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RAL-93-032

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June 1993

DTP/93/36
RAL-93-032
May 1993

Light gluinos in high–Q^2 deep inelastic scattering

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Abstract

A slight incompatibility in recent low-energy and high-energy α_s measurements can be interpreted as evidence for new light colour degrees of freedom. Assuming that these are the gluinos of a supersymmetric extension of the Standard Model, we investigate to what extent they change the standard QCD predictions for deep inelastic structure functions, and in particular whether thay can be detected in such measurements at HERA. We present a modified set of parton distributions which includes a light gluino distribution and which can be used for further phenomenological investigations.

Much attention has been focussed on α_s measurements in the last few years, motivated in part by the implications of the value of $\alpha_s(M_Z^2)$ for coupling constant unification and possible hints of supersymmetry at relatively low scales [1]. A large part of the debate has centred on the issue of which processes provide the most accurate measurements, the reliability of the quoted error values, and so on. Fig. 1 shows a recent compilation [3] of α_s measurements, plotted at the 'typical' energy scale Q of the particular process. From this compilation, an interesting point emerges: there is a *hint* of a disagreement between α_s values measured at low energies and those at high energies. The solid line in Fig. 1 corresponds to $\alpha_s(Q^2)$ evaluated and evolved at next-to-leading order in the $\overline{MS}$ scheme,

$$\begin{aligned} \frac{4\pi}{\alpha_s} + \frac{\beta_1}{\beta_0}\log\left(\frac{\beta_0^2\alpha_s}{4\pi\beta_0+\beta_1\alpha_s}\right) &= \beta_0\log\frac{Q^2}{\Lambda^2}, \\ \beta_0 = 11 - \tfrac{2}{3}n_f\,, \qquad & \beta_1 = 102 - \tfrac{38}{3}n_f\,, \end{aligned} \tag{1}$$

with $\Lambda_{\overline{MS}}^{(4)} = 230\ MeV$, a value consistent with all fixed-target deep inelastic experiments and related processes [2]. We see that when extrapolated to higher Q values, the coupling tends to lie below the high-energy measurements. Even allowing for the most optimistic estimates of the errors [3], it is clear from Fig. 1 that there is *no overall significant deviation from a unique value of* $\Lambda_{\overline{MS}}$. There is only a slight hint at an incompatibility. This notwithstanding, it has recently been argued [4, 5, 6] that a possible explanation of the mismatch in the evolved and measured high-energy couplings is that at some intermediate scale a new coloured degree of freedom is being excited, whose effect is to slow the running of α_s. A light supersymmetric gluino ($\tilde{g}$) has been suggested as a possible candidate. As the (Majorana) gluino mass threshold is crossed the β-function coefficients change:

$$\beta_i \;\rightarrow\; \beta_i \;+\; \Delta\beta_i\,\theta(Q - 2m_{\tilde{g}})\,, \tag{2}$$

where $\Delta\beta_0 = -2$ and $\Delta\beta_1 = -48$. With $m_{\tilde{g}} = 5\ GeV$, the coupling evolves as the dashed line in Fig. 1, and consistency with the high-energy measurements is restored. It is not our purpose here to discuss in detail the theoretical and experimental consistency or otherwise of this hypothesis: a discussion can be found in [5]. We are simply interested to see whether such a gluino can be detected at HERA. In our analysis, we assume the nominal value $m_{\tilde{g}} = 5\ GeV$, although of course taken literally the α_s measurements would allow a range of masses of this order.[1] The basic logic is that the gluino is heavy enough to largely decouple from fixed-target deep inelastic scattering, while at the same time light enough to allow the coupling to evolve to a significantly higher value at $Q \sim M_Z$ than the standard QCD value.

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[1] Note that the comparison in Fig. 1 of the running coupling including the gluino with the LEP measurements is anyway too naive, since the presence of the gluino influences to some extent the extracted α_s values, particularly those from jet rates. This is discussed in detail in [5].

