DO-TH-93-27

DO-TH 93/27
November 1993

On Dynamically Generated Partons in Hadrons and Photons

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Abstract

The perturbative properties of parton distributions generated radiatively from a valence-like input at some low resolution scale are discussed with the aim of explaining the physical aspects underlying the reliability of the predicted distributions in the small-x region. Aspects of higher-twist (shadowing) effects as well as small-x resummations are discussed, and possible implications for lattice calculations are pointed out.

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The original attempt [1] to generate purely dynamically all gluon (g) and sea ($\bar{q} = \bar{u}, \bar{d}, \bar{s}$) distributions merely from measured valence densities was based on the extreme boundary conditions at $Q^2 = \mu^2$ with $\mu = O(\Lambda)$,

$$g(x,\mu^2) = \bar{q}(x,\mu^2) = 0 \quad , \tag{1}$$

in order to avoid any free additional parameters and assumptions in the perturbative renormalization group (RG) evolution to $Q^2 > \mu^2$. Qualitatively this approach works suprisingly well and yields, in particular, the remarkable parameter-free prediction [1] for the momentum fraction carried by gluons, $\int_0^1 xg(x,Q^2)dx \simeq 0.45$ at $Q^2 = 1-5\ \mathrm{GeV}^2$. Quantitatively, however, the resulting predictions disagree with experiment since the detailed x-dependence of $g(x,Q^2)$ and $\bar{q}(x,Q^2)$ turns out to be much too steep in the small-x region [2,3] and thus too soft at larger values of x in disagreement with constraints imposed, for example, by the data on direct-photon production.

This purely dynamical approach based on eq. (1) would be indeed physically compelling if the valence distributions $q_v(x,Q^2)$, $q_v \equiv q-\bar{q}$, are identified with the constituent quarks in the proton. However, partonic quark distributions should rather be identified with the current quark content of hadrons. Therefore eq. (1) is not expected to be adequate and is replaced by the assumption that the sea-quarks and gluons follow the valence-quarks [3] at some low resolution scale μ, or more generally [4-6][f1]

$$xg(x,\mu^2) = Ax^{\alpha}(1-x)^{\beta} \ , \quad x\bar{q}(x,\mu^2) = A'x^{\alpha'}(1-x)^{\beta'} \tag{2}$$

[f1] Due to the gluonic hyperfine interaction ('Z-diagrams' in which gluons connect one quark to another), intrinsic (input) gluon and sea-quark distributions are expected to be always non-vanishing [7]. In the next-to-leading order (NLO) eq. (2) was implemented in the $\overline{MS}$ factorization scheme.

representing some valence-like ($\alpha, \alpha' > 0$) structure at $Q = \mu$. Here the gluonic and antiquark (sea) partons are conceived as being frozen upon the valence current quarks[f2] (the shapes of their x-dependence turn out to be indeed very similar [4,5]) at the scale $Q = \mu$ dividing the non-perturbative regime ($Q < \mu$) from the perturbative one ($Q \gtrsim \mu$). They are thus supposed to share the momentum distribution features of the (current!) valence-quark parton distributions.

Experience supports this latter view since the almost unique radiative (dynamical) predictions [4,5], being mainly due to the QCD dynamics and independent of any free (fit) parameters, in the small-x region, $x \lesssim 10^{-2}$, resulting from the valence-like input in eq. (2), seem to be confirmed, for the time being, by all present experimental ep, γp and $\gamma\gamma$ data [8-11]. Due to this, several questions were raised recently (see, for example, the review and summary talks in [12]) concerning the reliability of this somewhat "unbelievable" approach and the reasons for its seeming success which we attempt to further clarify.

