/P}^{\Delta\Delta}$
$Z_{1,P}^{N\Delta}$
$Z_{1,P}^{\Delta N}$
$Z_{1,P}^{N\mathrm{WT}}$
$Z_{1,P}^{\Delta\mathrm{WT}}$
$Z_{1,U/P}^{\mathrm{tad}}$
WEINBERG-TOMOZAWA
CONTACT
(TADPOLE)

$\boxed{\text{Chiral Extrapolation of Moments}}$

Chiral extrapolation of n-th moment of $u-d$:

$$\langle x^n \rangle_{u-d} \;=\; a_n \;+\; b_n \, \frac{m_\pi^2}{m_\pi^2 + m_b^2}$$

$$+\; c_n \; m_\pi^2 \log \left(\frac{m_\pi^2}{m_\pi^2 + \mu^2} \right)$$

Detmold, WM, Negele, Renner, Thomas,
Phys. Rev. Lett. **87** (2001) 172001

Coefficient of non-analytic term:

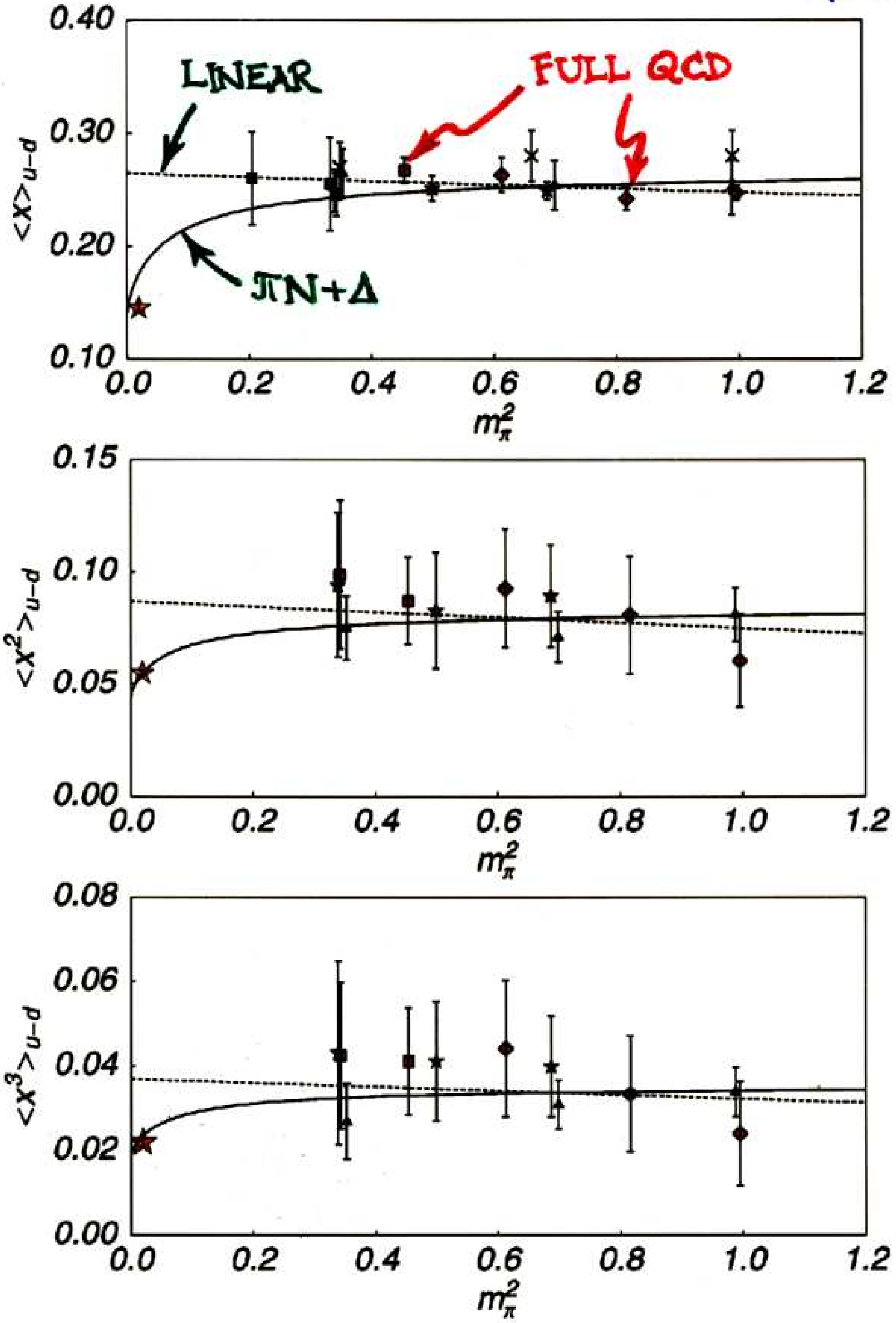
$$c_n \;=\; -a_n \, \frac{3 g_A^2 + 1}{4 \pi^2 f_\pi^2}$$

calculated in chiral perturbation theory

Chen, Ji, *Phys. Lett.* B **523** (2001) 107
Arndt, Savage, *Nucl. Phys.* A**697** (2002) 429

