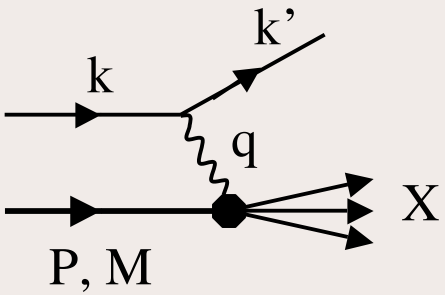
Lecture 4

Deep Inelastic Scattering:

Current versus Constituent Quarks

Inclusive Lepton Scattering off the Nucleon



k (k') = incoming (outgoing) lepton momentum

q = k - k' = four-momentum transfer

P = initial four-momentum of the nucleon *($P^2 = M^2$)*

<u>Invariants</u>: $\nu = \dfrac{q \bullet P}{M}$ = energy transfer in the lab frame (nucleon rest frame)

$Q^2 = -q \bullet q$ = squared four-momentum transfer

$x = \dfrac{Q^2}{2M\nu}$ = Bjorken variable = fraction of the total nucleon momentum carried by the struck quark (parton model)

$y = \dfrac{q \bullet P}{k \bullet P}$ = fraction of the lepton energy loss

$W^2 = (P+q)^2$ = squared mass of the system X

neutral current: exchange of virtual photon and Z-boson (and interference)

charged current: exchange of $W^{\pm}$ bosons

the only one parity conserving

electron scattering (of interest for JLab):

- cross section: $$\frac{d^2\sigma}{dx\,dy} = \frac{2\pi\, y\, \alpha_{em}^2}{Q^4} L_{\mu\nu} W^{\mu\nu}$$

electron helicity (±1)

- electron tensor: $$L_{\mu\nu} = 2\left(k_\mu k'_\nu + k'_\mu k_\nu - k \bullet k' g_{\mu\nu} - i\lambda_e \varepsilon_{\mu\nu\rho\sigma} k^\rho k'^\sigma\right)$$

- nucleonic tensor: $$W_{\mu\nu} = \frac{1}{4\pi}\int d^4z\, e^{iq\bullet z}\langle P,S|\left[J_\mu(z),J_\nu(0)\right]|P,S\rangle$$

$$= F_1\left(x,Q^2\right)\left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) + F_2\left(x,Q^2\right)\frac{\hat{P}_\mu \hat{P}_\nu}{P\bullet q}$$

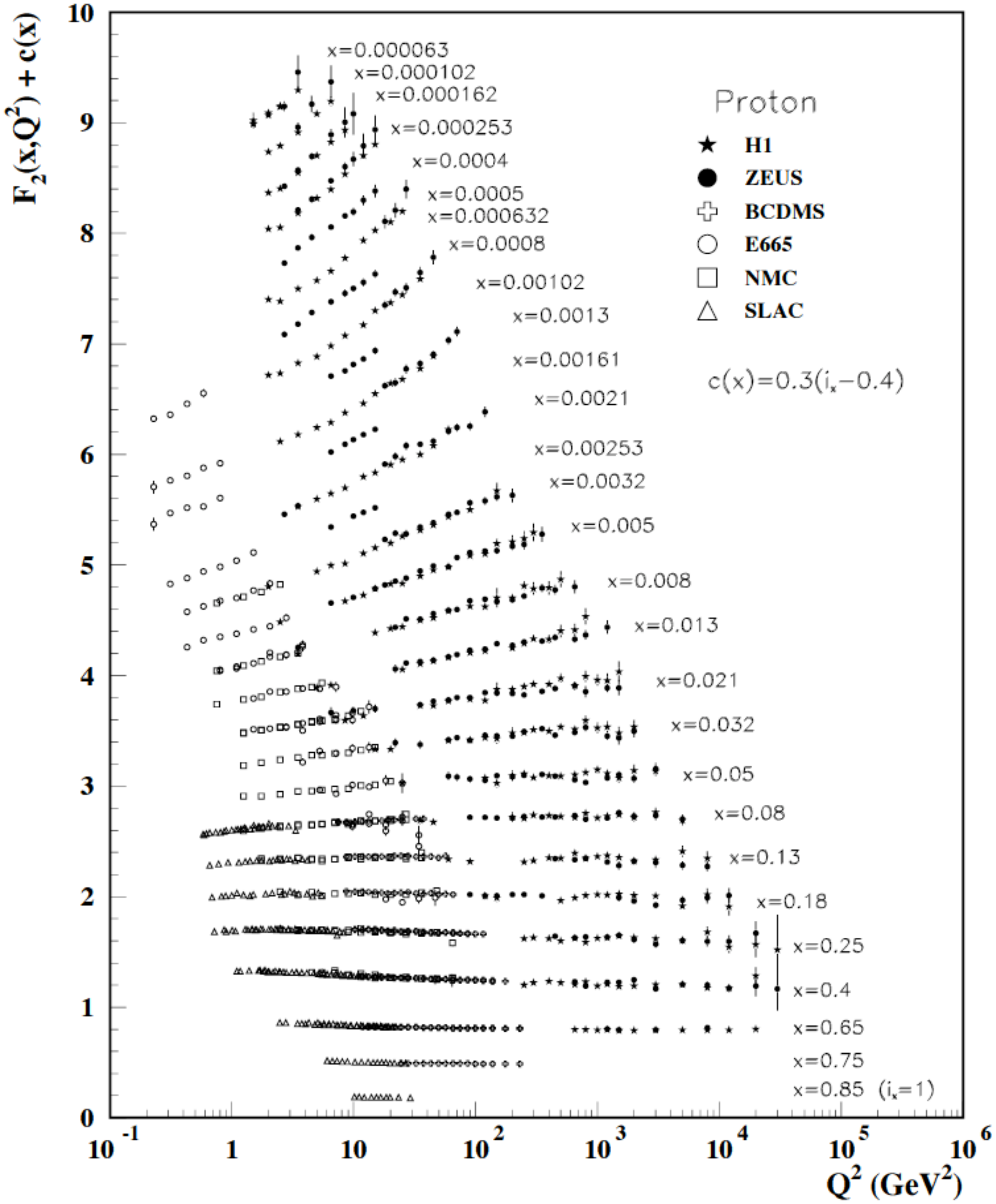
$$-i\varepsilon_{\mu\nu\rho\sigma}\frac{q^\rho}{P\bullet q}\left[g_1\left(x,Q^2\right) S^\sigma + g_2\left(x,Q^2\right)\left(S^\sigma - \frac{S\bullet q}{P\bullet q}P^\sigma\right)\right]$$

nucleon spin 4-vector

F_1 and F_2: unpolarized nucleon structure functions

g_1 and g_2: polarized nucleon structure functions

$$\hat{P}_\mu = P_\mu - q_\mu\, P\bullet q / q^2$$



[PDG ('02)]

Deep ($Q^2 >> M^2$)

Inelastic ($W^2 >> M^2$)

Scattering

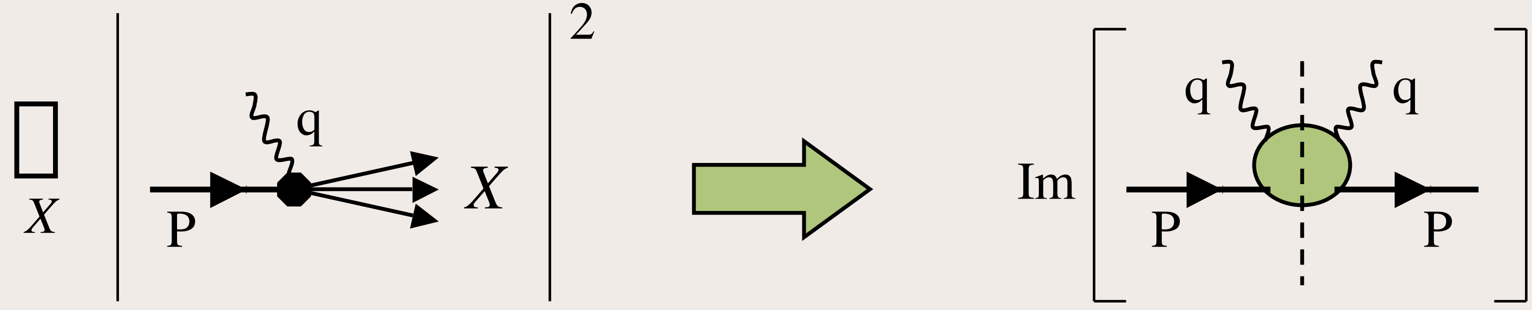
SLAC-MIT data

Bjorken scaling

$$\lim_{\substack{Q^2 \to \infty \\ x\ fixed}} F_2\left(x, Q^2\right) \to F_2(x)$$