(i) Perturbative reliability. Since the radiative RG-evolution starts at a low evolution scale $Q = \mu$ with $\mu \simeq 3\Lambda$ (typically $\mu_{LO} \simeq 0.5$ GeV and $\mu_{NLO} \simeq 0.55$ GeV where the gluons and antiquarks in the nucleon are valence-like [4,5]) one may wonder whether a perturbative treatment at such low momentum scales is admissible and reliable. Superficially such an objection is seemingly correct, but so far no one really knows[f3] the range of validity of perturbative QCD. This can be studied, as usual, only by a pragmatic approach trying to find out by methods of trial and error where this perturbative limit actually is. For the present case we find that the perturbative expansion parameters are indeed small by comparing

f2 These stuck-together objects form the constituents quarks !

f3 Recent lattice calculations of α_s from first principles [13] confirm the perturbative NLO (2-loop) predictions for $\alpha_s(Q^2)$ down to $Q \simeq 0.55$ GeV $\simeq \mu$.

the perturbative stability of our predictions in the leading (LO) and next-to-leading (NLO) orders. The emerging perturbative stability results not only due to $\alpha_s(\mu^2)/\pi \simeq 0.2 \ll 1$, but also due to the particular shapes of the 1- and 2-loop splitting functions $P_{ij}^{(0)}(x)$ and $P_{ij}^{(1)}(x)$, respectively, as well as due to the particular (different) shapes of the LO and NLO input parton distributions $f(x,\mu^2)$ where $f = q, \bar{q}, g$. These perturbatively stable predictions refer always to measurable quantities like $F_2(x,Q^2)$ etc. rather than to the auxiliary, not directly measurable, NLO parton distributions $f(x,Q^2)$ as illustrated in figs. 1 and 2. The perturbative instability of the latter quantities, i.e. $f^{LO}(x,Q^2) \neq f^{NLO}(x,Q^2)$ as exemplified in fig. 2, should be expected and even tolerated : Despite the sizeable difference of LO and NLO sea and gluon distributions in the small-x region in fig. 2, the sea ($\bar{u}$) dominated structure function F_2^{ep} in in fig. 1 and its gluon dominated ($\gamma^* g \to c\bar{c}$, etc.) heavy quark contribution F_2^c show a remarkable perturbative stability. A similar (even more pronounced) perturbative NLO stability is also obtained for other directly measurable quantities such as for example F_2^b, $F_L^{c,b}$ ($F_L \equiv F_2 - 2xF_1$), $\sigma(pp \to c\bar{c}X)$ and $\sigma(pp \to b\bar{b}X)$ all the way up to multi-TeV energies [14].

(ii) Specific dynamical predictions. Due to the valence-like structure of the input distributions in eq. (2), our radiative predictions [4] at $Q > \mu$ are rather unambiguous [5], i.e. parameter-free in the small-x region, $x \lesssim 10^{-2}$. At larger scales $Q^2 \gtrsim 5$ GeV^2 structure functions like $F_2(x,Q^2)$ and the singlet parton distributions $xg(x,Q^2)$ and $x\bar{q}(x,Q^2)$ are predicted to be steep at small-x, as can be seen in figs. 1 and 2 : Typically, at $Q^2 = 10 - 100$ GeV^2 $F_2, xg \sim x^{-\lambda}$ with $\lambda_{NLO} \simeq 0.3 - 0.4$ for $10^{-5} \lesssim x \lesssim 10^{-3}$, i.e. these distributions possess a 'Lipatov'-like ($\lambda \neq 0$) behavior, which has been confirmed by HERA [8,10]. At smaller scales $Q^2 = 1 - 2$ GeV^2, however, F_2 and xf are predicted to be rather flat [4,5] at small-x, i.e. develop the 'Regge (Pomeron)'-like x-dependence $\sim x^0$. Although such a trend towards