The HERA high-energy *ep* collider will, over the next few years, provide precision measurements of the proton structure functions at scales up to $Q^2 \sim 10^5\ GeV^2$. Since the light gluino introduced above is presumably electroweak neutral, its impact is expected to be very small. This was confirmed several years ago in references [7, 8, 9], where the modified evolution equations including light gluinos were presented for leading and next-to-leading order respectively. In fact, the present work can be regarded as an update of [8], taking into account (i) the increased precision of modern parton distribution analyses, (ii) the hint from α_s measurements that $m_{\tilde g} \sim 5\ GeV$, and (iii) the precise kinematic range relevant to HERA. Thus, if we consider the evolution of the quark, gluon and gluino distributions at leading order

$$\frac{dq(x,Q^2)}{d\log Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_0^x \frac{dy}{y}\left[q(y,Q^2)\ P_{qq}(\frac{x}{y}) + g(y,Q^2)\ P_{qg}(\frac{x}{y})\right] \tag{3}$$

$$\frac{dg(x,Q^2)}{d\log Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_0^x \frac{dy}{y}\left[q(y,Q^2)\ P_{gq}(\frac{x}{y}) + g(y,Q^2)\ P_{gg}(\frac{x}{y}) + \tilde g(y,Q^2)\ P_{g\tilde g}(\frac{x}{y})\right] \tag{4}$$

$$\frac{d\tilde g(x,Q^2)}{d\log Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_0^x \frac{dy}{y}\left[g(y,Q^2)\ P_{\tilde g g}(\frac{x}{y}) + \tilde g(y,Q^2)\ P_{\tilde g\tilde g}(\frac{x}{y})\right] \tag{5}$$

with the relevant splitting functions given in reference [7], we see that the only impact on the quarks (which are measured directly by $F_2(x,Q^2)$ for example) is through the coupling $\alpha_s(Q^2)$. In fact if we assume that there is no associated light squark, then the leading *direct* contribution to F_2 comes from the $O(\alpha_s^2)$ process $\tilde g\gamma^* \to \tilde g q\bar q$. The same process also gives a next-to-leading contribution to the longitudinal structure function F_L.

To investigate the effects of the light gluino more quantitatively we have repeated the next-to-leading order parton distribution analysis of reference [2] but now including a light gluino with $m_{\tilde g} = 5\ GeV$. Since the bulk of the fixed-target deep inelastic data is below the nominal gluino threshold of $Q^2 = 4m_{\tilde g}^2 = 100\ GeV^2$, there is essentially no change to the previous fits. For definiteness we base our study on the MRS-D'_0 fit with $\Lambda^{(4)}_{\overline{MS}} = 230\ MeV$. Fig. 2 compares the evolution of F_2 as a function of Q^2 at fixed x values with and without a light gluino. The HERA kinematic limit is also shown. In the $x \sim 0.01 - 0.1$ region where the Q^2 evolution is weakest the effect is very small. Only at high x and high Q^2 is there any discernible effect, but still the maximum deviation is only of order a few percent. The only hope would be to compare a precise $O(1\%)$ F_2 measurement at high x and Q^2 with a standard QCD fit evolved from lower energy deep inelastic data. Even then, any uncertainty on $\Lambda_{\overline{MS}}$ will effect the accuracy of the extrapolation. As an illustration, Fig. 1 also shows (dashed lines) the ratio of two F_2's: one corresponding to the standard MRS-D'_0 partons with $\Lambda^{(4)}_{\overline{MS}} = 230\ MeV$ and another based on a fit with the '$+1\sigma$' value

$\Lambda^{(4)}_{\overline{MS}} = 280\ MeV$. We see that at the highest Q^2 values the effect of changing $\Lambda^{(4)}_{\overline{MS}}$ by this amount is of the same order as the effect of the light gluino, although there is a clear difference in the shape of the evolution at lower Q^2 values.