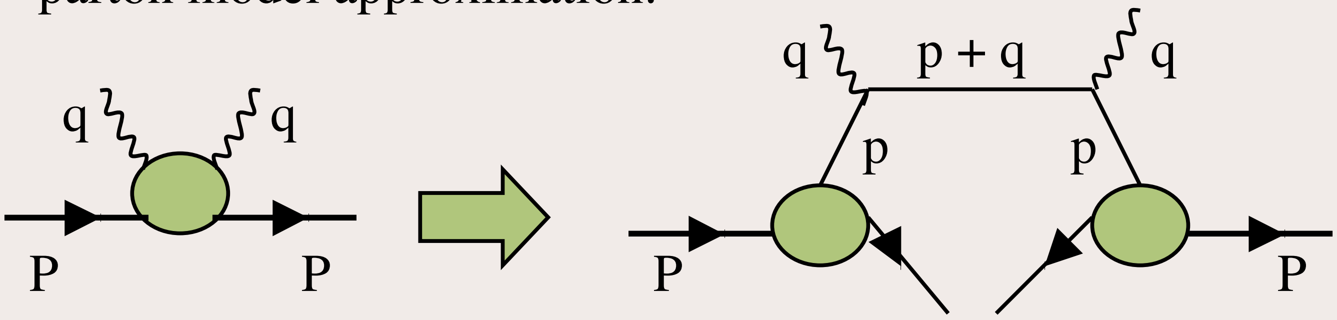
the naïve quark-parton model: [Bjorken, Feynman, …]

Bj scaling arises from elastic scattering on free partons



$$T^{\mu\nu} = \text{forward Compton amplitude} = \int d^4z\, e^{iq\cdot z} \langle P,S|\, T\left[J^{\mu}(z)\, J^{\nu}(0)\right] |P,S\rangle$$

- parton model approximation:



$p = \xi P$

+ exch. diagr.

- infinite momentum frame (neglect of transverse momenta):

$$T^{\mu\nu} \approx \int d^4 z\, e^{iq\bullet z} \int_0^1 d\xi \sum_j f_j(\xi)\, \frac{1}{\xi} \left\langle p, s \right| T\left[J^\mu(z)\, J^\nu(0)\right] \left| p, s \right\rangle \Big|_{p=\xi P}$$

$f_j(\xi)$ = distribution function of the parton j

ξ = light-cone fraction of the parton j

- spin-1/2 partons:

$$T^{\mu\nu} \approx \int_0^1 d\xi \sum_j f_j(\xi)\, \frac{1}{\xi}\, e_j^2\, \bar{u}(p,s)\, \gamma^\mu\, \frac{i(\not p + \not q)}{(p+q)^2 + i\varepsilon}\, \gamma^\nu\, u(p,s) + \text{exch. diagr.}$$

- unpolarized case:

$$T^{\mu\nu} \approx \int_0^1 d\xi \sum_j f_j(\xi)\, \frac{1}{\xi}\, e_j^2\, \frac{1}{2} \mathrm{Tr}\left[\not p\, \gamma^\mu (\not p + \not q) \gamma^\nu\right] \frac{-1}{2p\bullet q - Q^2 + i\varepsilon}\Bigg|_{p=\xi P}$$

$$\mathrm{Im}\left(T^{\mu\nu}\right) \approx \int_0^1 d\xi \sum_j f_j(\xi)\, \frac{1}{\xi}\, e_j^2\, \frac{1}{2} \mathrm{Tr}\left[\xi \not P\, \gamma^\mu (\xi \not P + \not q) \gamma^\nu\right] \pi\, \delta\left(2\xi P \bullet q - Q^2\right)$$

$$\frac{d^2\sigma}{dx\,dy}\left(ep \rightarrow eX\right) = \frac{2\pi\alpha_{em}^2}{x\,y\,Q^2}\left[1+\left(1+y\right)^2\right]\overline{F}_2^{\,p}\left(x\right)$$

$$\begin{cases} \overline{F}_2^{\,p}\left(x\right) = x\cdot\sum_j e_j^2\, f_j\left(x\right) \\ \overline{F}_1^{\,p}\left(x\right) = \frac{1}{2x}\,\overline{F}_2^{\,p}\left(x\right) \end{cases}$$

Callan-Gross relation

- in terms of quark (antiquark) flavors:

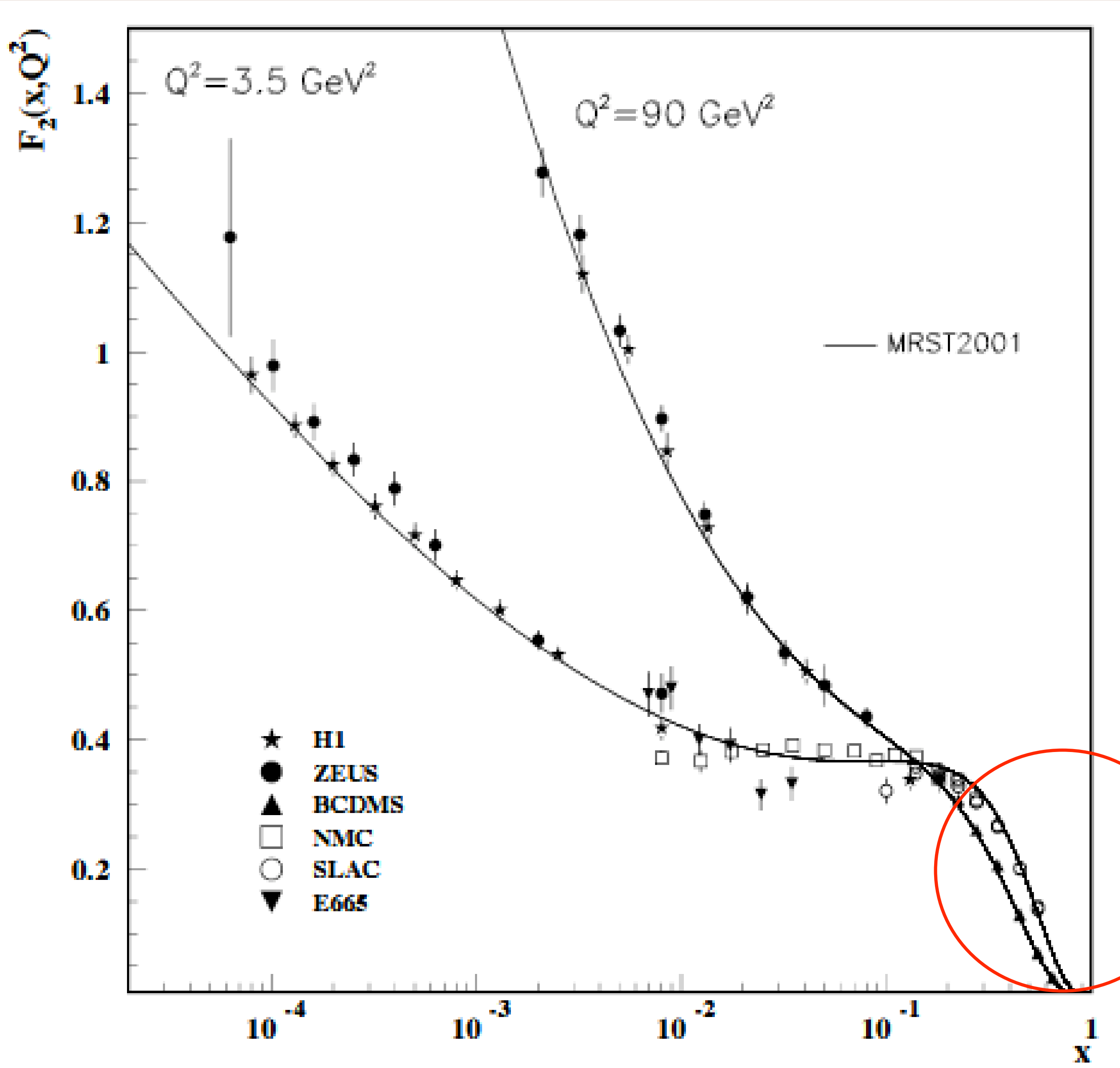
$$\overline{F}_2^{\,p}\left(x\right) = x\cdot\sum_f e_f^2\left[q_f\left(x\right)+\overline{q}_f\left(x\right)\right]$$

QCD-improved parton model: hard gluons can be radiated from quarks while gluons can convert into $q\overline{q}$ pairs

logarithmic scaling violations $\quad q_f\left(x\right) \rightarrow q_f\left(x,Q^2\right)$

- as Q^2 increases: 1) softening of initial quark distributions,

2) growth of gluon and $q\overline{q}$ sea densities as x decreases



[PDG ('02)]

valence quark region

evolution equations (Dokshitzer Gribov Lipatov Altarelli Parisi)