a small-x flattening of $F_2^{ep}(x,Q^2)$ for decreasing Q^2 is indicated by the recent H1-data [8,10], this latter prediction has to be still confirmed by future HERA measurements - it will constitute a fundamental test of the correctness of the radiatively (dynamically) calculated parton distributions.[f4] It should be furthermore emphasized that these scale dependent unique small-x predictions are not only a consequence of the 'standard' RG evolution equations (due to the large radiative evolution 'distance' $\xi(Q^2) \equiv \ln[\alpha_s(\mu^2)/\alpha_s(Q^2)]$), but follow in particular also from our assumed valence-like gluon and (light) sea content in eq. (2), $xf(x,\mu^2) \to 0$ for $x \to 0$, of the nucleon at a low resolution scale[f5] $\mu \simeq 3\Lambda$. Both ingredients, as well as the specific shapes of the perturbatively calculable splitting fucntions $P_{ij}^{(0,1)}(x)$ and of the Wilson expansion coefficients, seem to provide the correct small-x behavior of $F_2(x,Q^2)$ as measured at HERA [8,10]. (Here no further assumptions or small-x extrapolations of $f(x,Q_0^2)$ at, say, $Q_0^2 \simeq 4\ \mathrm{GeV}^2$ - usually implemented in all alternative, mainly fit-inspired, parametrizations of parton distributions [16] - are needed or employed.)

(iii) Higher-twist ('shadowing') effects. At the low scales $Q \simeq \mu$ higher-twist $\tau > 2$ effects, suppressed by powers of $1/Q^{\tau-2}$, might a priori become quite important, as compared with the dominant twist $\tau \equiv$ dimension-spin = 2 effects considered thus far. Here one should clearly distinguish between two different matters: (a) the possible higher-twist contributions

f4 It should be noted that such tests are not feasible for the alternative standard fits of parton distributions where an ansatz for the input distributions $xf(x,Q_0^2)$ with an assumed (flat or steep) small-x behavior is fitted to the data at $Q_0^2 = 4\ \mathrm{GeV}^2$ for example (see, e.g., [16]). In this case the highly unstable 'backward' evolution to $Q^2 < Q_0^2$ would lead to negative parton distributions [17].

f5 Note that there is only one scale μ where such a valence-like structure can exist, which is fixed by experiment in order to obtain a large enough amount [4,5] of $\bar{q}(x,Q^2)$ and $g(x,Q^2)$ at $Q^2 > \mu^2$ (and $x \gtrsim 0.01$).

to measurable quantities like $F_2(x,Q^2)$ and (b) their strict decoupling[f6] from the underlying Q^2-evolution equations for the standard covariant twist-2 parton distributions $f(x,Q^2)$ utilized in all our subsequent physical applications. Covariantly defined operators of different twists do not mix under renormalization! This should be distinguished from approaches [18,19] referring to k_T-cut-off regulated 'parton distributions' $\tilde{f}(x,Q^2)$ which, being non-covariant, may mix with higher-twist-like distributions[f7] leading to possible "shadowing" (or "screening") effects of the non-standard "twist-2" $\tilde{f}(x,Q^2)$ in the low-x region. Here these nonlinear shadowing effects ($\sim -C/R^2Q^2$ with R being the proton radius, $R \simeq 5\ \mathrm{GeV}^{-1}$, or a smaller "hot-spot" screening parameter, $R \simeq 2\ \mathrm{GeV}^{-1}$) cause a flattening of originally steep input distributions $x\tilde{f}(x,Q_0^2)$ in the small-x region. The recent steep HERA results [8,10] apparently do not support this approach.

Shadowing-like effects, as eventually required by unitarity, appear in our standard covariant twist-diagonal approach merely via the chosen valence-like input $xf(x,\mu^2)$ in eq. (2) as well as due to the particular influence of the two-loop splitting functions $P_{ij}^{(1)}(x)$ in the NLO evolution which reduce [4] the naive LO results in the small-x region.[f8] The remaining possible influence of higher-twist contributions on, say, $F_2(x,Q^2)$

f6 This is essential for obtaining universal, i.e process independent parton distributions $f(x,Q^2)$ which can be used for studying any other hard scattering process - the main virtue of the entire fundamental concept of the parton model.

f7 The twist concept is unambiguously defined only in covariant formulations of deep inelastic scattering which requires fermionic and gluonic Wilson operators of definite spin (i.e. traceless) and dimension (see, for example [20] and the appropriate discussion on pp. 442,443 of [19]).

f8 This should also apply to nuclear shadowing still to be studied within our dynamical approach.

at low Q^2 can only be inferred phenomenologically : Comparing our predicted results for $F_2(x,Q^2)$ with, say, the EMC-NA28, NMC and SLAC μ(e)d data we note [4,5] that higher-twist contributions at $x \lesssim 0.1$ are at most marginal even at $Q^2 \lesssim 1\ \mathrm{GeV}^2$.