Unlike the quark distributions and structure functions, the evolution of the gluon distribution *is* changed at leading order above threshold by the light gluino, Eq. (4). Unfortunately the size of the change is much smaller than the uncertainty in the gluon from any conceivable present or future measurement. This is illustrated in Fig. 3, which shows the standard MRS-D$'_0$ gluon evolved to $Q^2 = 5120\ GeV^2$ with and without a $m_{\tilde{g}} = 5\ GeV$ gluino. Also shown is the gluino distribution itself. Note that in calculating this we adopt exactly the same threshold philosophy as for heavy quarks, *i.e.* we assume that the distribution is zero for $Q^2 \leq 4m^2_{\tilde{g}}$ and evolves thereafter as if the parton was massless, Eq. (5). This procedure gives a reasonable description of the structure function data on the charm quark [10]. With the gluon and gluino distributions of Fig. 3 one could, for example, investigate the changes to the cross sections for such processes as large p_T jet production at hadron colliders.

By momentum conservation, a non-zero gluino distribution implies a reduction in the fraction of momentum carried by the other partons. This is illustrated in Fig. 4, where the momentum fraction carried by the quarks, gluon and gluino are shown as functions of Q^2, and for comparison, the momentum fractions without the gluino (dashed lines). The gluino momentum fraction increases steadily with Q^2, reaching 5% at $Q^2 = 10^4\ GeV^2$.

In conclusion, we find that the effect of a light gluino on the evolution of the structure functions at HERA is minimal, being comparable to the uncertainty of $\Lambda_{\overline{MS}}$ from analyses of present data. Thus attempts to detect light gluinos at HERA should rather concentrate on the analysis of $3+1$ jet events, with contributions from processes such as $\gamma q \rightarrow q\tilde{g}\tilde{g}$. This is analogous to searching for the process $Z \rightarrow q\bar{q}\tilde{g}\tilde{g}$ in 4 jet events at LEP [11]. Finally, we have only examined the consequences of allowing just one light SUSY particle to modify the evolution of F_2. If the gluino turns out to be really light, other SUSY particles may be light enough to further modify the β-function at the high Q^2 values relevant to HERA.

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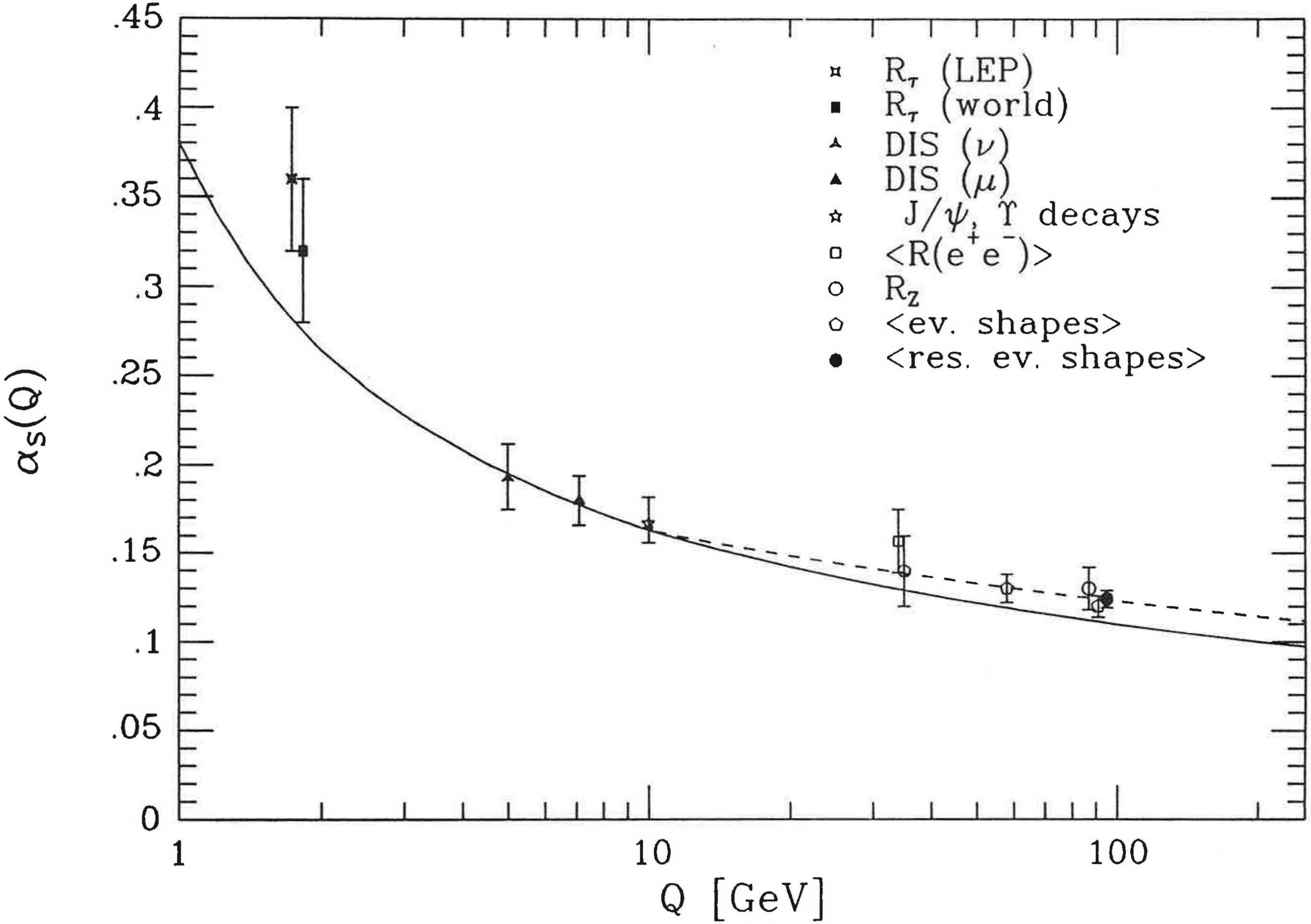
Figure Captions