- non-singlet (NS) and singlet (S) quark distributions:

$$q_f^{NS} = q_f - q^S / 2N_f \qquad q^S = \sum_f \left(q_f + \bar{q}_f \right)$$

$$\left\{ \begin{array}{l} \dfrac{\partial q^{NS}}{\partial \ln Q^2} = \dfrac{\alpha_s(Q^2)}{2\pi} P_{qq} \otimes q^{NS} \\[2ex] \dfrac{\partial}{\partial \ln Q^2} \begin{pmatrix} q^S \\ G \end{pmatrix} = \dfrac{\alpha_s(Q^2)}{2\pi} \begin{pmatrix} P_{qq} & 2N_f P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} q^S \\ G \end{pmatrix} \end{array} \right.$$

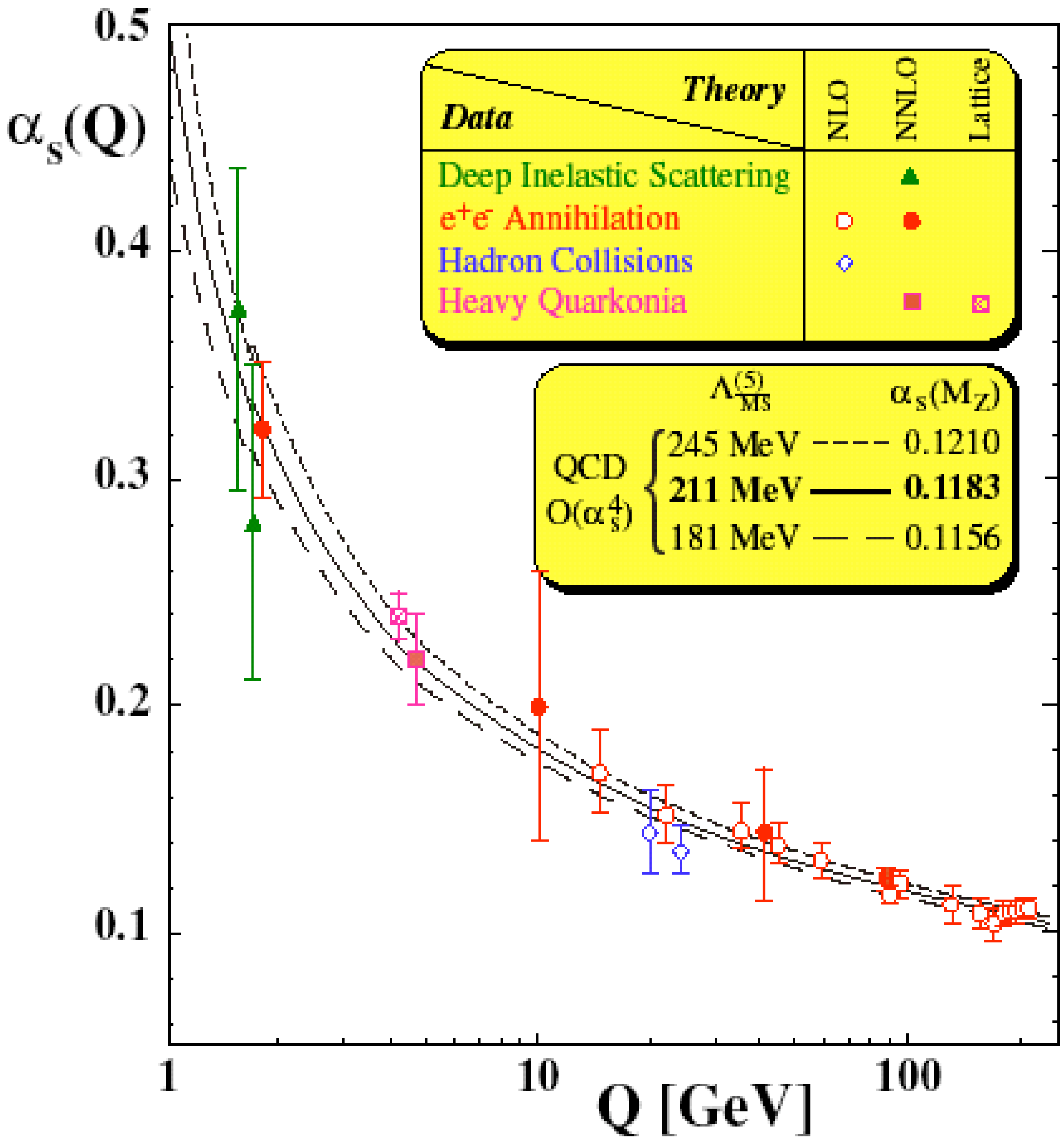
$$P \otimes q = \int_x^1 \frac{dy}{y} P(y)\, q\left(\frac{x}{y} \right)$$

P_{ij} = splitting functions

- running of α_s (β function): $\beta_0 > 0 \Rightarrow$ asymptotic freedom

$$\frac{\partial \alpha_s(Q^2)}{\partial \ln Q^2} = \beta(\alpha_s) = -\frac{\beta_0}{4\pi}\alpha_s^2 - \frac{\beta_1}{8\pi^2}\alpha_s^3 + \ldots$$

$$\left\{ \begin{array}{l} \beta_0 = 11 - \dfrac{2N_f}{3} \\[2ex] \beta_1 = 51 - \dfrac{19N_f}{3} \end{array} \right.$$

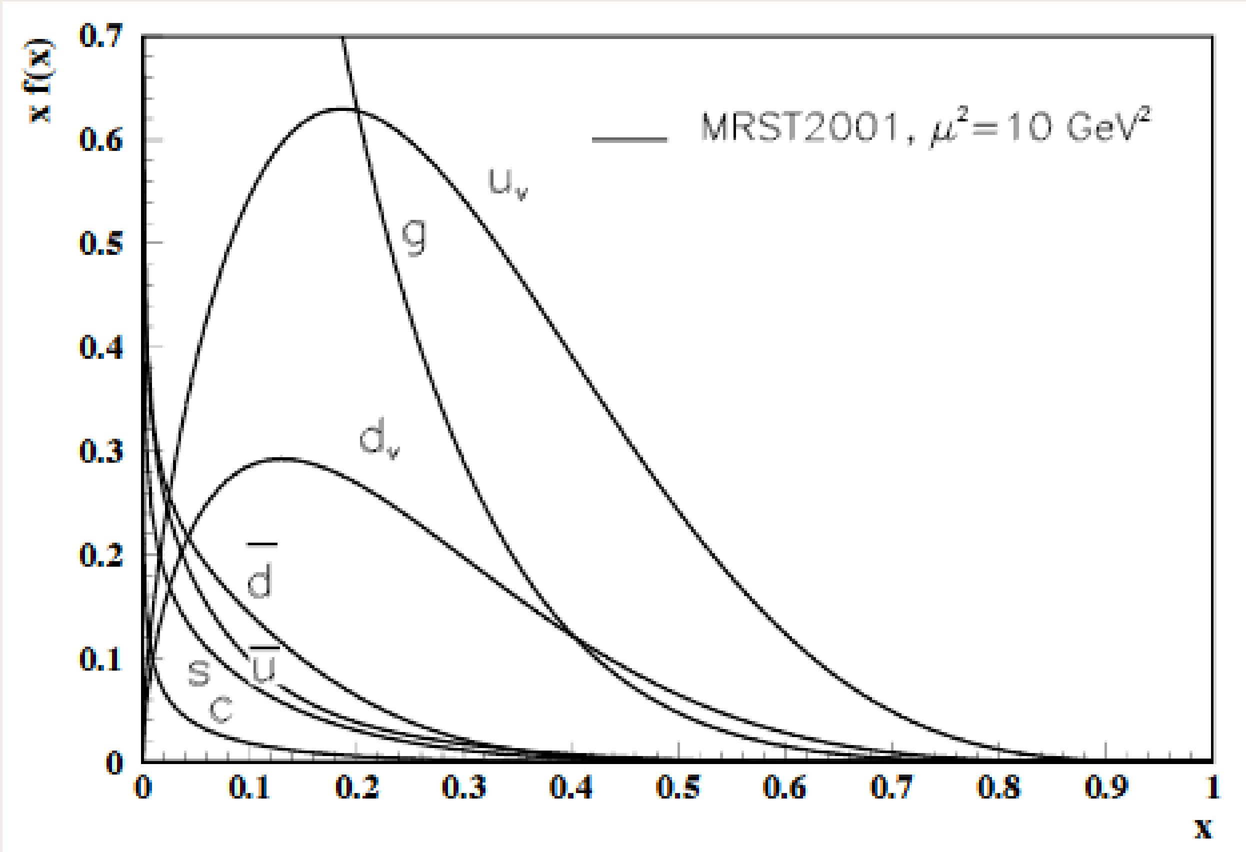


Bethke
(hep-ex/0211012)

running of α_s
is known

triumph of pQCD: explanation of scaling violations in DIS data

triumph of parton model: PDF’s are universal, process independent



[PDG (‘02)]

