Accidental \( \xi \)-scaling as a Signature of Nuclear Effects at \( x > 1 \)

Omar Benhar\(^\dagger\) and Simonetta Liuti\(^*\dagger\)

\(^\dagger\) INFN, Sezione Sanità. Physics Laboratory, Istituto Superiore di Sanità.  
Viale Regina Elena, 299. I-00161 Rome, Italy.

\(^*\) Institute of Nuclear and Particle Physics, University of Virginia.  
Charlottesville, Virginia 22901, USA.

Abstract

We propose an interpretation of the \( \xi \)-scaling behavior of nuclear structure functions observed at Bjorken \( x > 1 \) and \( Q^2 \lesssim 4 \text{(GeV/c)}^2 \). We show that at \( \xi \gtrsim 1 \), \( \xi \)-scaling might arise accidentally because of the approximate cancellation of two different \( Q^2 \)-dependent effects, namely Final State Interactions and the effects implicit in the choice of the scaling variable \( \xi \). We provide a new convolution formula for the nuclear structure function in terms of \( \xi \) and make predictions for the kinematical regions where Final State Interactions are expected to be small and the suggested balancing of scaling violations is expected to break down. Our analysis is aimed at the final goal of clarifying the range of applicability of local duality ideas in nuclei.
For many years inclusive scattering of high energy leptons from nuclei has been providing a continuous flow of information both on nuclear dynamics at short distances and on the internal structure of the nucleon. With the experimental discovery of the European Muon Collaboration (EMC) effect it has become clear that a better understanding of the mechanisms that modify quarks and gluons distributions inside nuclei would help unraveling unknown aspects of the dynamics of strong interactions. In nuclei one can explore the kinematical regime beyond Bjorken \( x = 1 \) \( (x = Q^2/2M_N\nu, Q^2 \text{ being the four-momentum transfer squared and } \nu \text{ the energy transfer}) \) where partons carry a higher momentum than in a single nucleon. In dynamical models one expects deep inelastic nuclear structure functions at \( x \gtrsim 1 \) not to vanish because of the existence of unusual configurations of the nucleus in which spectator particles are directly involved in the scattering process. A quite successful effective description of such configurations is given for example by nucleon-nucleon (NN) correlations viewed as two close nucleons strongly recoiling against each other. Unfortunately the cross sections in this kinematical domain fall very steeply, making the extraction of nuclear structure functions very challenging (published data at \( Q^2 > 50 \text{ (GeV/c)}^2 \) and \( x > 1.15 \) [1,2] only represent upper limits for the nuclear structure functions). Recently [3,4], it was suggested that an indirect experimental access to the deep inelastic structure functions could be obtained by exploiting the connection between the low \( Q^2 \) regime and the asymptotic limit, known as Bloom and Gilman duality [5]. As a matter of fact, the nuclear structure function per nucleon, \( \nu W^A_2/A \), extracted from the nuclear data on \( ^4He, ^{12}C \) and \( ^{56}Fe \) in the region \( 1 \leq Q^2 \leq 4 \text{ (GeV/c)}^2 \), was found to scale in Nachtmann’s variable \( \xi \) for \( \xi < 1 \), with some relatively small scaling violations at larger \( \xi \). The resulting \( \xi \)-scaling curve was suggested to be consistent with the high \( Q^2 \) structure function, therefore supporting the applicability of duality ideas to nuclei [3].

In this paper we propose an explanation for the \( \xi \)-scaling behavior of nuclear structure functions at low \( Q^2 \) and high Bjorken \( x \) by making a connection with scaling in West’s variable \( y \) [6]. Our main aim is to try to clarify a possible accidental nature of the scaling in \( \xi \). The removal of this ambiguity seems rather urgent to us in view of the forthcoming
experiments at the Continuous Electron Beam Accelerator Facility (CEBAF) [4].