[1] A compilation of α_s measurements, taken from reference [3]. The solid line is the standard next-to-leading order QCD coupling for $\Lambda^{(4)}_{\overline{MS}} = 230\ MeV$. The dashed line corresponds to a gluino with $m_{\tilde{g}} = 5\ GeV$ and the same value of $\Lambda^{(4)}_{\overline{MS}}$.

[2] Evolution in Q^2 of the structure function F_2 with a 5 GeV gluino, compared to the standard MRS-D_0' prediction [2], for various x values. Also shown (dashed lines) are the corresponding ratios for a structure function fitted to low-energy data with $\Lambda_{\overline{MS}} = 280\ MeV$.

[3] The gluon and gluino distributions as functions of x at $Q^2 = 5120\ GeV^2$. The dashed line is the standard MRS-D_0' gluon with no gluino.

[4] Momentum fractions carried by the quarks, gluon and gluino as functions of Q^2. The dashed lines are the standard MRS-D_0' fractions with no gluino.



.45
.4
.35
.3
.25
.2
.15
.1
.05
0
1
10
100
Q [GeV]
$\alpha_S(Q)$
R_τ (LEP)
R_τ (world)
DIS (ν)
DIS (μ)
J/ψ, Υ decays
<R(e^+e^-)>
R_Z
<ev. shapes>
<res. ev. shapes>