Cornwall-Norton moments: $M_n^{(CN)}\left(Q^2\right) = \int_0^1 dx\, x^{n-2}\, F_2\left(x,Q^2\right)$

$$F_2\left(x,Q^2\right) \xrightarrow[DIS]{} F_2^{NS}\left(x,Q^2\right) + F_2^{S}\left(x,Q^2\right)$$

$$F_2^{NS}\left(x,Q^2\right) = x \cdot \sum_f e_f^2 \left[q_f^{NS}\left(x,Q^2\right) + \bar{q}_f^{NS}\left(x,Q^2\right)\right] \qquad F_2^{S}\left(x,Q^2\right) = x \cdot \left(\frac{1}{N_f}\sum_f e_f^2\right) q^{S}\left(x,Q^2\right)$$

$$M_n^{(CN)}\left(Q^2\right) \xrightarrow[DIS]{} M_n^{NS}\left(Q^2\right) + M_n^{S}\left(Q^2\right)$$

$$M_n^{NS}\left(Q^2\right) \xrightarrow[NLO]{} a_n^{NS}\left[\alpha_s\left(Q^2\right)\right]^{\gamma_n^{NS}} \left(1 + \frac{\alpha_s\left(Q^2\right)}{4\pi} R_n^{NS}\right)$$

$$M_n^{S}\left(Q^2\right) \xrightarrow[NLO]{} a_n^{-}\left[\alpha_s\left(Q^2\right)\right]^{\gamma_n^{-}} \left(1 + \frac{\alpha_s\left(Q^2\right)}{4\pi} R_n^{-}\right) + a_n^{+}\left[\alpha_s\left(Q^2\right)\right]^{\gamma_n^{+}} \left(1 + \frac{\alpha_s\left(Q^2\right)}{4\pi} R_n^{+}\right)$$

$\gamma_n^{NS}, \gamma_n^{\pm}$ = anomalous dimensions

$R_n^{NS}, R_n^{\pm}$ = NLO coefficients

known from QCD

$a_n^{NS}, a_n^{\pm}$ $\Rightarrow$ to be determined from data

Operator Product Expansion [Wilson ('64), Shifman ('79), Shuryak&Vainshtein ('82), …]

$$T^{\mu\nu} = \int d^4 z\, e^{iq\cdot z} \langle P,S \,|\, T\left[J^{\mu}(z)\, J^{\nu}(0)\right] | P,S\rangle$$

- expand the T-product as a series of local operators

$$T\left[J^{\mu}(z)\, J^{\nu}(0)\right] = \sum_{m,\tau} C_n^{\tau}\left(-z^2 + i\varepsilon\right) z^{\mu_1} \ldots z^{\mu_m}\, O^{\tau}_{\mu_1 \ldots \mu_m}(0)$$

short-distance coefficients calculable in pQCD

symmetric traceless operators

- twist expansion of the moments:

$$M_n\left(Q^2\right) = \sum_{\tau \geq 2, even} E_n^{(\tau)}\left(\mu, Q^2\right) O_n^{(\tau)}(\mu) \left(\frac{\mu^2}{Q^2}\right)^{\frac{\tau-2}{2}}$$

μ = renormalization scale

$$= E_n^{(2)}\left(\mu, Q^2\right) O_n^{(2)} + E_n^{(4)}\left(\mu, Q^2\right) O_n^{(4)} \frac{\mu^2}{Q^2} + E_n^{(6)}\left(\mu, Q^2\right) O_n^{(6)} \left(\frac{\mu^2}{Q^2}\right)^2 + \ldots$$

leading twist + twist-4 + twist-6 + …

parton model

CQ's as quasi-particles: dressing of valence quarks with gluons and quark-antiquark pairs

CQ's as intermediate structures between current quarks and hadrons

two-stage model

Altarelli et al. ('74)
Cabibbo et al. ('78)
Hwa ('80)

hadrons are composed by a finite number of CQ's having a partonic structure

try to explain **DIS data** with two main ingredients:

1) partonic structure of the CQ's (**short-distance, high-Q^2 physics**)

$F_2^{CQ}\left(x/z, Q^2\right)$ = CQ structure function (independent of H)

2) motion of the CQ's inside the hadron (**long-distance, low-Q^2 physics**)

$f_{CQ}^{H}(z)$ = light-front CQ momentum distribution inside the hadron H

convolution formula in DIS: $F_2^H\left(x,Q^2\right)=\sum_{j=U,D,\ldots}\int_x^1 dz\, f_j^H(z)\, F_2^j\left(\frac{x}{z},Q^2\right)$

- same convolution for parton distributions:

$$q_f^H\left(x,Q^2\right)=\sum_{j=U,D,\ldots}\int_x^1 dz\, f_j^H(z)\, q_f^j\left(\frac{x}{z},Q^2\right)$$

- nucleon structure function: $\begin{cases} F_2^p = \frac{4}{9} f_U \otimes F_2^U + \frac{1}{9} f_D \otimes F_2^D \\ F_2^n = \frac{1}{9} f_U \otimes F_2^U + \frac{4}{9} f_D \otimes F_2^D \end{cases}$

with $f_U = f_U^p$ and $f_D = f_D^p$

- valence dominance at large x: $F_2^U \approx F_2^D \approx F_2^{CQ}$ [SU(2) symmetry]

$$\frac{F_2^n}{F_2^p} \xrightarrow{\text{large x}} \frac{(f_U + 4 f_D) \otimes F_2^{CQ}}{(4 f_U + f_D) \otimes F_2^{CQ}} \approx \frac{1 + 4 f_D / f_U}{4 + f_D / f_U}$$

light-front CQ momentum distributions in the proton (Q=U, D):

$$f_Q(x) = \frac{3}{2}\sum_{\nu_p} \int \prod \left[d\xi_i \, d\vec{k}_{i\perp} \right] \sum_{\{\nu_i \tau_i\}} \delta(x - \xi_1)\, \delta_{Q\tau_1} \left| \left\langle \{\xi_i \vec{k}_{i\perp}; \nu_i \tau_i\} \middle| \psi_p^{\nu_p} \right\rangle \right|^2$$

LF proton wave function

- normalizations: $$\begin{cases} \int_0^1 dx\, f_U(x) = 2 \\ \int_0^1 dx\, f_D(x) = 1 \end{cases}$$

- momentum sum rule: $$\int_0^1 dx\, x \cdot \left[f_U(x) + f_D(x) \right] = 1$$

- LF wave function: $$\psi_p = \psi\left(\xi_i, \vec{k}_{i\perp}; \nu_i\right) = \sum_{\nu_i'} \langle \nu_i \,|\, R^+ \,|\, \nu_i' \rangle\, \psi^{(c)}\left(\vec{k}_i; \nu_i'\right)$$

R = Melosh rotation (it does not affect spin-averaged quantities)

$\psi^{(c)}$ = canonical wave function

$$\square^{(c)} = a_S\, w_S(\vec{p}_{12},\vec{p})\,\square_S(S_{12},T_{12}) + \frac{a_{S\square}}{\sqrt{2}}\left\{w_{S\square}(\vec{p}_{12},\vec{p})\,\square_{S\square}(S_{12},T_{12}) + w_{S\square}(\vec{p}_{12},\vec{p})\,\square_{S\square}(S_{12},T_{12})\right\}$$

$$+\, a_A\, w_A(\vec{p}_{12},\vec{p})\,\square_A(S_{12},T_{12})$$

Jacobian momenta: $\begin{cases}\vec{p}_{12} \equiv \vec{p}_1 \,\square\, \vec{p}_2 \\ \vec{p} \equiv \vec{p}_3\end{cases}$

$[\vec{p}_1 + \vec{p}_2 + \vec{p}_3 = 0]$

$\square_S(S_{12},T_{12}) = \frac{1}{\sqrt{2}}\left\{|S_{12}=0,\ T_{12}=0\rangle + |S_{12}=1,\ T_{12}=1\rangle\right\}$ = completely symmetric

$\square_{S\square}(S_{12},T_{12}) = \frac{1}{\sqrt{2}}\left\{|S_{12}=0,\ T_{12}=0\rangle \,\square\, |S_{12}=1,\ T_{12}=1\rangle\right\}$ = mixed symmetry (1 $\square$ 2 symmetric)

