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Some Phenomenological Aspects of an Exotic Υ Quark

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ABSTRACT

We discuss several experiments that can provide information about the color properties of the Υ quark. In particular we note that a color octet quark as proposed recently should give a dramatic rise in R in $e^+e^- \to \Upsilon$ and give observable effects in μp deep inelastic scattering at presently available energies.

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The discovery[1] of the upsilon $\Upsilon(9.4)$ resonance strongly suggests the existence of a fifth quark. However the mass splitting of the Υ and $\Upsilon'(10.0)$ seems to be bigger than expected in a linear potential picture.[2] In the quark-confining string (QCS) model[3] (which is presumably a phenomenological model derivable from Quantum chromodynamics (QCD)) the strength of the nonrelativistic linear potential is given by the relation $k = \frac{1}{2} g^2 C_2(R)$. Due to gauge invariance the quark-gluon coupling constant g (with dimension mass) is universal for all quarks and $C_2(R)$ is the value of the (quadratic) Casimir operator for the quark representation R of the color group SU(3). $C_2(\underline{3}) = 4/3$ for a color triplet quark, giving a Υ-Υ' mass splitting of 0.4 GeV instead of the observed 0.6 GeV. If the Υ' is indeed the first radially excited state of the Υ, this observed mass splitting poses a serious problem for the QCS.

A possible solution[4] to this difficulty is to put the Υ quark Q in a color representation other than the triplet. Recently this possibility has been further investigated.[5] In particular it has been observed that a quark in the color octet representation ($C_2(\underline{8}) = 3$) gives the observed mass splitting. Due to uncertainties in the theory, a quark in the sextet representation ($C_2(\underline{6}) = 10/3$) can not be ruled out. Other representations (e.g. $\underline{10}$) give too big mass splittings.

e^+e^- annihilation clearly provides the best tests of the possible existence of such an exotic quark:[5] the number of (1^{--}) resonances below the continuum threshold (c.t.), the energy of the c.t., the decay pattern of the Υ, the rise in R above the c.t. and the spectroscopy of hadrons with a single Q or $\bar{Q}$. However it is important to examine also other experiments which can provide clean tests of the nature of the Υ quark. In this note we enumerate and discuss some of the ongoing (or scheduled to run) experiments which may provide evidence either for or against this speculation. Results of these experiments are expected to be available before those from the PETRA, PEP and CESR machines.

1. Stable particle search.[5] Hadrons with a single Q or $\bar{Q}$ are expected to be stable or metastable. For an octet quark with charge e_Q we expect fermionic hadrons $(Qq\bar{q})$ with charge $e_Q, e_Q \pm 1$ and a mass of 5.8 ± 0.5 GeV and bosonic hadrons (Qqqq) with charge $e_Q, e_Q \pm 1, e_Q + 2$ and a mass of 6.0 ± 0.5 GeV (q stands for any light quark). For a sextet quark we expect hadrons with similar masses but the charges are different. If $e_Q = 1/3 + n$, fermionic hadrons $(Q\bar{q}\bar{q})$ have $e = \pm(n \pm 1)$, $\pm n$ and bosonic hadrons $(Q\bar{q}qq)$ have $e = \pm n$, $\pm(n \pm 1)$, $\pm(n+2)$. For a standard t or b quark a possible stable hadron[6] (with $e = 0, \pm 1, \pm 2$) would be lighter (~ 5 GeV). For the octet case we expect equal numbers of e_Q and $(e_Q \pm 1)$ stable hadrons to be produced, while for the standard triplet (t or b) case mostly $|e| = 1$ charged stable hadrons are expected, if any.

2. R at the Υ resonance.[7] For e^+e^- annihilation it is reasonable to assume that the total width of the Υ is much smaller than the beam resolution. Hence the value of R at the Υ resonance is proportional to

the leptonic width Γ_ℓ. Typical values for Γ_ℓ are 0.7 keV for the b quark[8] ($e = -1/3$) and $\sim 16\, e_Q^2$ keV for an octet quark (Comparing to Γ_ℓ for the b quark, Γ_ℓ for Q is enhanced by a factor $9\, e_Q^2$ from the charge and a factor 8/3 from the color). As an illustration let us assume the beam resolution $\sigma_b \simeq 10^{-3}(E_{beam})$. This gives (including radiative corrections) $R(\underline{8}) \simeq 160\, e_Q^2$ and R (b quark) $\simeq 7$ above the background. For a sextet quark with $e_Q = 1/3$ one obtains $R(\underline{6}) \simeq 14$.