DETMOLD ET AL. PRL 87 (2001) 172001

DETMOLD, WM, THOMAS PRD (2002), hep-lat/0206001



$\boxed{\textbf{Spin Depdendent Distributions}}$

Moments of spin dependent distributions:

$$\langle \Delta x^n \rangle \;=\; \int_0^1 dx x^n \left(\Delta q(x) + (-1)^n \; \Delta \bar{q}(x)\right)$$

helicity

$$\langle \delta x^n \rangle \;=\; \int_0^1 dx x^n \left(\delta q(x) + (-1)^{n+1} \; \delta \bar{q}(x)\right)$$

transversity

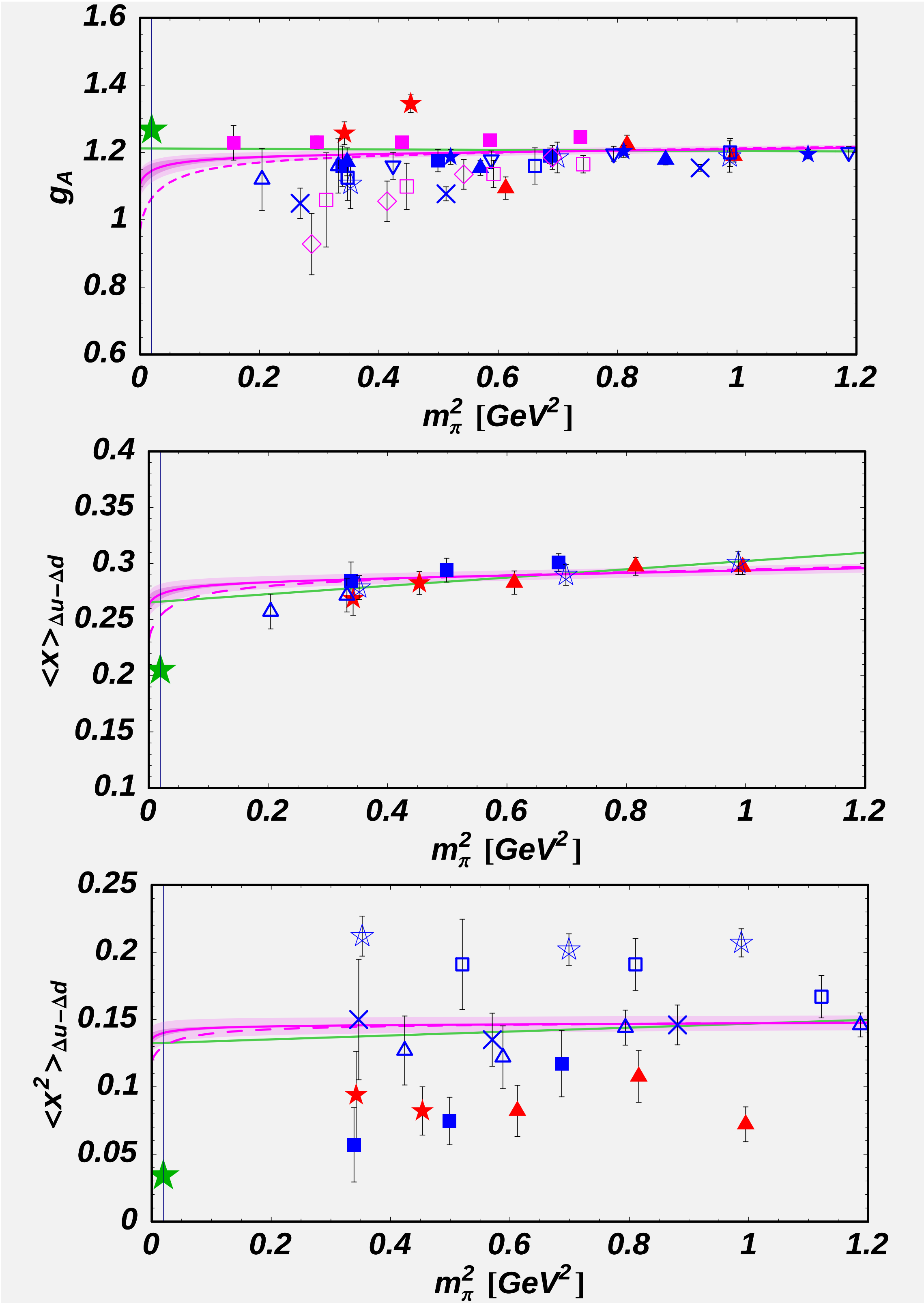
from matrix elements of $\tau = 2$ operators:

$$\langle N | \bar{\psi} \; \gamma_{\{\mu_1} \gamma_5 \; D_{\mu_2} \cdots D_{\mu_{n+1}\}} \; \psi | N \rangle \;\longrightarrow\; \langle \Delta x^n \rangle$$

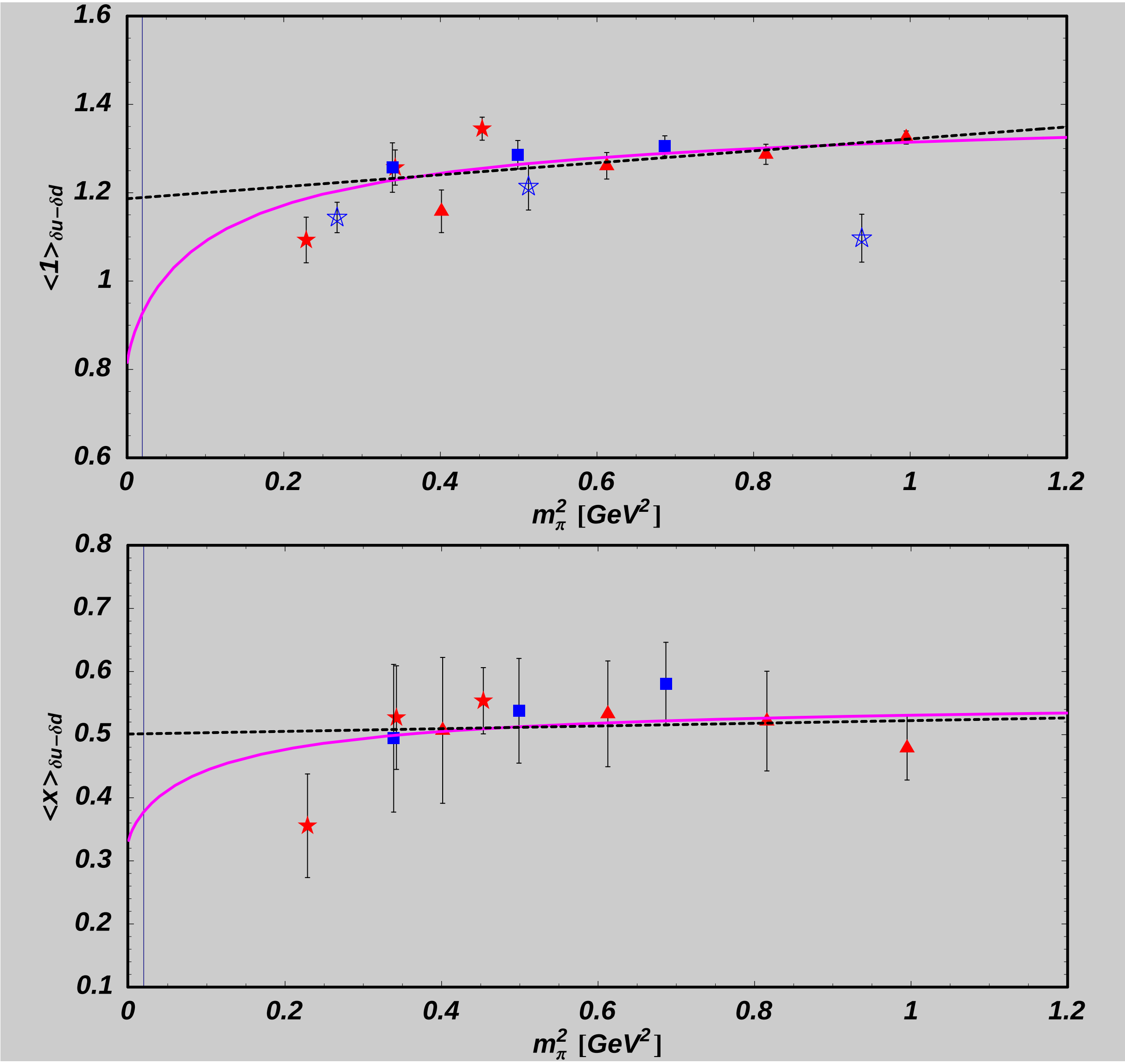
$$\langle N | \bar{\psi} \; \sigma_{[\alpha\{\mu_1]} \gamma_5 \; D_{\mu_2} \cdots D_{\mu_{n+1}\}} \; \psi | N \rangle \;\longrightarrow\; \langle \delta x^n \rangle$$

