Higher twist, QCD vacuum structure, and duality in spin structure functions

C. Weiss (JLab), JLab Hall C Workshop 06–Aug–09

- QCD vacuum characterized by non–perturbative short–distance scale $\rho \approx 0.2 - 0.3\,\text{fm} \ll R_{\text{hadron}}$

  Size of chiral symmetry breaking gluon fields

  "Size of constituent quark"

- Governs quark–gluon correlations responsible for higher–twist effects in polarized DIS

  $\rightarrow$ Estimates of matrix elements f_2, d_2

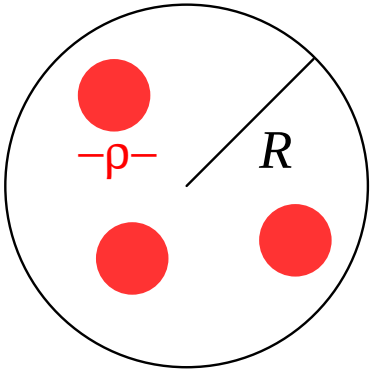
  $\rightarrow$ x–dependence of higher twist

  $\rightarrow$ Partonic interpretation: Short–range correlations NEW

  $\rightarrow$ Duality in spin structure functions

Balla, Polyakov, Weiss, NPB **510**:327, 1998. Sidorov, Weiss PRD **73**:074016, 2006. CW, in progress.

Short–distance scale: "Constituent quarks"



- Success of constituent quarks as effective degrees of freedom

  $\rightarrow$ Spectroscopy: $SU(3)$ flavor symmetry, etc.

  $\rightarrow$ Magnetic moments

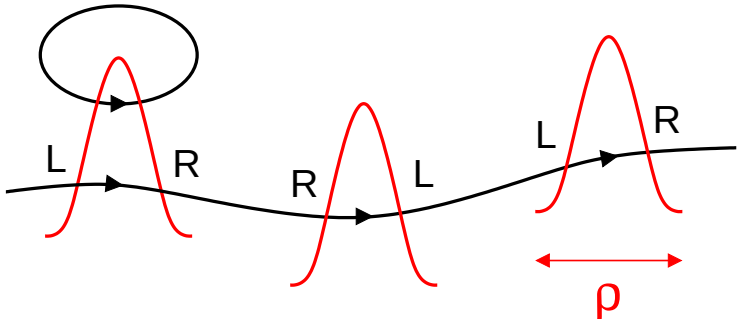
  $\rightarrow$ High–energy hadron–hadron scattering

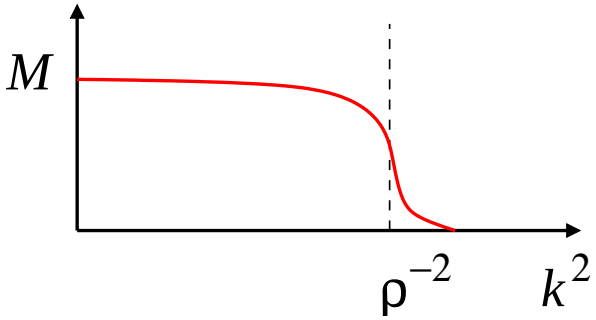
- Implies existence of "size" $\rho \ll R$: Two–scale picture of hadron structure!

  $\leftrightarrow$ Bag model: Single scale R only!

How does scale ρ arise in QCD?
How to quantify it?

Short–distance scale: QCD vacuum structure



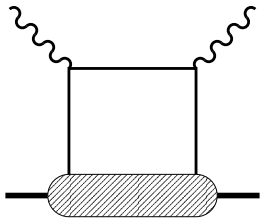
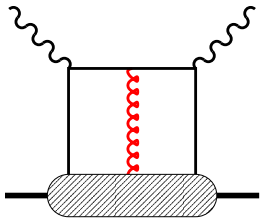


- Dynamical chiral symmetry breaking by non–perturbative gluon fields
  - Strongly localized: $\rho \ll 1\,\mathrm{fm}$
  - Condensate of $q\bar{q}$ pairs of size ρ
  - Objective measure: Average virtuality

    $$\frac{\langle\bar{\psi}\nabla^2\psi\rangle}{\langle\bar{\psi}\psi\rangle} > 0.5\,\mathrm{GeV}^2 \quad \text{(lattice)}$$

- Dynamical models: Effective quark mass
  - Cf. Instanton vacuum, Schwinger–Dyson equations
  - Gauge–dependent concept!