We show that at high $x$ ($\xi \gtrsim 1$), where scattering occurs prevalently in the Quasi Elastic (QE) channel, $\xi$-scaling is approached from below as a result of the compensation of two opposite effects. In fact it is a well known prediction of calculations based on Impulse Approximation (IA), that QE data should exhibit $y$-scaling at high $Q^2$ (for a recent review on $y$-scaling see e.g. [7]). At the $Q^2$ values of the present data $y$-scaling is indeed observed in proximity of the QE peak ($y \approx 0, x \approx 1$) and scaling violations due to Final State Interaction (FSI) effects set in as the energy transfer gets closer to its threshold, corresponding to large negative $y$ and $x > 1$. These scaling violations produce an overall enhancement of the cross section at negative $y$ with respect to the IA one (i.e. $y$-scaling is approached from above). By studying the nuclear structure functions in terms of the variable $\xi$, one shatters the pattern of $y$-scaling violations because the relationship between the variables $y$ and $\xi$ is $Q^2$ dependent. This $Q^2$ dependence might conspire, as we shall see, to counterbalance FSI effects giving rise to a better scaling behaviour.

At lower values of $x$, corresponding to $\xi < 0.6$, the cross section receives a larger contribution from the inelastic channels and scaling in $\xi$ follows from the scaling of the nucleon structure function, assuming that the bound-nucleon structure function’s $Q^2$-dependence is not sensibly modified inside the nuclear medium. At $0.6 \leq \xi \leq 0.8 - 0.9$, we expect both inelastic and quasi elastic channels to contribute to the structure functions. Their separation is obviously model dependent. However, according to our calculation, at e.g. $\xi \approx 0.8$ inelastic channels start to give a significant contribution only at the highest values of $Q^2$ of present data ($Q^2 \approx 3 \text{ (Gev/c)}^2$) and one can isolate a kinematical region dominated by the quasi-elastic peak. In the last part of this paper we will try to clarify the question of why should the nuclear structure functions in this region fall along a scaling-limit curve as the available data seem to show.

We begin by defining the the nuclear structure function, $F_2^A(\nu, Q^2) = \nu W_2^A(\nu, Q^2)$, in IA as a convolution of the structure function for the bound nucleon, $F_2^N$, with the spectral function, $P^N(|k|, E), N = p, n$ (see also Ref. [8]):
\[ F_2^A(\nu, Q^2) = \int d\mathbf{k} \int dE \, Z \, P^p(|\mathbf{k}|, E) \]
\[ \times \tilde{F}_2^p((kq), Q^2, k^2) \mathcal{F} + \]
\[ (\text{similar terms for neutrons}) \, , \quad (1) \]

where \( Z \) is the number of protons; \( k_\mu \equiv (k_\nu = M_A - (M_{A-1}^* + k^2)^{1/2}, \mathbf{k} = -\mathbf{P}_{A-1}) \) is the bound nucleon four-momentum, \( \mathbf{P}_{A-1} \) is the momentum of the \( A - 1 \) nucleus and \( M_{A,(A-1)} \) are the nuclear masses, \( M_{A-1}^* = M_{A-1} + E^* \), \( E^* \) being the excitation energy of the \( A - 1 \) nucleus; \( E \) is the nucleon removal energy, defined as \( E = E_{\text{min}} + E^* \), with \( E_{\text{min}} \equiv M_{A-1} + M_N - M_A \). \( \mathcal{F} \) is a kinematical factor determined by the choice of the off-shellness extrapolation from the free nucleon structure functions (see e.g. [8,9]). \( \mathcal{F} \) approaches unity at large \( Q^2 \).

We now make the following change of variables: \( d^3dk_o \equiv d\mathbf{k}kdEd\xi' J_A^\xi \), with \( \xi' \equiv 2x'/\left(1 + \sqrt{1 + 4k^2x'/Q^2}\right) \), and \( x' = Q^2/2(kq) \). \( \xi' \) and \( x' \) play the role of Nachtmann \( \xi = 2x/(1 + \sqrt{1 + 4M_N^2x/Q^2}) \) and Bjorken \( x \) for an off-shell nucleon. \( J_A^\xi \) is the jacobian of the transformation, whose form we will specify below. We consider for illustration the case of infinite Nuclear Matter (NM) where kinematics is simpler because one does not account for the recoil kinetic energy of the \( A - 1 \) system and calculations of realistic spectral functions and FSI effects are available [10]. \( F_{2N}(\xi, Q^2) \) reads:

\[ F_{2NM}(\xi, Q^2) = 2\pi Z \int_0^1 d\xi' \, F_2^p(\xi', Q^2) \int_{E_{\text{min}}}^\infty dE \]
\[ \times \left[ \int_{k_{\text{min}}(Q^2, \xi', E)}^{k_{\text{max}}(Q^2, \xi', E)} d|\mathbf{k}| \, |\mathbf{k}| \, P^p(|\mathbf{k}|, E) \right] \]
\[ \times \mathcal{F} \, J_{2NM}^\xi(Q^2, \xi', |\mathbf{k}|, E) \]
\[ + (\text{similar terms for neutrons}) \, , \quad (2) \]

with \( J_{2NM}^\xi = 1/(2q)(k^2 + Q^2\xi') \). In practical calculations we identify the off-shell nucleon structure function, \( \tilde{F}_2^N((kq), Q^2, k^2) \), in Eq.(1) with the on-shell one, \( F_2^N(\xi, Q^2) \), calculated at \( \xi = \xi' \). This correspond to disregarding the dependency upon the invariant \( k^2 \) which would imply strong nuclear medium modifications of the bound nucleon. The integration limits on \( |\mathbf{k}| \) are:
\[ k_{\text{min}} = \left| M_N \left( 1 - \frac{\xi}{\xi'} \right) - E \right| \]

\[ k_{\text{max}} = M_N \left( 1 + Q^2 \frac{\xi}{\xi'} \right) - E \approx \infty. \]

Eqs. (2) and (3) describe both QE and inelastic scattering, depending on the form of \( F_2^N \). In particular, for QE scattering \( F_2^N \) is a linear combination of the nucleon elastic form factors times the delta function: \( \delta(\xi - \xi_p) \), with \( \xi_p \equiv 2/(1 + \sqrt{1 + 4M_N^2/Q^2}) \).

Nuclear structure functions extend into the \( x > 1 \) region according to the amount of high momentum and energy components in \( P^N(k, E) \). A quantitative determination of the relative contributions of QE and inelastic channels at \( x > 1 \) is obviously model dependent (see e.g. [8,10]). However, presently available calculations [8,10,12] indicate that at \( Q^2 \leq 4 \text{(GeV/c)}^2 \), i.e. in the range of current data, QE scattering overrides completely inelastic scattering; as \( Q^2 \) increases, QE scattering dies off along with the nucleon form factors and the relative importance of inelastic channels increases until one reaches a region where neither process is clearly dominating; in the very high \( Q^2 \) limit \( (Q^2 \gtrsim 20 \text{(GeV/c)}^2 \text{ for } x \approx 1.5) \), deep inelastic scattering finally dominates the cross section.

In Figure 1 we show as an example our results at fixed \( \xi \) and in the \( Q^2 \) range covered by the data of [3]. Figures (1a-1c) correspond to three different kinematical regions: (a) the region where inelastic channels are almost completely suppressed and IA breaks down; (b) an intermediate region where inelastic channels start to contribute significantly only at the highest \( Q^2 \) values; (c) the region beyond the QE peak where inelastic channels are expected to give the major contribution to the cross section. In what follows we will demonstrate that \( \xi \)-scaling can occur accidentally in regions (a) and (b).

We expect data to exhibit a transition from \( y \)-scaling to \( \xi \)-scaling, proceeding from region (a) to (c). \( y \)-scaling for the QE reduced cross sections \( (i.e. the nuclear cross sections divided by the single nucleon cross sections, \( d^2\sigma_A/d^2\sigma_N \equiv F(y, Q^2) \)) was predicted in the high \( Q^2 \) limit under the hypotheses that only nucleon degrees of freedom are participating in the scattering process and that IA is valid [6]. \( y \) is the minimum longitudinal momentum carried by the struck nucleon assuming that the spectator \( A - 1 \) system recoils with no excitation.
energy \([\text{1}]\). The definition of \(y\) depends on both the target and the recoiling system masses and at a given kinematics its value changes depending on the nucleus \([\text{1}1]\). In nuclear matter \(y\) is defined as:

\[
y_{\text{NM}} = -q + \sqrt{(\nu - E_{\text{min}})^2 + 2M_N(\nu - E_{\text{min}})}.
\]

(4)

\(y\)-scaling was observed in experiments along with scaling violations at low \(Q^2\), interpreted as an effect of FSI \([\text{1}]\). \(y\) is related to \(\xi\) through:

\[
y = y_0(\xi) - \frac{M_N^2}{2q} + O(1/q^2)
\]

\[
\equiv y_0(\xi) - \frac{M_N^2 \xi}{Q^2} + O(1/Q^4),
\]

(5)

with \(y_0(\xi) \equiv M_N(1 - \xi) - E_{\text{min}}\).