Leading nonanalytic chiral coefficients recently calculated for both $\langle \Delta x^n \rangle$ and $\langle \delta x^n \rangle$

Chen & Ji, *Phys. Lett.* B 523 (2001) 73



g_A
m_π^2 [GeV^2]
$<x>_{\Delta u-\Delta d}$
m_π^2 [GeV^2]
$<x^2>_{\Delta u-\Delta d}$
m_π^2 [GeV^2]



Moments of the transversity distribution

Detmold, WM, Thomas
Phys. Rev. D 66 (2002) 054501

Conclusions & outlook

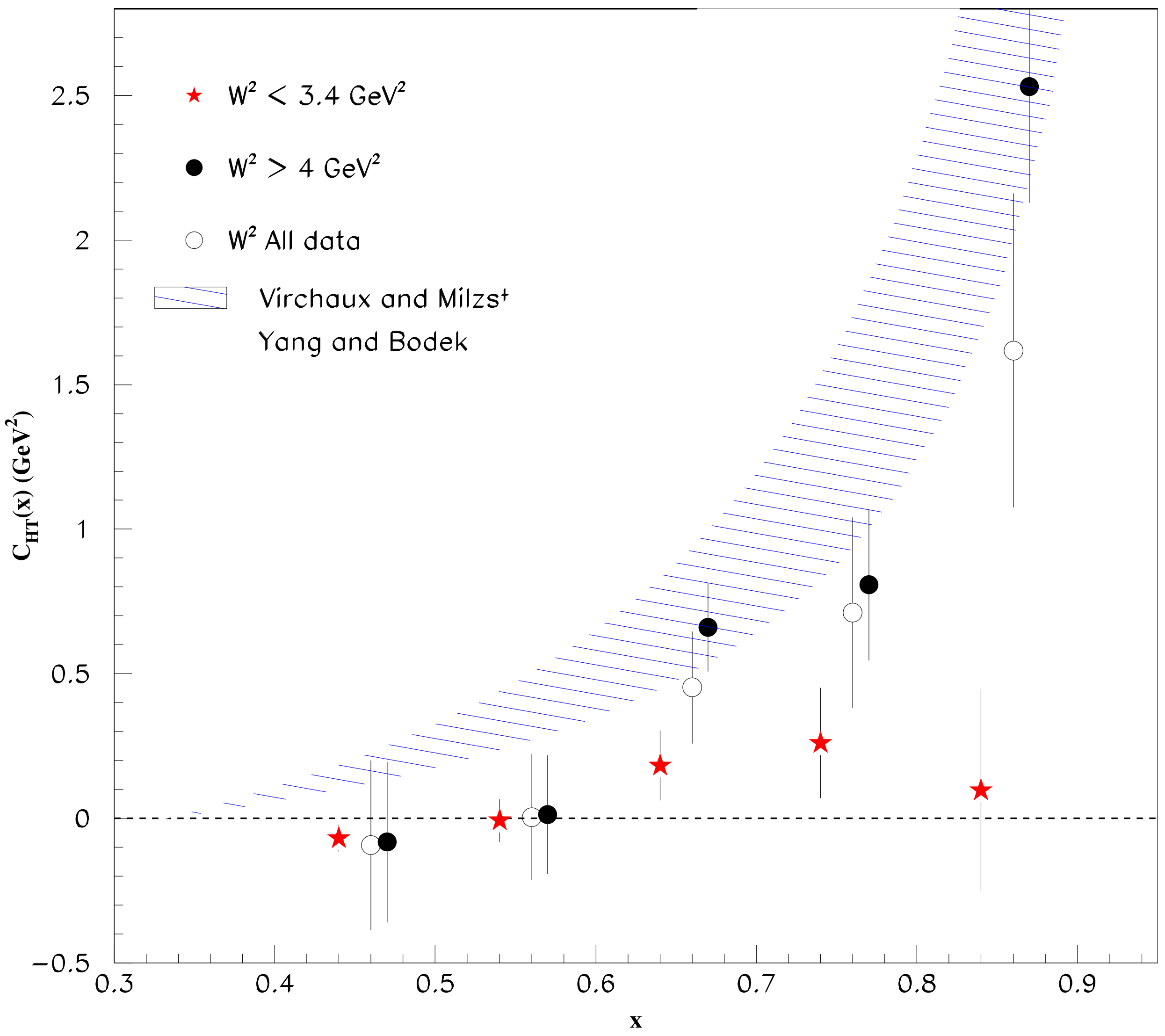
- Great strides made over past few years in understanding quark and gluon substructure of nucleon
  $\longrightarrow$ unprecedented quality of recent data pushing theory to new frontiers