Fig. 1

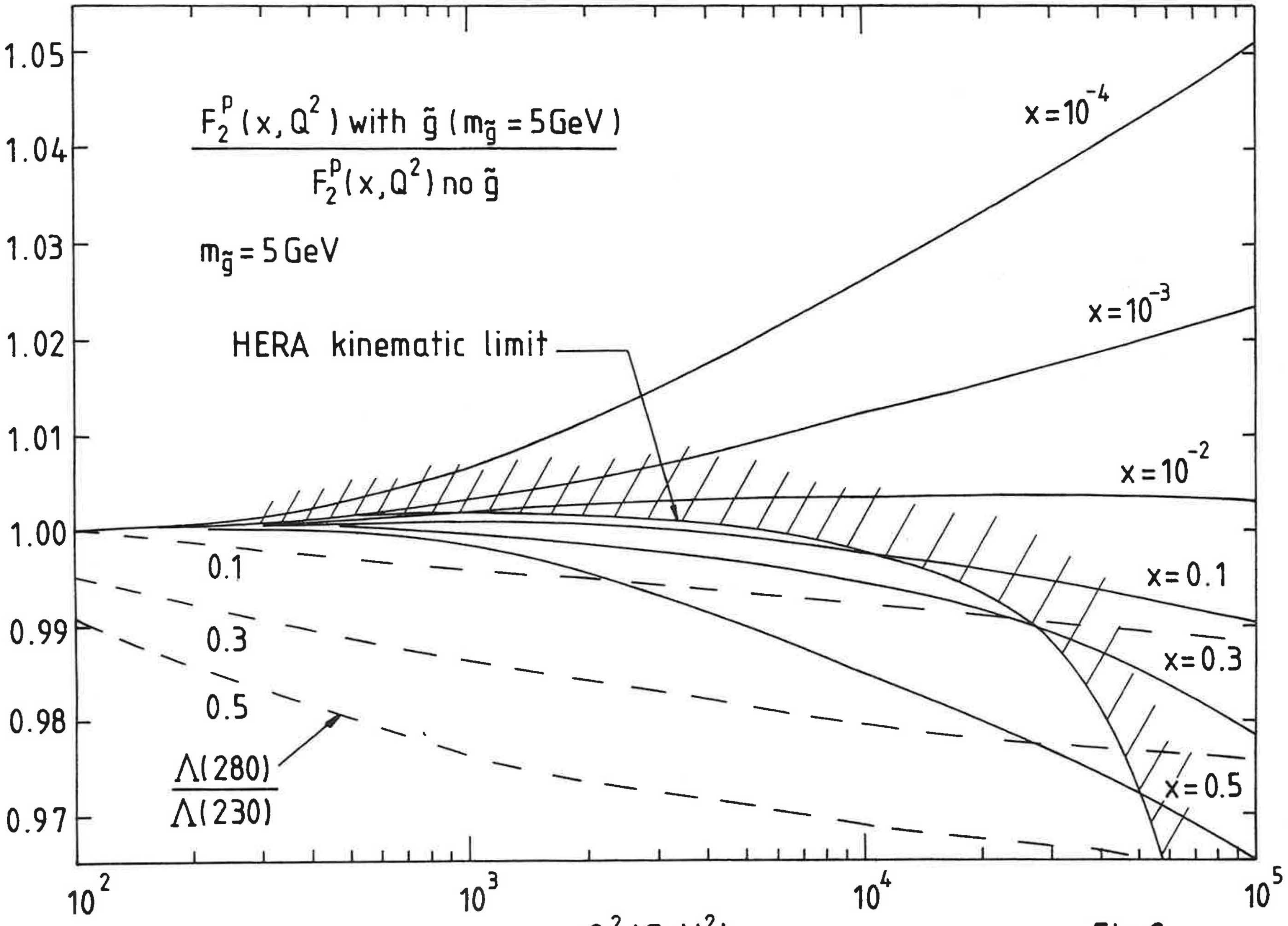

$\frac{F_2^p(x,Q^2) \text{ with } \tilde{g} \ (m_{\tilde{g}} = 5\,\text{GeV})}{F_2^p(x,Q^2) \text{ no } \tilde{g}}$
$m_{\tilde{g}} = 5$ GeV
HERA kinematic limit
$x = 10^{-4}$
$x = 10^{-3}$
$x = 10^{-2}$
$x = 0.1$
$x = 0.3$
$x = 0.5$
0.1
0.3
0.5
$\frac{\Lambda(280)}{\Lambda(230)}$
1.05
1.04
1.03
1.02
1.01
1.00
0.99
0.98
0.97
10^2
10^3
10^4
10^5
Q^2 (GeV^2)