By calculating the structure functions at a fixed \(\xi\), one introduces a spurious \(Q^2\) dependence coming from the relationship between \(y\) and \(\xi\). We now consider the possibility that the \(Q^2\) dependence of FSI effects can counterbalance it. We first write an expression for the reduced cross section which includes the effect of FSI, \(F_{\text{FSI}}(y, Q^2)\), in terms of the \(y\)-scaling quantity, \(F_{\text{IA}}(y)\):

\[
F_{\text{FSI}}(y, Q^2) = F_{\text{IA}}(y + b_{\text{FSI}}(y, Q^2)).
\]

(6)

Here we define a shift in the variable \(y\), \(b_{\text{FSI}}(y, Q^2)\), which is the projection onto the \(y\) axis of the variation in the cross section due to FSI, \(\Delta(y, Q^2) = F_{\text{FSI}}(y, Q^2) - F_{\text{IA}}(y)\). We can define such a shift because the following properties are valid at \(x > 1\): \(i)\) both \(F_{\text{FSI}}(y, Q^2)\) and \(F_{\text{IA}}(y)\) are monotonously increasing functions of \(y\), and, \(ii)\) \(F_{\text{FSI}}(y, Q^2) > F_{\text{IA}}(y)\). We

\[^{1}\text{For consistency with previous literature [1] we consider here reduced cross sections instead of nuclear structure functions. The IA calculation for } F_{2}^{\text{NM}} \text{ scales in } y \text{ relatively to the calculation including FSI, even if } F_{2}^{\text{NM}} \text{ obviously does not scale } \textit{per se}, \text{ or when compared to the reduced cross section.}\]
obtained $b_{FSI}(y,Q^2)$ numerically by calculating $F_{FSI}$ using the approach of Ref. \[10\] (see also \[13\]).

We now replace $y$ on the right hand side of Eq.(6) with the expression in Eq.(5):

$$F_{FSI}(y,Q^2) = F_{IA}(y_0(\xi) + a_\xi(Q^2) + b_{FSI}(y,Q^2)), \quad (7)$$

One can clearly see that $F_{FSI}(y,Q^2)$ becomes a function of $y_0(\xi)$ only and therefore it exhibits $\xi$-scaling, to the extent to which $a_\xi$ and $b_{FSI}$ compensate for each other.

In Figure 2 we show the quantities $a_\xi$ and $b_{FSI}$, at the fixed value of $y = -0.4$ GeV/c (corresponding to $\xi \gtrsim 0.9$). The dashed line corresponds to IA. $a_\xi$ and $b_{FSI}$ have opposite sign and therefore they generate “scaling violations” that tend to compensate for each other. Moreover, $|a_\xi| > b_{FSI}$ particularly at low $Q^2$ and this is precisely why in the available data, scaling seems to be approached from below. For comparison in Figure 2 we also show the quantity $a_x$, defined as:

$$y = M_N(1 - x) - E_{\min} - a_x(Q^2), \quad (8)$$

$$a_x(Q^2) = \frac{M_N^2 x(1 - x^2)}{Q^2} + O(1/Q^4). \quad (9)$$

At $x > 1$, $a_x$ being of the same sign of $b_{FSI}$, contributes to enhance the scaling violations due to FSI and this is at the origin of the large $x$-scaling violations reported in \[3\]. We would also like to point out that, as also shown in Figure 2, while FSI is expected to become negligible at $Q^2 \approx 6$ (GeV/c)$^2$, the difference between $y$ and $\xi$ persists up to much higher $Q^2$ values. As a further proof of the validity of our argument we predict $\xi$-scaling violations to persist even at very high $Q^2$ (in Figure 2 we show values of $Q^2$ as large as 10 (GeV/c)$^2$, in the range of CEBAF experiments \[4\]). As shown in Figure 2 such violations will approach the scaling behavior from below and they will be of the same magnitude as the ones observed at lower $Q^2$. It is interesting to add that a similar effect to the one that we just discussed was referred to in \[14\] as a possible explanation for the $\omega'$ scaling observed in the earlier data on nucleon structure functions (Ref. \[5\] and references therein). The authors of \[14\] indeed suggested that logarithmic corrections were compensating for the $Q^2$ dependent relationship between $\omega = 1/x$ and $\omega' = \omega + M_N^2/Q^2$. 