- Systematic study of structure functions in resonance region
  $\longrightarrow$ mystery of Bloom-Gilman duality still with us!
  $\longrightarrow$ have qualitative understanding of coherent $\rightarrow$ incoherent transition
  $\longrightarrow$ closer connection with phenomenology sought
  $\longrightarrow$ restate problem in terms of higher twists (calculated on lattice)
  $\longrightarrow$ x dependence of higher twists

- First glimpse into (hitherto unexplored) large x region of valence quarks
  - $\longrightarrow$ no sign of hadron helicity conservation in $x \rightarrow 1$ dependence !
  - $\longrightarrow$ need to systematically incorporate target mass effects in Q^2 evolution
  - $\longrightarrow$ Sudakov effects at large x ?
  - $\longrightarrow$ JLab @ 12 GeV will resolve 30-year old question about $x \rightarrow 1$ behavior of parton distributions
  - $\longrightarrow$ new frontier of transverse (momentum and spin) dependence
    $\longrightarrow$ *GPD section*

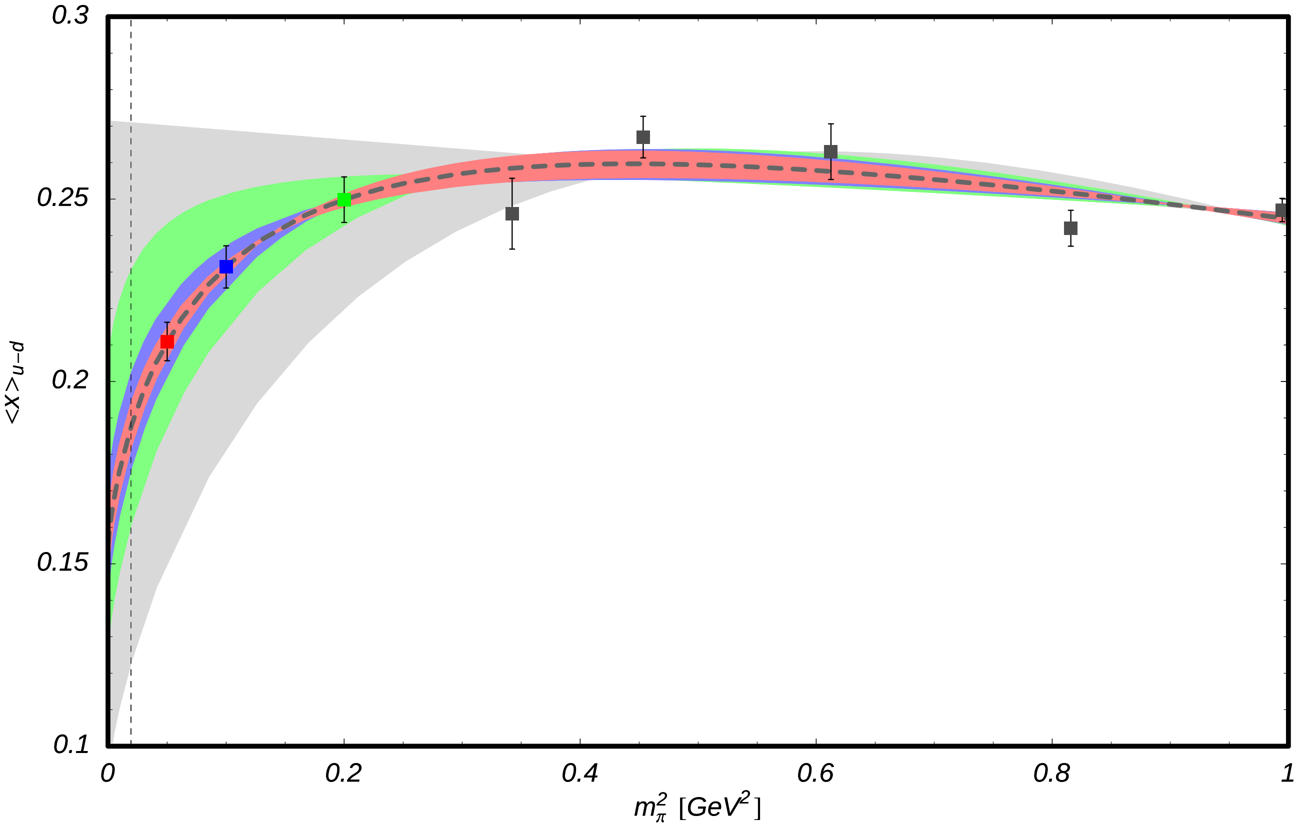
- Significant progress expected from lattice QCD over next 7 years
  - $\longrightarrow$ e.g. JLab-MIT Lattice Hadron Physics Collaboration
  - $\longrightarrow$ 0.5 $\rightarrow$ 8 Tflops cluster 2003 $\rightarrow$ 2006
  - $\longrightarrow$ $\sim$ 5% unquenched calculations of PDF moments at small m_q