Higher twist: Polarized DIS

$$\sigma_{\rm pol}^{\gamma^* N} \;=$$  $$+$$ 

$$\langle N|\bar\psi \ldots \psi|N\rangle \qquad \langle N|\bar\psi \ldots F_{\mu\nu} \ldots \psi|N\rangle$$

- QCD operator product expansion: Scaling $+1/Q^2$ corrections

$$\int dx\; g_1(x,Q^2) \;=\; g_A \;+\; \frac{d_2 + f_2}{Q^2}$$

$$\int dx\; x^2 \left[g_2 - g_2^{\rm WW}\right](x,Q^2) \;=\; \frac{d_2}{Q^2}$$

- Moments of nucleon spin structure functions [also: Target mass corr.]

$$d_2 \;\sim\; \langle N|\; \bar\psi\, \widetilde{F}_{\mu\nu}\, \gamma_\rho\, \psi\; |N\rangle \qquad \text{Twist–3}$$

$$f_2 \;\sim\; \bar\psi\, \widetilde{F}_{\mu\nu}\, \gamma_\nu\, \psi \qquad \text{Twist–4}$$

- Matrix elements of local quark–gluon operators

Which scale governs quark–gluon matrix elements?

Higher twist: Short–distance scale

- Twist–4 operator: $\bar{\psi}\widetilde{F}_{\mu\nu}\gamma_\nu\psi \xrightarrow{\text{EOM}} \bar{\psi}\gamma_\mu\gamma_5(-\nabla^2)\psi$ Virtuality of polarized quarks

  $\rightarrow$ Sensitive to short–distance scale ρ^{-2}

  $\rightarrow$ Expect matrix element $f_2 \sim g_A\,\rho^{-2}$

  $\rightarrow$ Large isovector $g_A^{(3)} \gg g_A^{(0)}$

- Twist–3 operator: No relation to short–distance scale!

- Microscopic model: Instanton vacuum

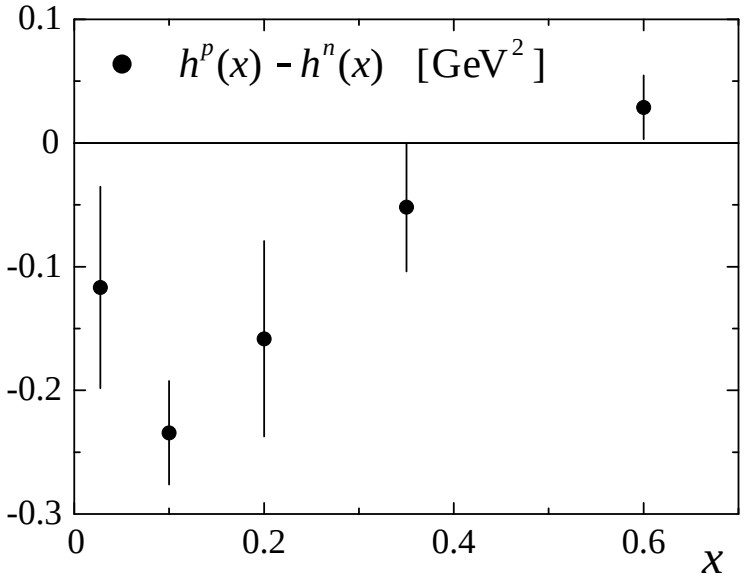
$$f_2^{u-d} \sim -0.5\, g_A^{(3)}\, \rho^{-2} = -0.22\,\text{GeV}^2$$

$$d_2 \sim O\left(\frac{\rho^4}{R^4}\right) < 0.01 \quad \text{“parametrically small”}$$

“Hierarchy” of higher–twist matrix elements

[Balla, Polyakov, CW 98]

Higher twist: Experimental results



$$g_1(x, Q^2) \;=\; \text{LT} \;+\; \text{TMC} \;+\; \frac{h(x)}{Q^2}$$

"Empirical" higher twist

x–dependent fit, moments by integration

[Sidorov, CW, 2006]

- Twist–3 from g_2(non-WW)
  SLAC E155 2002, JLab Hall A 2004

  $d_2^{p,n} \;<\; 10^{-2}$ . . . small!

- Twist–4 from $1/Q^2$ corrections to g_1
  incl. Hall A n 2004, COMPASS d 2005

  $f_2^{u-d} \;=\; -0.31 \pm 0.11\,\text{GeV}^2$

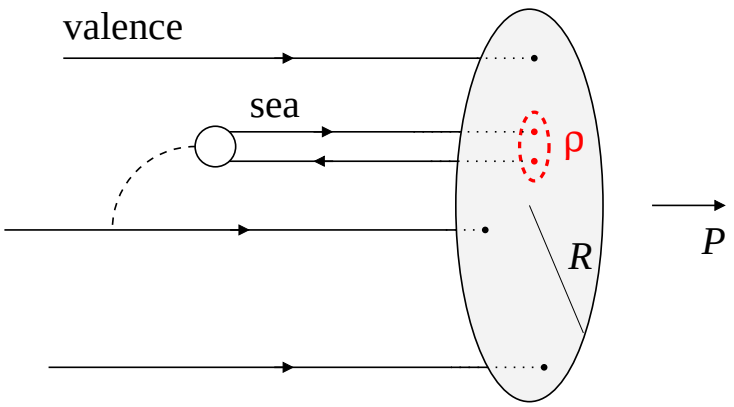
  . . . large isovector!