$\square_{S\square}(S_{12},T_{12}) = \frac{1}{\sqrt{2}}\left\{|S_{12}=0,\ T_{12}=1\rangle + |S_{12}=1,\ T_{12}=0\rangle\right\}$ = mixed symmetry (1 $\square$ 2 antisymmetric)

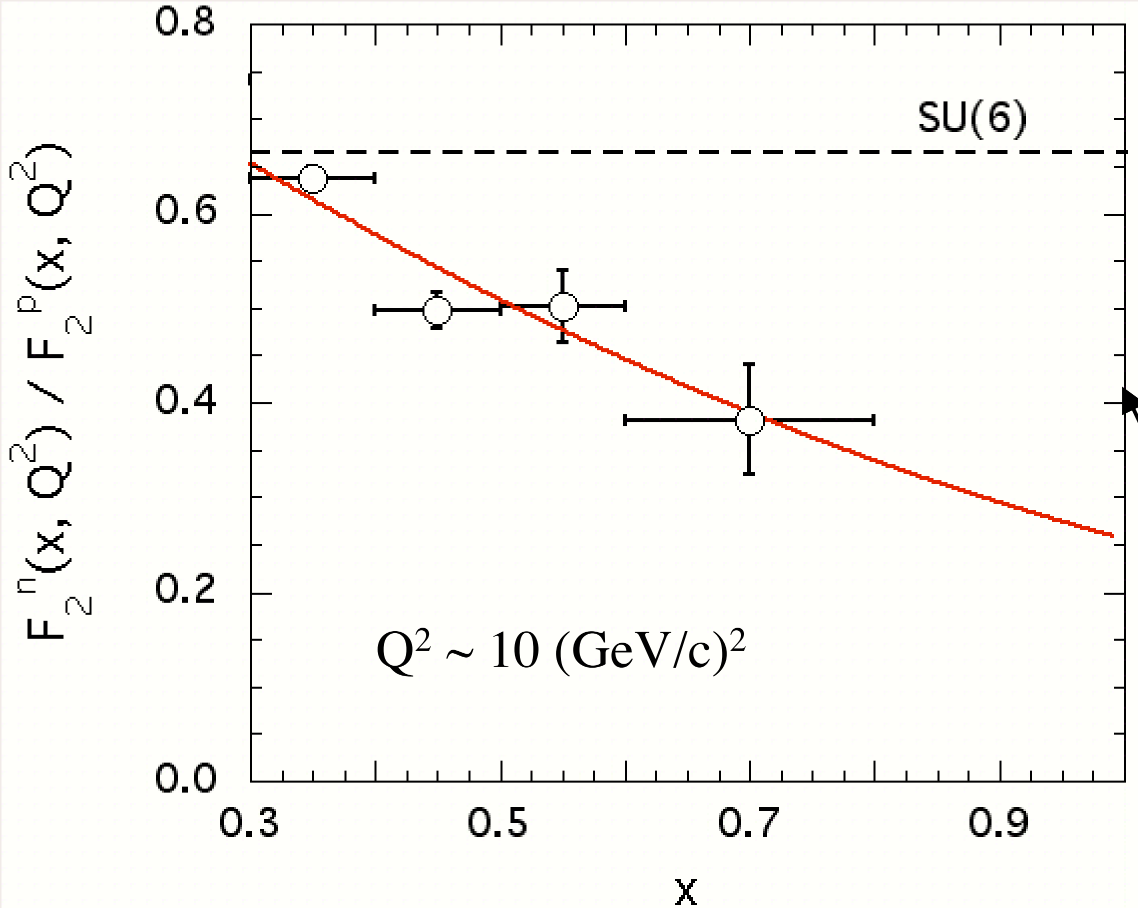
$\square_A(S_{12},T_{12}) = \frac{1}{\sqrt{2}}\left\{|S_{12}=0,\ T_{12}=1\rangle \,\square\, |S_{12}=1,\ T_{12}=0\rangle\right\}$ = completely antisymmetric

SU(6) symmetry ⇨ $a_{S\square} = a_A = 0$

spin-spin interaction ⇨ $a_{S\square} \neq 0$

CQ potential models ⇨ $a_A \,\square\, 0$

SU(6) symmetry implies $f_D = 0.5\, f_U$, which means $\frac{F_2^n}{F_2^p} \xrightarrow[x \to 1]{} \frac{2}{3}$



○ NMC data ('94)

SLAC parm. of F_2

$d/u \to 0$

$n/p \to 1/4$

[Feynman, Isgur, Close]

pQCD: $d/u \to 1/5$

$n/p \to 3/7$

[Brodsky, Farrar, Jackson]

f_D / f_U □ 0 is a consequence of the dominance of the $S_{12} = 0$ component

$$\square^{(c)} \square \square_S(\vec{p}_{12}, \vec{p}) \frac{1}{\sqrt{2}} \left\{ \left| S_{12} = 0,\ T_{12} = 0 \right\rangle + \left| S_{12} = 1,\ T_{12} = 1 \right\rangle \right\}$$

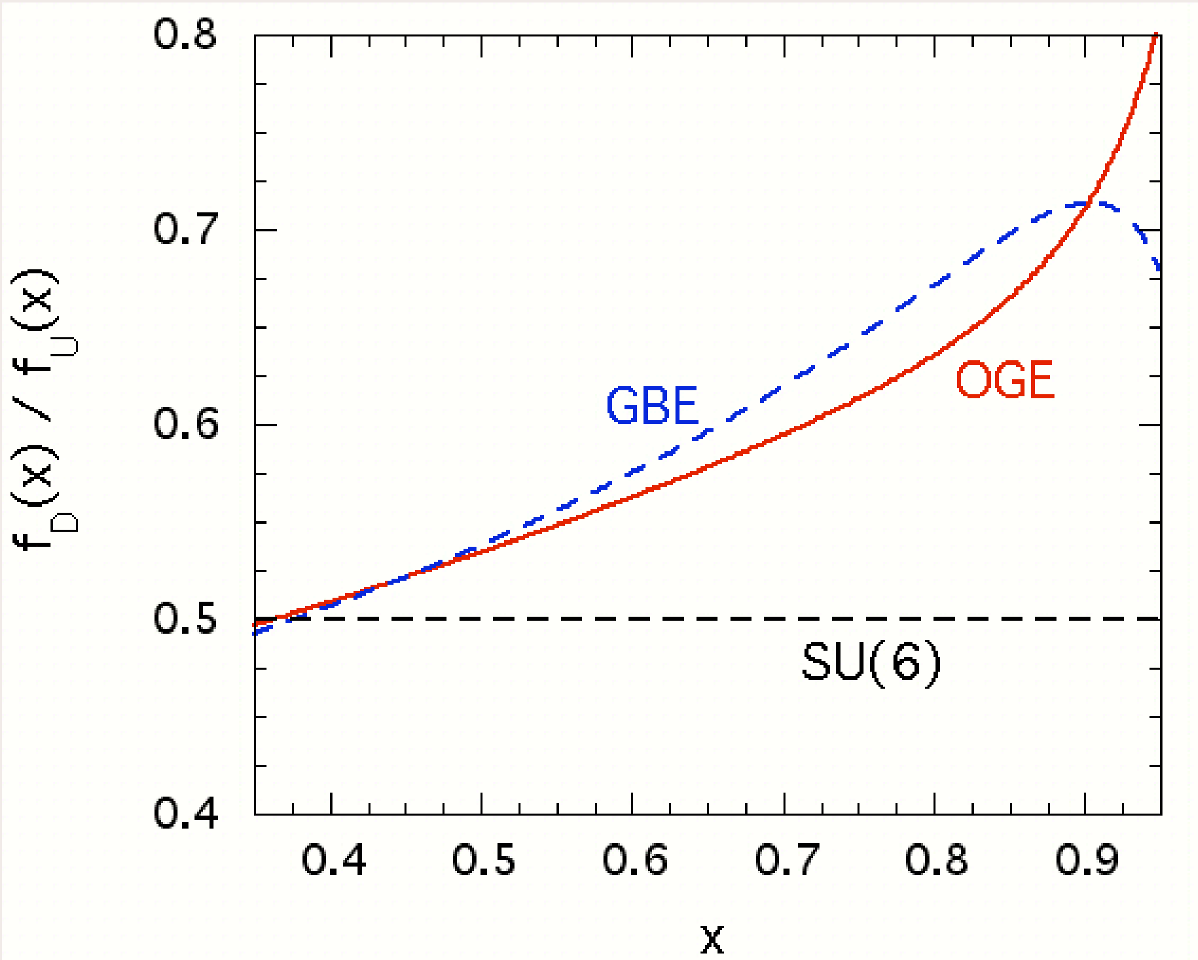
$$+ \square_{S\square}(\vec{p}_{12}, \vec{p}) \frac{1}{\sqrt{2}} \left\{ \left| S_{12} = 0,\ T_{12} = 0 \right\rangle \square \left| S_{12} = 1,\ T_{12} = 1 \right\rangle \right\}$$

$$\square f_D \square \square_{\text{high momenta}} \square \square \square \square \square \square_S^2 \square 2\square_S \cdot \square_{S\square}$$

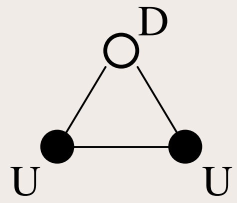
$$\square f_U \square \square_{\text{high momenta}} \square \square \square \square \; 2\square_S^2 + 2\square_S \cdot \square_{S\square}$$

if $\square_S \cdot \square_{S\square} > 0$, then $f_D / f_U < 0.5$

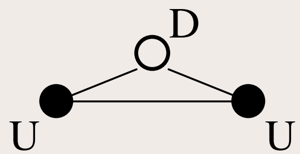
however, effects from spin-spin interaction leads to $f_D > 0.5\ f_U$!!!