$$F_2 = F_2^{LT+TMC}\left(1 + \frac{C_{HT}(x)}{Q^2} + \Delta H(x, Q^2)\right)$$



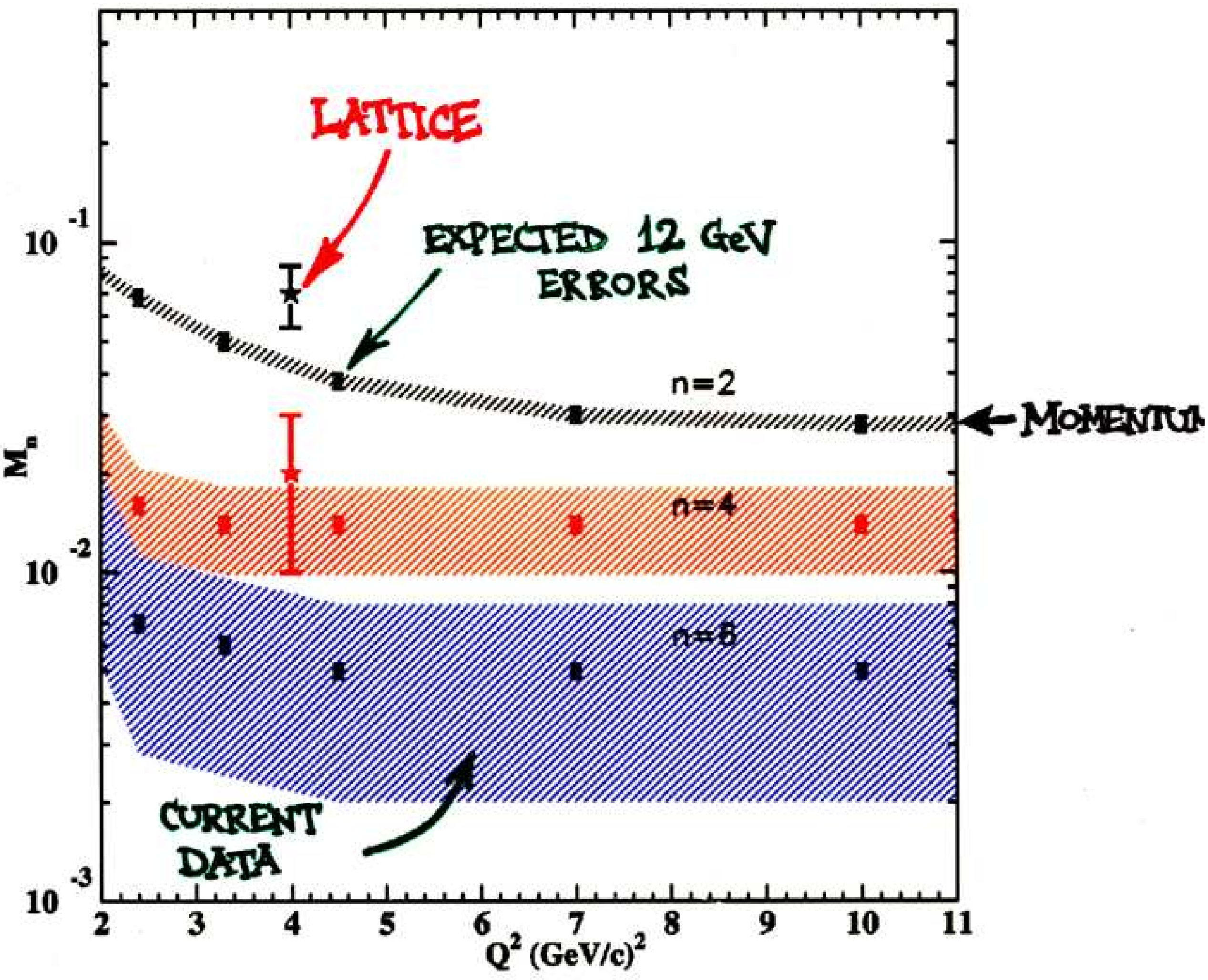
Liuti, Ent, Keppel, Niculescu