3. Deep inelastic μp scattering. The effect of a heavy quark in deep inelastic electroproduction (above threshold) is poorly understood phenomenologically. The general belief is that the effect of the b quark is negligible at present (and probably all) muon energies ($E_\mu \lesssim 300$ GeV). Here we would like to argue that the effect of an octet quark above threshold would be roughly an order of magnitude bigger than that expected of the b quark; hence an additional observable (positive) violation of the already known scaling violation is expected once Q^2 is above threshold, given by $Q^2_{th} \simeq (W^2 - M_N^2)/(\frac{1}{x} - 1)$, where x is the scaling variable and W is the hadronic energy; its lowest value is $m_\Upsilon + M_N = 10.4$ GeV. To illustrate our point, let us consider three models. Individually none of them gives us a reliable heavy quark production rate, but together they do give an order of magnitude estimate.

a. A Generalized Vector Meson Dominance Model (GVMD). It is believed that this model can be used for small values of x.[9,10]

The corresponding contributions to F_2 are given by[10]

$$F_2^{\beta}(x,Q^2) \cong \frac{3}{4\pi^2\alpha^2}\left(\sigma_{tot}(V_\beta p)m_\beta^2\right)\left(\frac{m_\beta\,\Gamma_\beta^{e^+e^-}}{\Delta m_\beta^2}\right)\left(\frac{Q^2}{\Delta m_\beta^2}\right)\xi\left(2,\ \frac{Q^2+m_\beta^2}{\Delta m_\beta^2}\right) \tag{1}$$

with $\xi(z,a) = \sum_{n=0}^{\infty}\frac{1}{(a+n)^z} \simeq \frac{1}{(z-1)a^{z-1}}$ if $a \gg 1$. β indicates the type of vector particles V_β involved $(\rho,\omega,\phi,\psi,\Upsilon)$. $\Delta m_\beta^2 = m_{V'_\beta}^2 - m_{V_\beta}^2$. This gives for the ratio of $Q\bar{Q}$ to $c\bar{c}$ production:

$$\epsilon_{Qc}(x,Q^2) = \frac{F_2^{\Upsilon}(x,Q^2)}{F_2^{\psi}(x,Q^2)} \simeq \left(\frac{\sigma_{tot}(\Upsilon p)m_\Upsilon^2}{\sigma_{tot}(\psi p)m_\psi^2}\right)\left(\frac{m_\Upsilon\,\Delta m_\psi^2\,\Gamma_\Upsilon^{e^+e^-}}{m_\psi\,\Delta m_\Upsilon^2\,\Gamma_\psi^{e^+e^-}}\right)\frac{Q^2+m_\psi^2}{Q^2+m_\Upsilon^2} \tag{2}$$

$$\simeq \frac{9}{4}\,e_Q^2\left(\frac{8}{3}\left(\frac{3}{2}\right)^2\right)\frac{Q^2+m_\psi^2}{Q^2+m_\Upsilon^2} = 13.5\ \frac{Q^2+m_\psi^2}{Q^2+m_\Upsilon^2}\ e_Q^2\,. \tag{3}$$

The 9/4 describes the difference in color group factors assuming that the total cross section is dominated by two gluon exchanges[11] and that $(\sigma_{tot}(V_\beta p)m_\beta^2)$ is otherwise roughly independent of β. The $8/3(3/2)^2 e_Q^2$ is the ratio between $\Gamma_\Upsilon^{e^+e^-}$ and $\Gamma_\psi^{e^+e^-}$ due to color and charge. So $\epsilon_{Qc}\,e_Q^{-2}$ ranges from 1.5 for $Q^2=0$ (i.e. photoproduction) to 13.5 for $Q^2\to\infty$ for energies above threshold (here threshold effects are not included).

A slightly different model for charm production has been proposed,[12] where a threshold factor of $((S-S_0)/S)^3$ is incorporated into the GVMD model. If one includes the threshold effect $((S-S_0)/S)^3$ in the above GVMD ratio (which leads to a factor 0.55 for a beam energy of 300 GeV) one gets

$\epsilon_{Qc} \simeq 7.4\, e_Q^2\, (Q^2 + m_\psi^2)/(Q^2 + m_T^2)$. Figure 1 shows ϵ_{Qc} as a function of Q^2; these formulae are valid for small x and correspondingly small $Q^2 (Q^2 = S x Y = 2M_N E_\mu x Y)$; so $\epsilon_{Qc} e_Q^{-2}$ is roughly of order unity for $Y = 1$ and x small. For the $\underline{6}$ quark, $\epsilon_{Qc} = 6.2\, e_Q^2 \times (Q^2 + m_\psi^2)/(Q^2 + m_T^2)$.

