Signals of Local Duality from a Perturbative QCD Analysis of Inclusive ep Scattering.

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"... understanding and controlling the accuracy of quark-hadron duality is one of the most important and challenging problems for the QCD practitioners today."

M. Shifman  
hep-ph/0009131
\[ W^2 \geq 5 \text{ GeV}^2 \]

<table>
<thead>
<tr>
<th>( Q^2 ) [GeV(^2)</th>
<th>( x_{\text{ Bj}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( \leq 0.19 )</td>
</tr>
<tr>
<td>2</td>
<td>( \leq 0.33 )</td>
</tr>
<tr>
<td>5</td>
<td>( \leq 0.55 )</td>
</tr>
<tr>
<td>10</td>
<td>( \leq 0.71 )</td>
</tr>
<tr>
<td>20</td>
<td>( \leq 0.83 )</td>
</tr>
</tbody>
</table>

\[ x = \frac{Q^2}{W^2 - M^2 + Q^2} \]

\[ W^2 = Q^2 \left( \frac{1}{x} - 1 \right) + M^2 \]
A Few Facts about Experiment:

Jet studies in $pp$
A. Korytov and A. Safonov, CDF4996 and hep-ex/0007037

Jet studies in $e^+e^-$

Semi-inclusive $ep$
J. Breitweg et al. (ZEUS) EPJ C11 (1999)
S. Chekanov et al. (ZEUS) PL B510 (2001)

Deep Inelastic Scattering at Large $x_{Bj}$
**Jlab data**

⇒ All resonance data average to an *average* smooth curve.

⇒ Resolution in $W^2$: Data for $\Delta$, $S_{11}$, $F_{15}$, and higher mass region ($3.1 \leq W^2 \leq 4 \text{ GeV}^2$) average to different smooth curves.

⇒ **PQCD definition of duality:** Data at large $Q^2, W^2$ are connected to data at lower $Q^2, W^2$ by pQCD evolution + “small” power corrections.

⇒ Power Corrections can be extracted,

S.L., R. Ent, C. Keppel, I. Niculescu
hep-ph/0111063

⇒ A partonic picture seems to hold down to low $Q^2$ and even at low $W^2$. 
$W^2 = 1.6 \text{ GeV}^2$

$W^2 = 2.3 \text{ GeV}^2$

\[ F_2(x, Q^2) = F_2^{\text{pQCD+TMC}}(x, Q^2) + \frac{H(x, Q^2)}{Q^2} + O\left(\frac{1}{Q^4}\right) \]

\[ H(x, Q^2) = F_2^{\text{pQCD+TMC}}(x, Q^2)C_{HT}(x) \]
\[
\frac{F_2^{\text{exp}}}{F_2^{\text{pQCD+TMC}}} = 1 + \frac{C_{HT}(x)}{Q^2} + \Delta H(x, Q^2)
\]
Conclusions I

⇒ We are able to make an assessment based on current data, of the extent to which pQCD works at low momentum transfer and/or low invariant mass.

⇒ Analysis includes:
  • Large $x$ resummation
  • Target Mass Corrections
  • Evaluation of Power Corrections $1/Q^2, 1/Q^4...$

⇒ pQCD-defined Parton-Hadron Duality holds down to $W^2 \approx 2.5$ GeV$^2$

⇒ "Standard" analysis does not describe the data for $W^2 \leq 2.5$ GeV$^2$

⇒ Richer $Q^2$ dependence at low $Q^2$ and $W^2$

⇒ Bloom and Gilman in QCD context:

What causes the observed pattern of scaling and duality violations?
A Model of Structure Functions at Low $Q^2$

** How do color degrees of freedom evolve during the scattering process? **

Large $N_c$ limit ⇒ **Fragmentation:**

- Each final quark/anti-diquark produced in the parton cascade from $Q^2 \rightarrow Q_o^2$ is connected by a color line — "color connected" — to an antiquark/diquark ⇒ they form a **color singlet cluster** (basis of HERWIG, hep-ph/0011363).

- Pre-confinement property of QCD predicts a cluster mass distribution:
  
  (1) peaked at low values,
  (2) falling rapidly for large cluster masses,
  (3) independent of the hard process' $Q^2$.

- Confinement of partons is **local in color** and independent of $Q^2$.

- **Limiting case:** In $e^+e^-$ hadron fragmentation functions are proportional to parton fragmentation functions with constants $K_\pi, K_p, ...$ independent of $Q^2$. (Dokshitzer, Khoze and Troyan, Ochs)
Large $N_c$ limit $\Rightarrow$ Deep Inelastic Scattering:

- Convolution of pQCD matrix elements with parton distributions — probability of finding a quark/gluon in the hadron.

- Parton distributions are fitted to data using parametrizations at low $Q^2$ with little if any physical meaning: physical models can help understanding the transition $pQCD \leftrightarrow npQCD$.

- Backward Evolution: In DIS the color structure of the initial hadron is "disassembled" through the np "forced" emission of a gluon $\rightarrow$ quark anti-quark pair at a scale $k^2$: $\mu^2 \approx \Lambda^2 < Q_o^2 \equiv k^2 < Q^2$.

- The proton remnant undergoes rescattering.

- Transition: $p \rightarrow$ cluster $\rightarrow$ partons.
DIS
Working Formula

\[ F(x, Q^2) = \sum_j e_j^2 \int_{\mu^2}^{Q^2} \frac{dk^2}{k^2} \frac{\alpha_s(k^2)}{2\pi} \times \]
\[ \times f_j(x; Q^2, k^2) \int \frac{dx_1}{x_1} \int \frac{dx_2}{x_2} P(x_1, x_2; k^2, \mu^2) \]

\[ \Rightarrow \]
Cluster “mass distribution”

\[ P(x, k^2, \mu^2) = \int \frac{dx_1}{x_1} \int \frac{dx_2}{x_2} \sum_{j, j_1, j_2} \int_{x_1}^{x-x_2} \frac{dz}{z} \tilde{P}_{j, j_1}(z/x) \]
\[ \times \Gamma_{q, j_1} \left( x_1, k^2, \mu^2 \right) \Gamma_{q, j_2} \left( x_2, k^2, \mu^2 \right) \]

\( \Gamma \) evolves as a color connected distribution \( \Rightarrow \) Sudakov type damping at large \( k^2 \).

Amati & Veneziano, Bassetto, Ciafaloni & Marchesini

Parton Evolution

\( f_j \) evolves with DGLAP, \( f_j(y, Q_0^2, Q_0^2) = \delta(1-y) \)
$Q^2$ dependence of data

$W^2 = 1.6 \, \text{GeV}^2$
Conclusions and Outlook

- We have a model for the low \( Q^2 \) behavior of the structure functions in the whole range of \( x \) that interpolates between the perturbative and np regimes, using the concept of color-singlet clusters in large \( N_c \) limit.

- It explains "duality" observations in inclusive \( ep \) scattering

- Explore connection with low \( x \) low \( Q^2 \) models

- Extension to semi-inclusive processes

- Extension to nuclear structure functions