Phys. Rev. Lett. 89 (2002) 162001

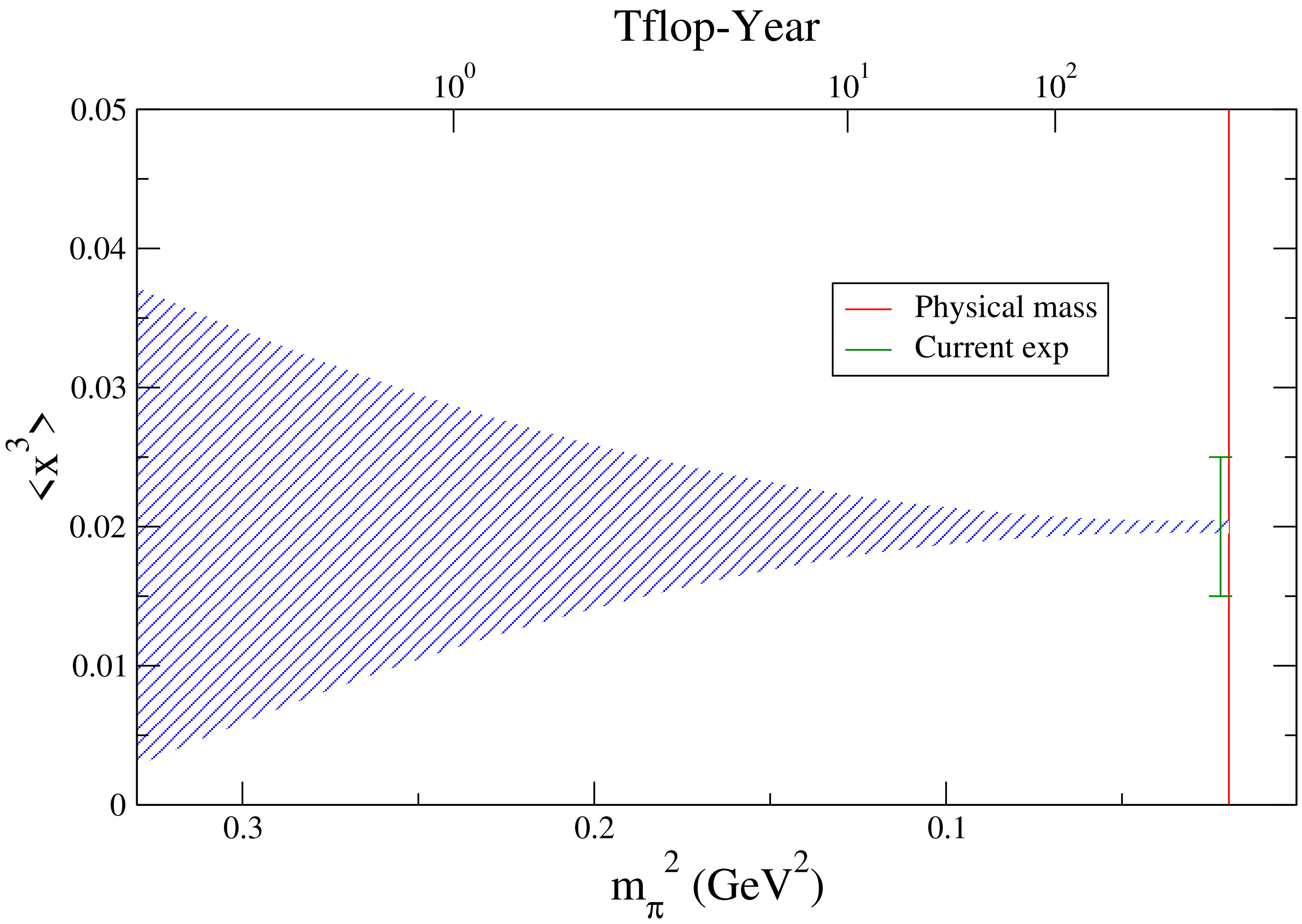


Momentum carried by $u{-}d$ quarks in the the proton
with projected lattice errors on chiral extrapolation