(iv) No strong k_T-ordering in ladder summations, i.e. in Q^2-evolutions. The leading logarithms resummed by the Altarelli-Parisi RG evolution equations at the LO correspond to a summation of quark and gluon ladders with strongly ordered transverse momenta in the n rungs ($Q^2 > k_{nT}^2 > \ldots > k_{1T}^2 > Q_0^2$). For small x but moderate Q^2 this simple and naive LO approach is expected to break down since ladder contributions with no strong k_T-ordering will obviously become important and one clearly has to integrate over the full k_T phase space [21,18]. Such contributions have been formulated (BFKL summation) and calculated just for gluon ladders in the LO resulting in a steeper small-x 'Lipatov'-like gluon distribution $xg \sim x^{-\lambda}$ with $\lambda \leq \lambda_{max} = (3\alpha_s/\pi)4\ln 2 \simeq 0.5$ as already referred to in (ii). Unfortunately this BFKL result carries little predictive power since it does not refer to any specific Q^2-scale where it is supposed to hold and furthermore only represents some LO 'asymptotic' small-x ($x \to 0$) behavior of the gluon distribution.[f9] It is thus certainly true that the LO Q^2-evolution based on $P_{ij}^{(0)}(x)$ becomes unreliable in the small-x region due to the summation of just strongly k_T-ordered ladders. However, as soon as NLO Q^2-evolutions, containing the two-loop $P_{ij}^{(1)}(x)$, are considered, non-ordered k_T ladder contributions are involved which moreover are treated in a strictly covariant way in contrast to the k_T-regularized distributions $\tilde{f}(x,Q^2)$ in [18,19,21] which, as mentioned

[f9] It is difficult to envisage how the conceptionally important NLO contributions can be calculated within the non-covariant k_T-cut-off regulated ladder approach, which are essential for establishing the reliability of the LO BFKL-results.

before in (iii), should not be directly compared with our strictly covariantly evolved $f(x,Q^2)$.

(v) Resummations of small-x singularities of splitting functions? It has been frequently claimed [22] that the singular behavior of $P_{ij}^{(0)}(x)$ and $P_{ij}^{(1)}(x)$ in the small-x region requires a resummation of leading small-x singularities in

$$P_{ij}(x,Q^2) = \frac{\alpha_s(Q^2)}{2\pi} P_{ij}^{(0)}(x) + \left(\frac{\alpha_s(Q^2)}{2\pi}\right)^2 P_{ij}^{(1)}(x) + \ldots \qquad (3)$$

before performing any (reliable) Q^2-evolution analysis in the small-x region. However, as noted recently [14], this seemingly alarming danger disappears as soon as one recognizes that the P_{ij}'s always appear in the Q^2-evolution equations convoluted with some very specific parton distribution functions and that the question of the low-x perturbative stability of the investigated Q^2-evolutions crucially depends on the particular shapes of the involved LO and NLO parton distributions. As already noted in (i) our particular radiatively generated LO and NLO parton distributions do not give rise to physically relevant perturbative instabilities for directly measurable quantities in the small-x region despite of the noted [22] bad convergence of $P_{ij}(x,Q^2)$ itself as $x \to 0$. This implies in particular also that one has always to perform a full NLO analysis (i.e. to keep the full $P_{ij}^{(n)}(x)$ and Wilson coefficients) for obtaining perturbatively relevant and reliable results. Recent studies of NLO and NNLO contributions [23] have explicitly demonstrated that the "1/x approximation", used in most small-x studies [19,21,22], is insufficient even down to $x = 10^{-5}$ and thus that resummations of 1/x and $\ln x/x$ terms are not very useful and even misleading. This further demonstrates the care needed before making any general statements concerning perturbative stability [22], non-physical small-x behavior [18,21], etc.