SU(6) symmetry



spin-spin term



D is closer to the c.m.

⇓

higher momenta

alternative: mix the dominant S-wave with a P-wave [Altarelli et al. ('74)]

$$\square^{(c)} \; \square \; b_S \, \square_S + b_P \, \square_P$$

$\square\square_S$ belongs to the 56^+ multiplet of $SU(6)$

$\square\square_P$ belongs to the $70^{\square}$ multiplet of $SU(6)$

- it works with $|b_P|^2 \sim 10\%$, however:

a P-wave can be generated in the nucleon w.f. only by a

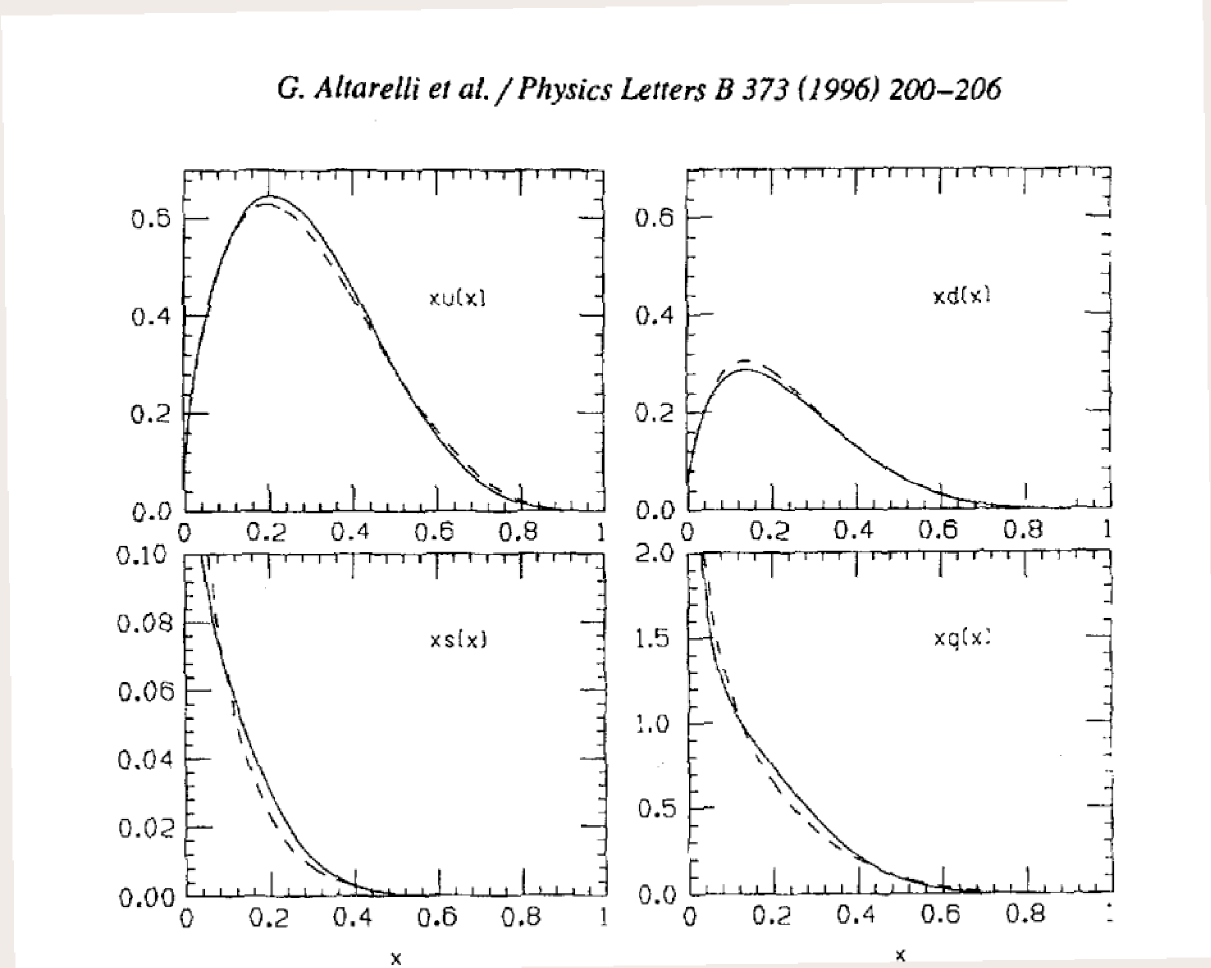
spin-orbit interaction term

absence of spin-orbit splitting in baryons and $|b_P|^2 \sim 10\%$ are totally inconsistent

D / U puzzle !!!

reproduce PDF's at a given scale Q_0^2 : $q_f^N\left(x,Q_0^2\right) = \sum_{j=U,D,\ldots} \int_x^1 dz\, f_j^N(z)\, q_f^j\left(\frac{x}{z},Q_0^2\right)$

evolution equations are not affected by the two-stage convolution



$Q_0^2 = 4\,GeV^2$

$q_f^j \propto x^{\alpha}(1-x)^{\beta}$

[phen. param.]

——— two-stage model

- - - - - MRS(G) PDF set

- given a reasonable model for $f_j^H(z)$ the CQ structure functions $F_2^j(x/z, Q^2)$ can be obtained by deconvolution of known hadron data on $F_2^H(x, Q^2)$
- then, using $F_2^j(x/z, Q^2)$ and a reasonable model for $f_j^{H'}(z)$ one can predict the structure function of another hadron H' $F_2^{H'}(x, Q^2)$

this procedure has been applied in Altarelli et al. ('96): within the two-stage model the pion structure function has been predicted from nucleon data

⇓

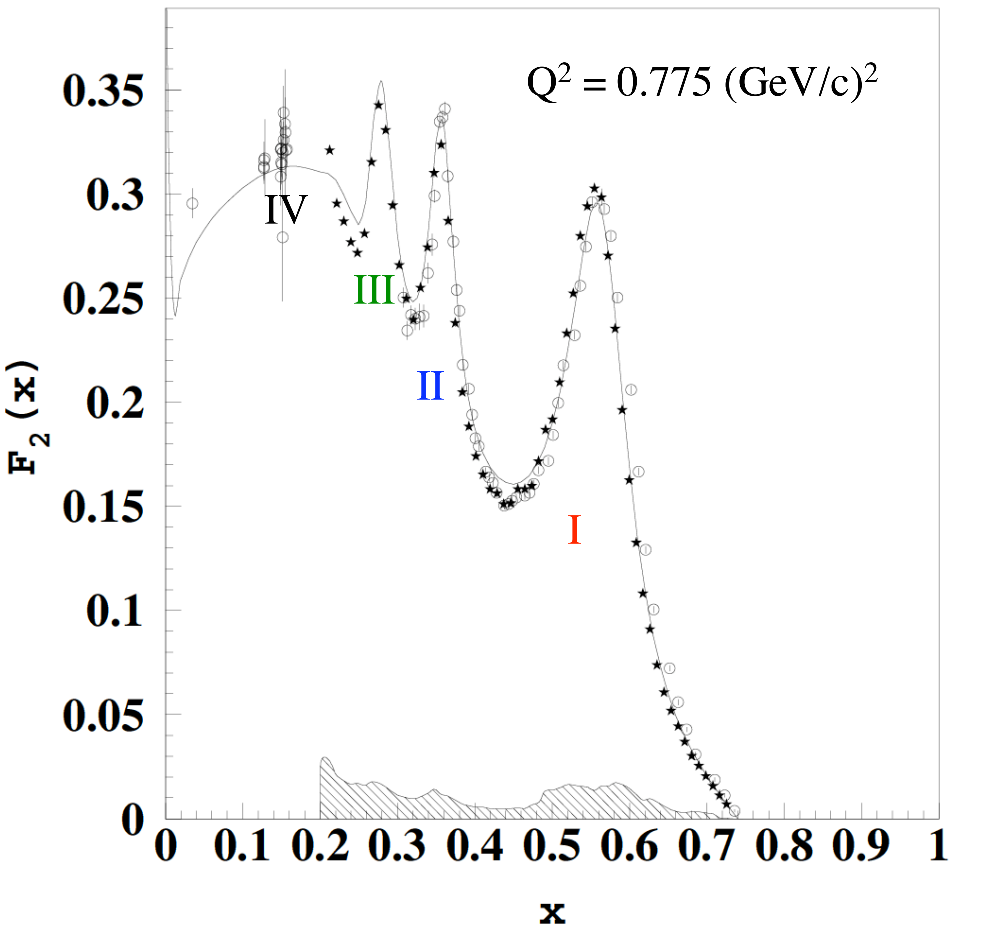
two-stage model ~ O.K., at least as a first approximation

the idea of CQ's with a partonic structure has been applied to polarized structure functions, off-forward parton distributions, …[Hwa, Hwa&Yang, Arash&Khorramian, Vento&Scopetta, Traini&Scopetta, …]

overall consistency with DIS data

how is the structure function F_2 away from DIS kinematics ?