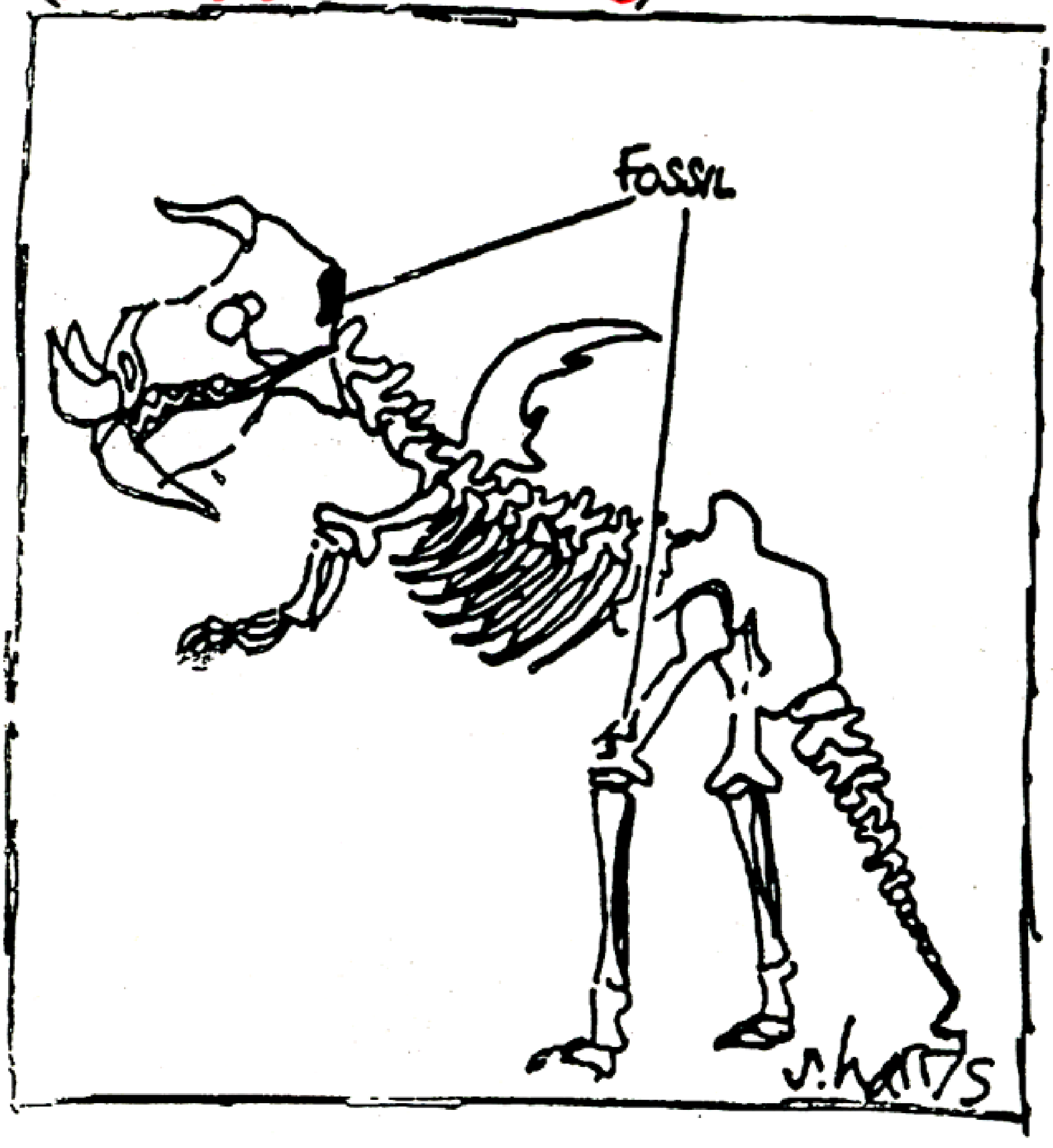
Detmold, WM, Thomas (2002)



Lowest moments of F_2^p, compared with lattice calculations.


Tflop-Year
10^0
10^1
10^2
0.05
0.04
0.03
0.02
0.01
0
$<x^3>$
Physical mass
Current exp
0.3
0.2
0.1
m_π^2 (GeV^2)

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



"STRUCTURE SAURUS"

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