(vi) Possible implications for lattice calculations. It is more than surprising that the 'quenched' or 'valence' approximation, where the effect of virtual $q\bar{q}$-excitations on the lattice is ignored for technical reasons, works that well in describing the observed hadron mass spectra (for a recent review, see [24]). It is tempting to speculate that our dynamical valence-like parton model [3-5] offers some rationale for this success since at a length scale $\mu^{-1} \simeq (0.55\ \mathrm{GeV})^{-1} \simeq 0.5$ fm the proton consists dominantly of valence quarks and valence-like gluons, i.e. with practically no $q\bar{q}$-excitations (sea quarks). The latter become important only at perturbative length scales less than μ^{-1} but are negligible at scales larger than $\mu^{-1} \simeq 0.5$ fm typical for lattice calculations. It would be interesting to see whether the non-perturbative valence-like distributions at $Q^2=\mu^2$, which we have determined purely phenomenologically, can be obtained, in some forthcoming lattice QCD analysis, from first principles.

(vii) Universality. Finally we emphasize the universal character of our radiative (dynamical) valence-like parton model approach which allows for its application also to other objects such as the pion [25] and the photon [26][f10] where it enables one to explore the yet unknown photonic gluon distribution $g^{\gamma}(x,Q^2)$. These predictions seem to lie in the right ball park of preliminary LEP, TRISTAN (e^+e^-) and HERA (ep)

f10 In NLO the valence-like hadronic VMD input was implemented in a specific factorization scheme (DIS_{γ}) chosen so as to minimize NLO corrections to measurable quantities such as $F_2^{\gamma}(x,Q^2)$, etc. This factorization scheme amounts to choosing a vanishing photonic Wilson coefficient, which contributes in NLO to F_2^{γ}, while keeping the partonic Wilson coefficients in the $\overline{MS}$ factorization scheme as in the corresponding hadronic case discussed so far.

measurements [9-11].[f11] Furthermore the dynamical radiative concept also provides us with access to the time-like region ($Q^2 \equiv -q^2 < 0$), e.g. for analyzing the fragmentation functions of partons into photons [27] which have so far, however, not been measured.

f11 Obviously there are inherent uncertainties due to the hadronic valence-like vector-meson-dominance input at $Q^2=\mu^2$ which, however, do not affect our small-x predictions as in the corresponding case of the nucleon.

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Figure Captions

Fig. 1. Dynamical LO and NLO GRV predictions [4] for F_2^{ep} which have been already confirmed, for $Q^2 \geq 8.5\ \mathrm{GeV}^2$, by recent HERA data [8,10]. The LO and NLO heavy quark (charm) contributions have been calculated via the $\gamma^* g \to c\bar{c}$ and $\gamma^* g$, $\gamma^* q(\bar{q}) \to c\bar{c}X$ fusion subprocesses [14,15], respectively, using $m_c = 1.5\,\mathrm{GeV}$. These LO and NLO charm contributions, F_2^c, are shown separately as well.

Fig. 2. Dynamical LO and NLO GRV predictions [4] for the light sea $(\bar{u})$ and gluon distributions.