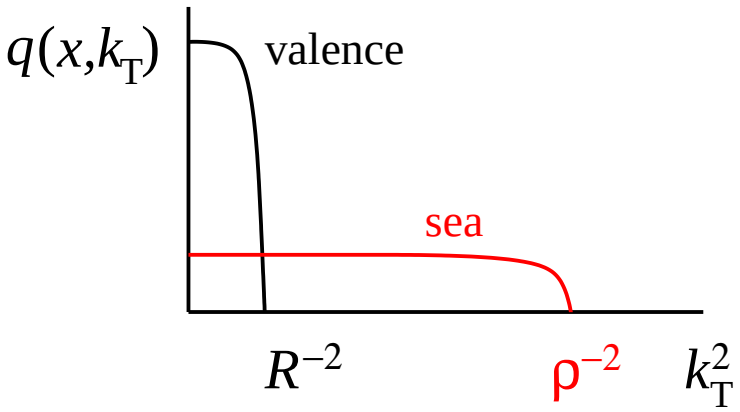
  – Agrees with moment analysis [Deur 2004]
  – Isovector renormalization–scheme independent, robust

Polarized moments support role of short–distance scale in HT

What about x–dependence?

Short–distance scale: Partonic interpretation





[CW 2009]

- Partonic wave function: $q\bar{q}$ pairs with transverse size $\rho \ll R$

  $\rightarrow$ Short–range correlations (cf. nuclei)

  $\rightarrow$ Intrinsic k_T^2 of sea quarks $\sim \rho^{-2}$

- Twist–4 operator (x–dep.)

  $\bar{\psi}\,\gamma_\mu\gamma_5 \ldots\ \nabla_T^2\,\psi$ transverse derivative

  $f_2 \ \sim\ \langle k_T^2 \rangle_{\rm pol}$ average k_T^2 of polar. quarks $\sim \rho^{-2}$

- x–dependence of twist–4 similar to sea quark distribution

  $\rightarrow$ Seems to agree with data

  $\rightarrow$ Higher twist not at large x!

Short–distance scale: Partonic interpretation

- Interesting analogy with nuclear physics

  Parton density $\longleftrightarrow$ mean field (independent particles)

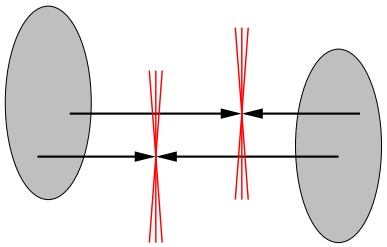
  Higher twist short–range correlations

- Implications for semi–inclusive DIS

  k_T (valence quarks) $\ll$ k_T (sea quarks)

  $\rightarrow$ different p_T dependence of fragmentation products [CW, in progress]

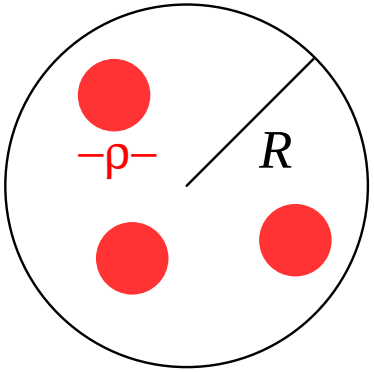
- Parton–parton correlations in high–energy pp scattering [Tevatron, LHC]



CDF data on double hard scattering
consistent with transverse correlations
of size $\rho \approx 0.2 - 0.3\,\text{fm}$

Frankfurt, Strikman, CW Annalen Phys. **13**:665, 2004

Short–distance scale: Duality



- Resonances: Motion of constituent quarks over distances R

  $$E(\text{excitation}) \sim R^{-1}$$

- Dominant higher twist $\sim \rho^{-2}/Q^2$:
  Short–range correlation,
  structure of constituent quark

  "average" x, not $x \to 1$

$\to$ Dominant higher twist plays no role in duality!

$\to$ "Special" higher twist $\sim R^{-2}/Q^2$ at $x \to 1$
dual to resonance structure

Summary

- Higher twist corrections in DIS dominated by short–distance scale ρ related to QCD vacuum structure

- Hierarchy of higher twist matrix elements Twist–4 $\gg$ Twist–3 confirmed by polarized DIS data

- New interpretation of higher twist: Transverse short–range correlations in nucleon's partonic wave function

  . . . numerous implications!