the most striking feature is the appearance of bumps due to resonance production and subsequent decay in the final state



four regions

I region: □(1232)

II region: $D_{13}(1520)$, $S_{11}(1535)$

III region: mainly $F_{15}(1680)$

IV region: higher resonances

★ CLAS data

○ previous exp.'s

[Osipenko et al. ('03)]

investigation of resonant and non-resonant processes (exclusive channels)

Bloom-Gilman (local quark-hadron) **duality** [Bloom&Gilman ('70)]

- empirical observation made on SLAC data

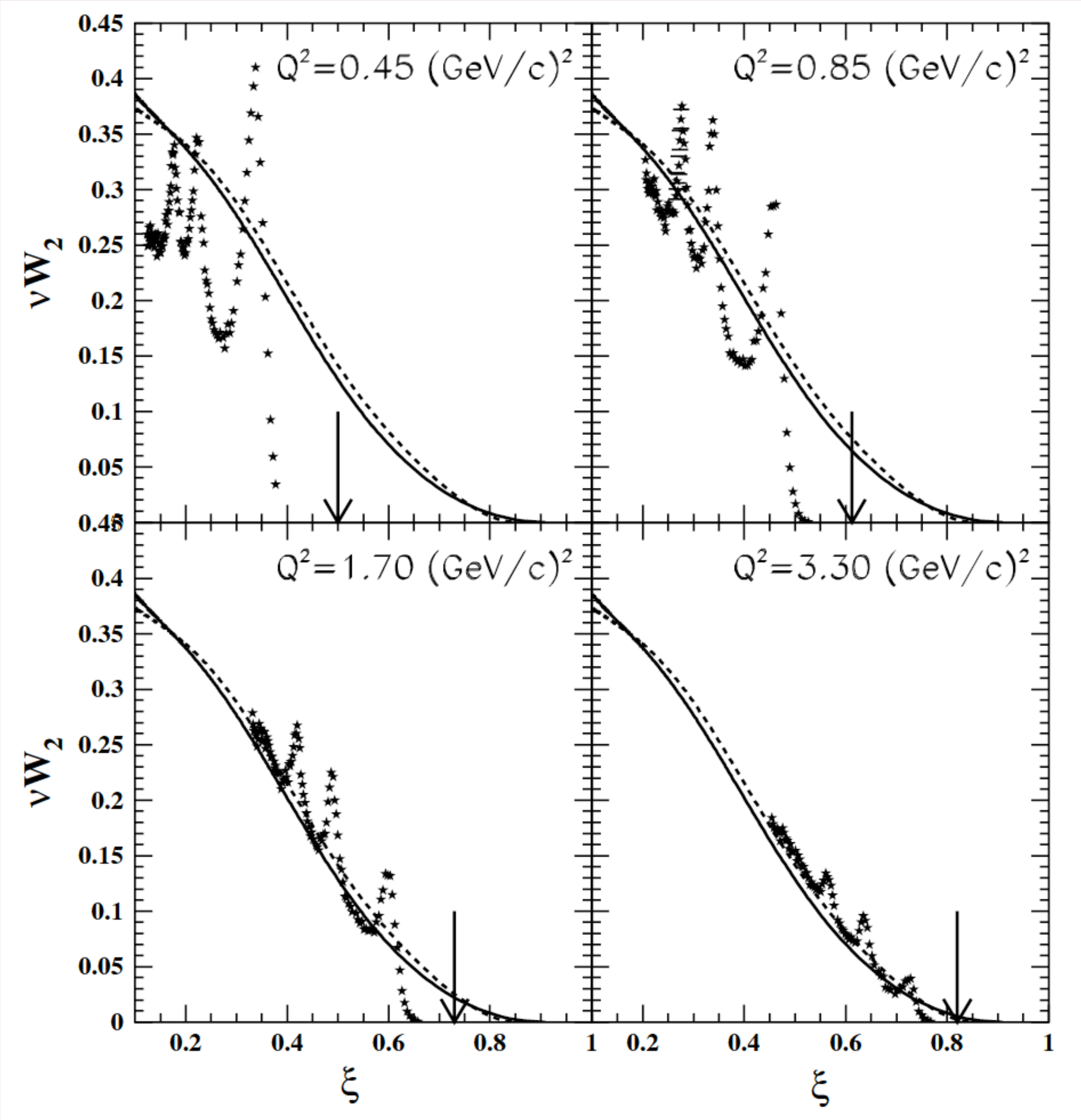
The smooth scaling curve measured in the DIS region at high Q^2 represents the average over the resonance bumps seen at low Q^2 at corresponding values of the improved empirical variable $x' = x / (1 + M^2 x^2 / Q^2)$

onset of BG duality at $Q^2 \sim 1 \div 2$ $(\mathrm{GeV}/c)^2$

the BG duality implies that there should be a relation between the physics in the nucleon-resonance region and the one in the DIS kinematics

such a relation is not yet fully understood

new precise measurements from JLab



Hall C data

[Niculescu et al. (‘00)]

$$\nu W_2 = F_2$$

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

NMC fit

- - - - $Q^2 = 5\ (\mathrm{GeV/c})^2$

——— $Q^2 = 10\ (\mathrm{GeV/c})^2$

↓ elastic peak location

a partial explanation based on QCD was proposed by De Rujula, Georgi and Politzer (‘77)

- consider the moments of the structure function F_2:

$$M_n(Q^2) = \int_0^1 d\xi\, \xi^{n-2}\, F_2(\xi, Q^2) \qquad \xi = \frac{2x}{1+\sqrt{1+4M^2x^2/Q^2}}$$

ξ is the Nachtmann variable (which takes into account target-mass corrections to the Bjorken scaling variable x) $\quad \xi \xrightarrow{\text{large}\, Q^2} x + O\left(\frac{M^4}{Q^4}\right)$

- using OPE and some generic “democratic” arguments

$$M_n(Q^2) = A_n(\ln Q^2) + \sum_{k=1}^{\infty} \left(n \frac{\mu^2}{Q^2} \right)^k B_{nk}(\ln Q^2) = \text{leading twist} + \text{higher twists}$$