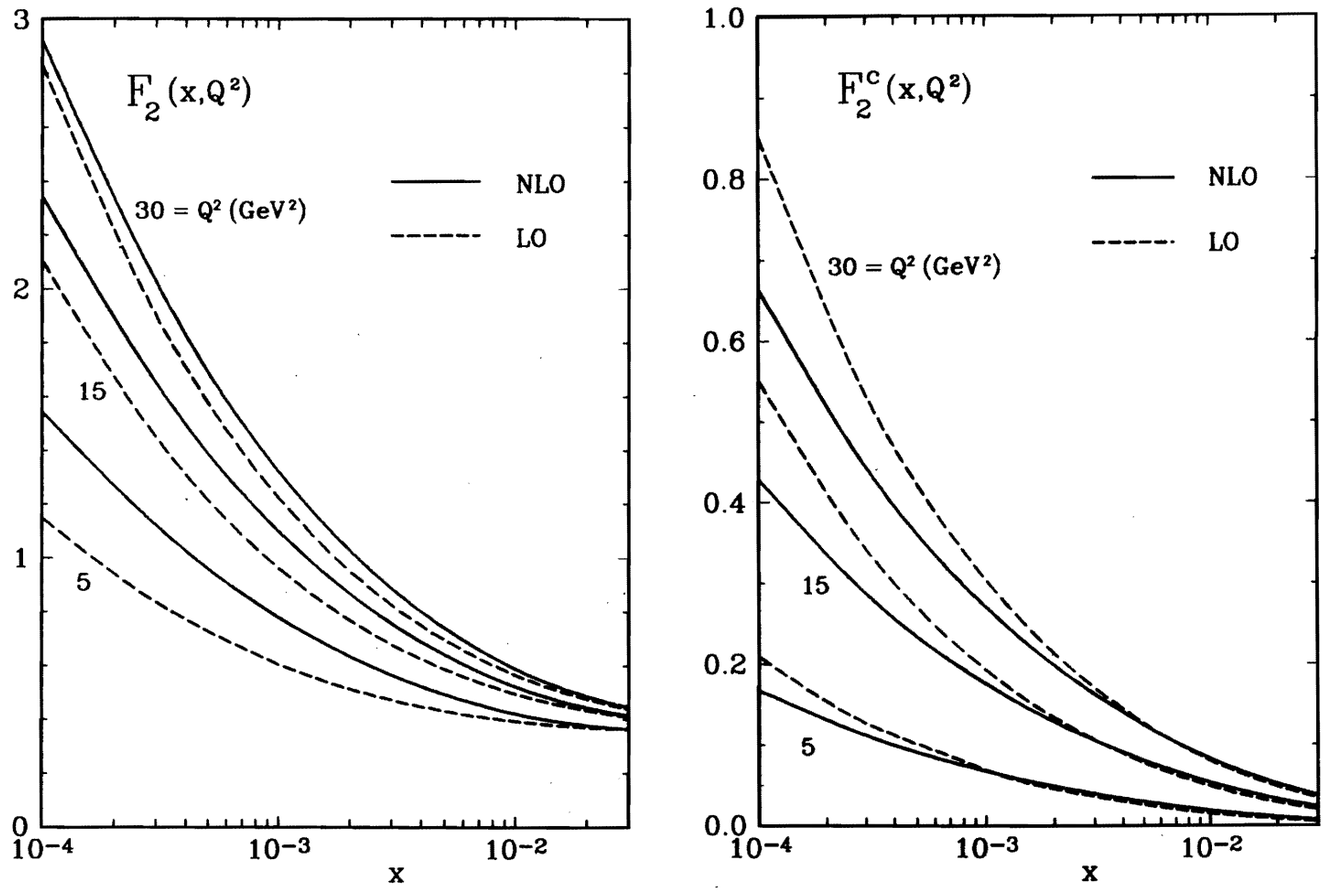
$F_2(x,Q^2)$
30 = Q^2 (GeV^2)
15
5
NLO
LO
3
2
1
0
10^{-4}
10^{-3}
10^{-2}
x
$F_2^c(x,Q^2)$
30 = Q^2 (GeV^2)
15
5
NLO
LO
1.0
0.8
0.6
0.4
0.2
0.0
10^{-4}
10^{-3}
10^{-2}
x