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We now turn to the $\xi \approx 0.8 - 0.9$ region (Figure (1b)). One is studying here the nuclear structure functions in proximity of the QE peak; FSI effects are small and the mechanism proposed to explain $\xi$-scaling in region (a) cannot be applied. The QE peak is positioned at: $\xi_{\text{peak}} \approx \xi_p (1 - \langle E \rangle / M_N)$, corresponding to $k_{\text{min}} = 0$ in Eq.(3a) ($\langle E \rangle$ is the average value of the removal energy and we disregard a small $Q^2$-dependent correction due to FSI). We notice that due to the $Q^2$ dependence of $\xi_p$, $\xi_{\text{peak}}$ increases with increasing $Q^2$. The height of the peak can be readily obtained from Eq.(2):

$$H_{\text{peak}} \equiv F_{2}^{NM}(\xi_{\text{peak}}) \propto \sigma_2(Q^2),$$

with

$$\sigma_2(Q^2) \approx \frac{Z}{A} \frac{2M_N}{1 + \frac{Q^2}{4M_N^2}} \left( \left[ G^p_E(Q^2) \right]^2 + \frac{Q^2}{4M_N^2} \left[ G^p_M(Q^2) \right]^2 \right) + \left( \text{similar terms for neutrons} \right),$$

and $G^p_E$ and $G^p_M$ being the usual nucleon electric and magnetic form factors. Eq.(10) is a consequence of the fact that one is integrating over the whole range of momentum and energy in Eq.(2) and the nucleon spectral function is normalized to one: $\int dE \int dk k^2 P(k, E) = 1$. $H_{\text{peak}}$ decreases with $\xi \equiv \xi_{\text{peak}}$ according to:

$$\sigma_2 \equiv \sigma_2 \left( Q^2 \equiv \frac{4M_N^2}{\frac{1}{\xi} \left( 1 - \frac{\langle E \rangle}{M_N} \right) - 1} \right)$$

In Figure 3 we show for illustration our IA calculation of the QE peaks in $^{56}Fe$ and deuteron at different values of $Q^2$ ($1 \text{ (GeV/c)}^2 < Q^2 < 10 \text{ (GeV/c)}^2$) versus $\xi$. We also show for comparison the curve for $H_{\text{peak}}$, corresponding to Eq.(12). $H_{\text{peak}}$ falls short with respect to the data at high $Q^2$ where in fact inelastic channels start to set in. However $\xi$-scaling was observed in a very small range of $Q^2$ (corresponding to the QE peaks farthest to the left in Figure 3) where it seems to be mainly a consequence of the rather large smearing at the top of the peaks for Fe. In other words, from Figure 3 it is evident that the occurrence or not of $\xi$-scaling depends on the way the peak is smeared: one might expect a scaling effect...
in a complex nucleus such as iron, and not in deuteron for instance, where the smearing is smaller. The smearing in turn reflects well known features of nuclear dynamics i.e. the shape of the nucleon momentum distribution at low momentum \((k \leq 300 \text{MeV})\). We cannot envisage any fundamental reason behind this scaling behavior. Our observation can be tested by performing a similar analysis as the one presented in [3] using the data on deuteron [15] and \(^3\)He [16]. We would like to notice, however, a more intriguing feature in this kinematical region, namely the falloff of QE peaks at different \(Q^2\)’s relative to the Deep Inelastic Scattering (DIS) limiting curve (the dots in Figure 3).

The falloff of the QE peak along the “theoretical” DIS curve suggests an interpretation analogous to Bloom and Gilman’s duality [3]. However, we believe that duality ideas should be phrased in a different way in a nucleus.

We would like to state clearly that here one is observing the interplay between two different “resonance to background” relationships, namely the usual parton-hadron duality [3,14] for the bound nucleon structure function and the occurrence of scattering into channels in which the final \(A - 1\) system either recoils coherently or it undergoes breakup. These breakup channels are identified with the nuclear background; coherent recoil generates the low momentum and energy peaks corresponding to the ground state for the \(A - 1\) nucleus, followed by its shell model excitations.