Fig. 2

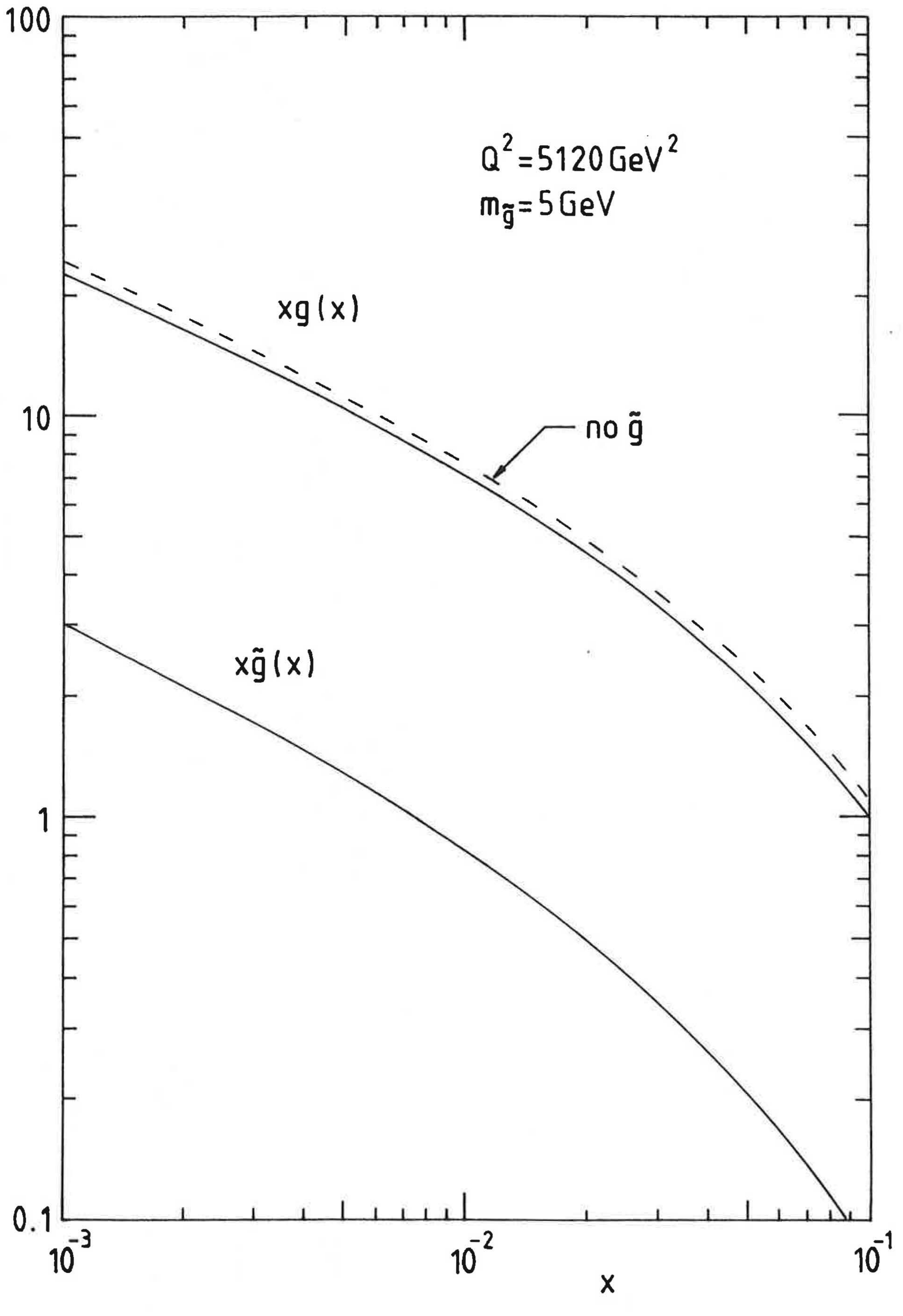

100
10
1
0.1
10^{-3}
10^{-2}
10^{-1}
x
$Q^2 = 5120\,GeV^2$
$m_{\tilde{g}} = 5\,GeV$
$xg(x)$
no $\tilde{g}$
$x\tilde{g}(x)$