FIG. 1

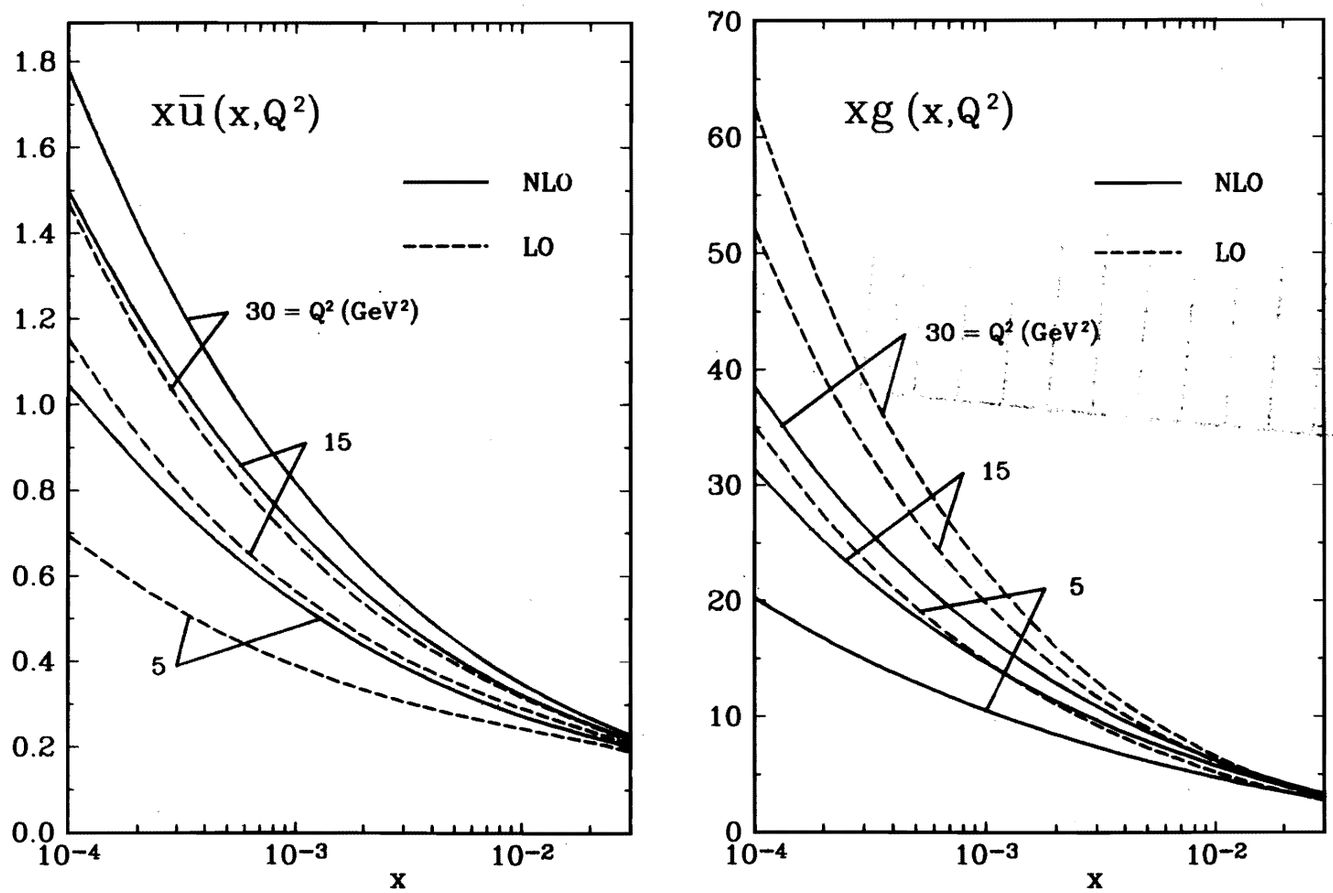
$x\bar{u}(x,Q^2)$
NLO
LO
30 = Q² (GeV²)
15
5
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10⁻⁴
10⁻³
10⁻²
x
$xg(x,Q^2)$
NLO
LO
30 = Q² (GeV²)
15
5
70
60
50
40
30
20
10
0
10⁻⁴
10⁻³
10⁻²
x

FIG. 2