Now, nuclear dynamics contributes to \(\xi_{\text{peak}}\) and \(H_{\text{peak}}\), Eq.(10), through the average value of the removal energy, \(\langle E \rangle\) and the normalization of the nucleon spectral function, respectively. These quantities in turn depend mostly on the low energy and momentum components of \(P(k; E)\). Therefore, if one were to extract the DIS contribution from the elastic cross section, according to the duality prescription [3,14], one would not get any information on the short distance nuclear dynamics which is expected to strongly contribute in this region. As a matter of fact, from Eqs.(2) and (3) one can see that \(\xi\) limits the phase space allotted for the contribution of the nucleon spectral function to the DIS structure function. As a result, at high enough \(\xi\) \((\xi > 0.8)\) the continuous background of \(F_2^N\) is folded with the high \(k\) part of the nucleon spectral function, that is with the nuclear background.
obtained when breakup configurations for the $A - 1$ system are included. As $\xi$ increases, only the highest $k$ components contribute, which occur with a decreasing probability and this is what determines the structure function’s falloff.

To summarize, the behavior of the low $Q^2$ structure function at $\xi \approx 0.8$ is determined by the elastic nucleon cross section and by the low momentum components of the nuclear spectral function. The high $Q^2$ structure function is determined by the DIS nucleon structure function folded with the high momentum components of the spectral function. Because we are dealing with different parts of the nucleon spectral function these to quantities cannot be related in a straightforward way using the usual duality ideas. Our point of view is illustrated also in Figure 3 where we compare the QE peak falloff (dashed line) with the deep inelastic limit curve (dotted line).

Finally we would like to comment briefly on the region of low $\xi$ ($\xi < 0.6$). Here the scaling in $\xi$ should reflect the scaling in the nucleon structure function, modulo nuclear effects that we expect to be of the same size of the EMC-effect.

Our conclusions are that the $\xi$-scaling found in the high-$x$ data seems to be most likely an accident. When the data are plotted vs. $\xi$ the presence of FSI effects in nuclei is hidden by the $Q^2$-dependent relationship between Nachtmann’s $\xi$ and West’s $y$. In the particular region of $Q^2$ explored so far, the pattern of $\xi$-scaling and $\xi$-scaling violations does not seem to allow any space for any further theoretical speculation. Our interpretation can be tested readily with the forthcoming experiments at CEBAF that will extend measurements to higher $Q^2$. Here we predict that if the mechanism that we suggest is correct, $\xi$-scaling violations should persist with a comparable magnitude as the one seen at lower $Q^2$. At $x \approx 1$ a new aspect of duality ideas is envisaged. We emphasize that duality ideas in nuclei should be considered within a more general framework which includes together with the resonance to background behavior implicit in nucleon structure, the resonance and background behavior of nucleons in nuclei, generated by the presence of short distance NN configurations. A more accurate discerning of the underlying dynamics of hadronic configurations participating in electron-nucleus scattering processes in the multi-GeV region and at $x > 1$ is a prerequisite in order
to explore consistently the exciting new aspects of QCD in this region.

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FIGURES

FIG. 1. Comparison of the theoretical structure function per nucleon for Fe with the experimental data of [3] plotted vs. $Q^2$ at different values of $\xi$. Solid lines: full calculation, including both the quasielastic and the inelastic channels and the effect of FSI; dashes: contribution of the inelastic channels.

FIG. 2. Shift in $y$, $a_\xi$ (short-dashed line) and $b_{FSI}$ (full line) contributing to Eq.(7), plotted vs. $Q^2$ at fixed $y_{NM} = -0.4$/GeV/c. For comparison, the term $a_x$, Eq.(8), is also shown (dots).

FIG. 3. Different contributions to the nuclear structure function in deuteron (a), and $^{56}Fe$, (b), vs. $\xi$. The short-dashed curves in (a) and (b) represent the QE peaks calculated in IA for values of $Q^2$ in the range $1(GeV/c)^2 < Q^2 < 8(GeV/c)^2$, are shown ). The full lines in (a) and (b) are the deep inelastic limit of Eq.(2). The dashed line in (b) represents $H_{peak}$ (Eq.(10)). The data in (b) correspond to one of the kinematics of [3] where scaling at low $\xi$ was reported.