Fig. 3

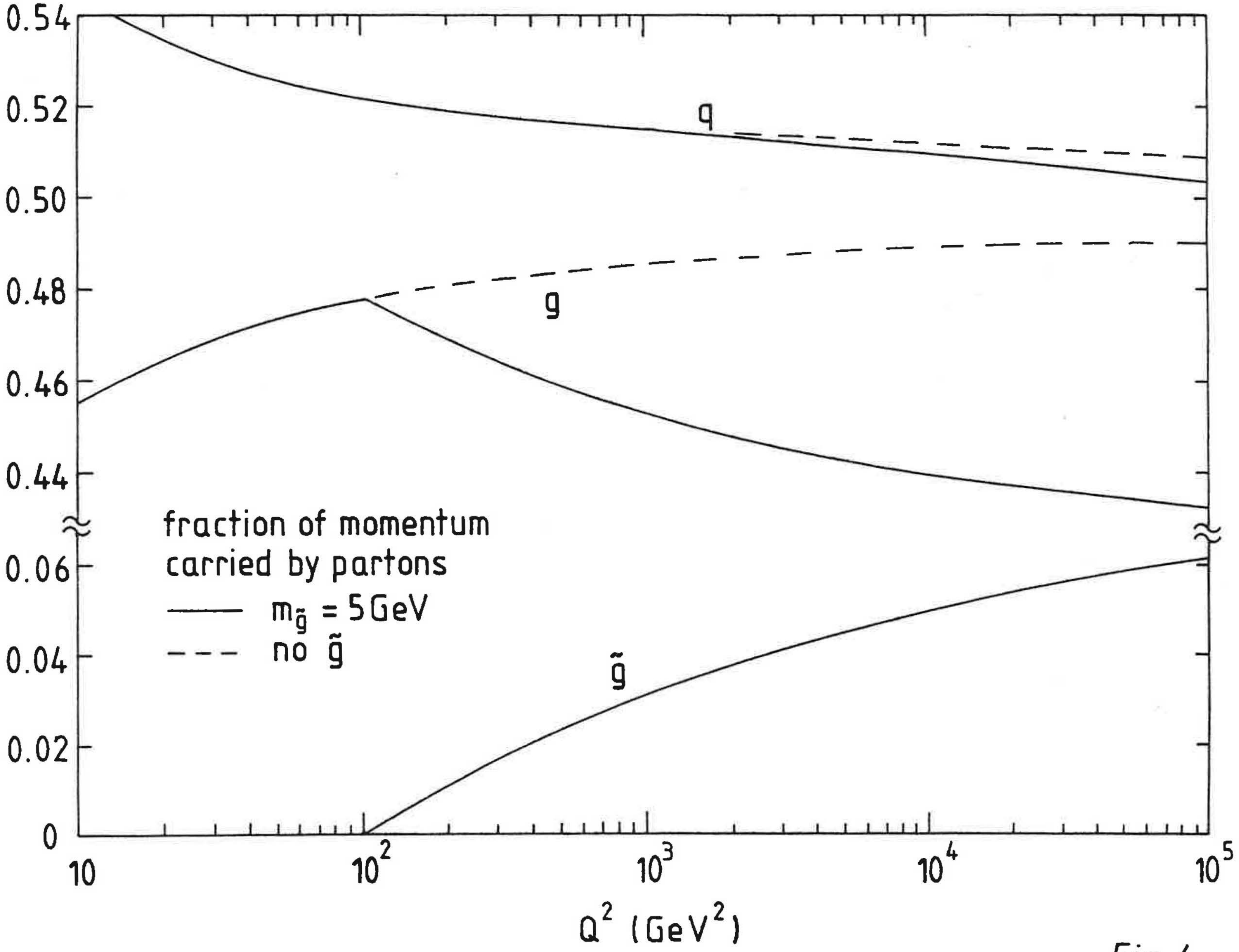

0.54
0.52
0.50
0.48
0.46
0.44
0.06
0.04
0.02
0
10
10^2
10^3
10^4
10^5
Q^2 (GeV^2)
q
g
$\tilde{g}$
fraction of momentum
carried by partons
$m_{\tilde{g}} = 5$ GeV
no $\tilde{g}$

Fig. 4