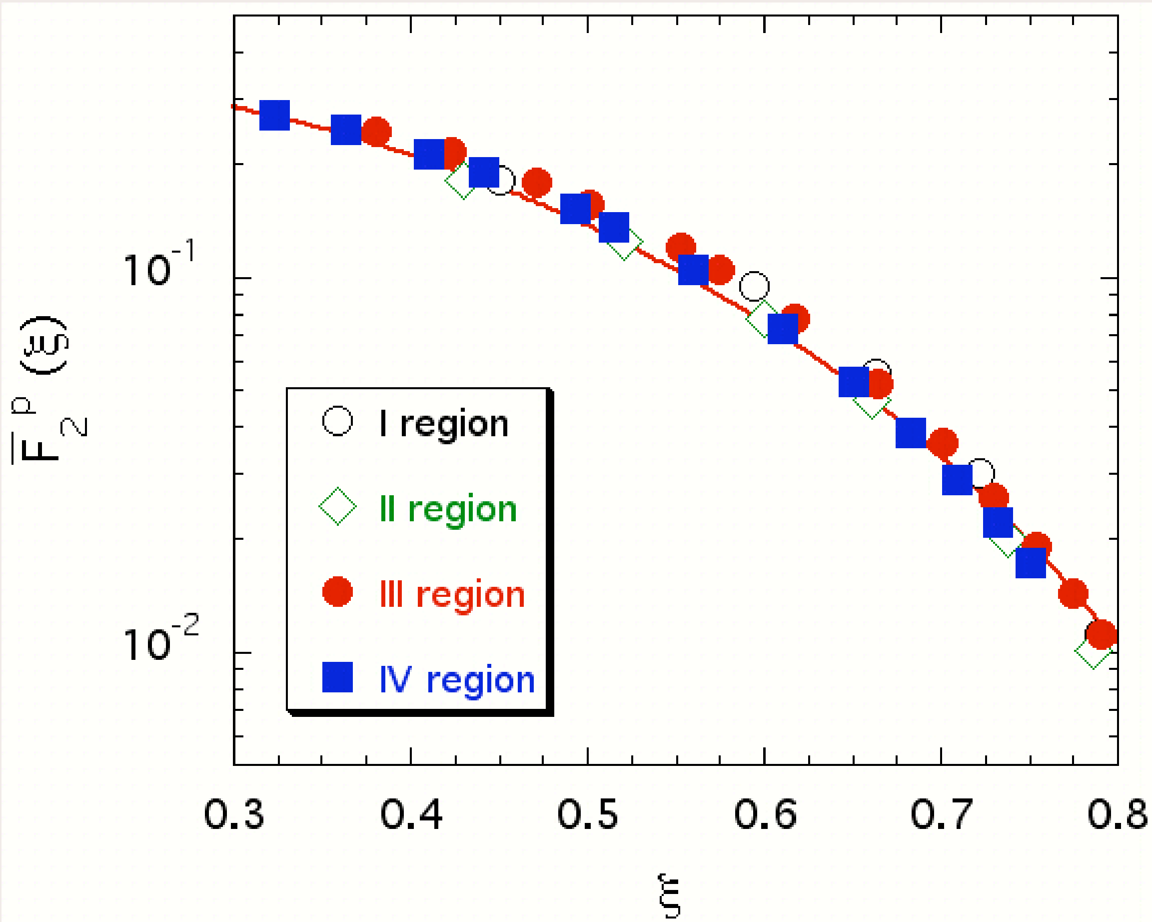
$$\mu^2 \sim \langle k_\perp^2 \rangle \sim \Lambda_{QCD}^2 \sim 0.1 \div 0.2\, GeV^2 \quad \Longrightarrow \quad M_n(Q^2) \xrightarrow{Q^2 > M^2} A_n(\ln Q^2)$$

precocious dominance of the leading twists for $Q^2 > M^2 \sim 1\ (GeV/c)^2$

~ onset of BG duality

$$\bar{F}_2^p(\xi = \xi_R) = \frac{1}{\xi_U - \xi_L} \int_{\xi_L}^{\xi_U} d\xi \, F_2^p(\xi, Q^2)$$

$$\begin{cases} \xi_L = \xi(W_U, Q^2) \\ \xi_U = \xi(W_L, Q^2) \end{cases} \qquad \xi_R = \xi(W_R, Q^2)$$



W_L and W_U in GeV

region	W_L	W_U
I (Δ)	1.14	1.38
II (S_{11})	1.38	1.58
III (F_{15})	1.58	1.76
IV	1.76	1.97

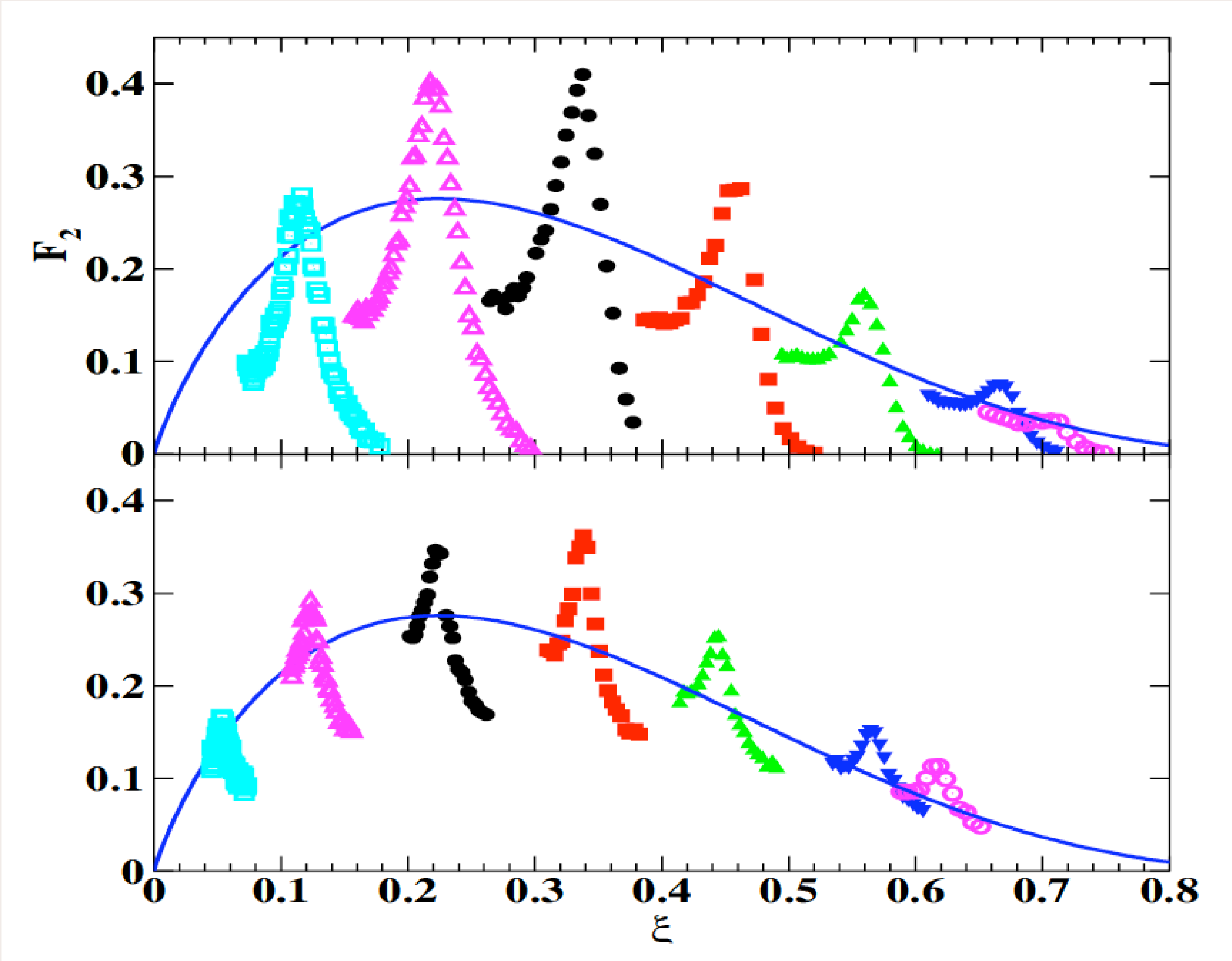
NMC DIS fit

$Q^2 = 10\ (\mathrm{GeV}/c)^2$

[Niculescu et al. ('00), Simula ('01)]

averages over resonance bumps define the dual curve $\bar{F}_2^p(\xi)$

$$0.07 < Q^2\ (GeV/c)^2 < 3$$



[Armstrong et al. (‘01)]

I region: Δ(1232)

II region: S_{11}(1535)

—— dual curve

what's the origin of the BG duality ? Not yet understood.

see: F. Close and N. Isgur: PLB 509, 81 (2001).
N. Isgur et al.: PRD 64, 054005 (2001)

intense theoretical and experimental activity at JLab on the BG duality:

- can the local quark-hadron duality hold as well for the unpolarized longitudinal and/or polarized structure functions ?
- can duality be extended to exclusive processes ?
- can duality be beneficial for investigating the behavior of structure functions at $x \to 1$?

<u>some approved experiments at JLab</u>

00-002 (Keppel, Niculescu)

00-116 (Keppel)

BG duality in nuclei ? Its onset appears to be anticipated !!!

[Ricco et al. : PRC 57, 356 (1997)]

first paper on BG duality after many years

SUMMARY

CQ's as quasi-particles: dressing of valence quarks with gluons and $q\bar{q}$ pairs

CQ's as intermediate structures between current quarks and hadrons

hadrons are composed by a finite number of CQ's having a partonic structure

two-stage model

O.K. with DIS data, except for the d/u ratio at large x

a nucleon P-wave seems to be required to get $d/u < 0.5$, but baryon spectroscopy requires mainly an SU(6) breaking due to the spin-spin contact term which produces $d/u > 0.5$

away from DIS regions the local quark-hadron duality is one of the most interesting phenomenon

extension of the two-stage model to low momentum transfer is mandatory

next lecture