b. The reaction $\gamma^* g \to q\bar{q}$. In QCD, the diagram for this interaction is shown in Fig. 2a. The contributions of this interaction to the structure functions are given by[13]:

$$F_i^{\gamma^* g \to q\bar{q}}(\nu, Q^2) = \frac{2\alpha_S}{\pi} e_q^2 C_2(R_q) A_i \int_{z^-}^{1} dz\, G_g(z, Q^2)$$

$$\left[\frac{(S_z - 2m^2)^2 - 12m^4 + Q^4 - m^2 Q^2 b_i}{(S_z + Q^2)^2} \ln\left(\frac{S_z \left(1 + \sqrt{1 - \frac{4m^2}{S_z}}\right)^2}{4m^2} \right) - \left\{ 1 + 4\, \frac{(m^2 - a_i Q^2) S_z}{(S_z + Q^2)^2} \right\} \sqrt{1 - \frac{4m^2}{S_z}} \right] \tag{4}$$

with $S_z = z M_N (\nu + \sqrt{\nu^2 + Q^2}) - Q^2 \geq 4m^2$, which gives $z^- = (Q^2 + 4m^2)/M_N(\nu + \sqrt{\nu^2 + Q^2})$. m is the quark mass, M_N the nucleon mass. $G_g(z, Q^2)$ is the gluon distribution function. $a_1 = 1, a_2 = 2, b_1 = 0, b_2 = 8, A_1 = 1$, $A_2 = \frac{\nu}{M_N}(Q^2/(Q^2 + \nu^2)), e_c = 2/3, e_b = -1/3$, $C_2(\underline{3}) = \frac{1}{2}$, $C_2(\underline{6}) = \frac{5}{2}$, [illegible] $C_2(\underline{8}) = 3$. The ratio $\epsilon^{\gamma^* g \to q\bar{q}}(x, Q^2)$ is also shown in Fig. 1. For simplicity we took $\alpha_S = (0.50)/(1 + 0.36 \ln m^2)$, and $G_g(x, Q^2) = \frac{3}{x}(1 - x)^5$. $m_Q = 4.3$ GeV and $m_c = 1.15$ GeV. The corresponding signal of a b quark can be estimated easily via the relation $\epsilon_{bc}^{\gamma^* g \to q\bar{q}} = \frac{e_Q^{-2}}{54}\, \epsilon_{Qc}^{\gamma^* g \to q\bar{q}}$. This effect is obviously too small to be seen in current experiments. For $\underline{6}$ quark with charge 1/3, $\epsilon_{Qc}^{\gamma^* g\to q\bar{q}}(\underline{6}) = \frac{5}{54}\, e_Q^{-2}\, \epsilon_{Qc}^{\gamma^* g\to q\bar{q}}(8)$. However the process $\gamma^* g\to q\bar{q}$ accounts for only $\sim 10\%$ of the observed charm signal.[14]

c. Another process that could contribute to F_2 is presented in Fig. 2b; An offshell photon and a gluon combine into a Υ and a gluon. The color factor is now 27 for an octet, 25 for a sextet and 2 for a triplet, giving again large enhancements, in addition to the charge factor. We have only studied this process at $Q^2 = 0$. For $E_\mu = 300$ GeV the contributions to the structure function F_1 have the ratio $1 : 10\, e_Q^2 : 0.1$ for charm, the octet quark and the b quark respectively.

4. Trimuon events in μp deep inelastic scattering. This process can also be studied in the trimuon channel as a significant fraction of the Υ is expected to decay into $\mu^+\mu^-$: $\mu p \to \mu + \Upsilon + X$ and $\Upsilon \to \mu\mu$.

Comparing the trimuon signals for the b and the octet quarks, we have

$$R = \frac{\sigma(\Upsilon(Q\bar{Q}))}{\sigma(\Upsilon(b\bar{b}))}\ \frac{B(\Upsilon(Q\bar{Q}))}{B(\Upsilon(b\bar{b}))}$$

$$= 9\, e_Q^2 \left(\frac{27}{2}\right) \frac{0.1}{0.03} \sim 400\, e_Q^2, \tag{5}$$

where $\sigma(\Upsilon) = \sigma(\mu p \to \mu + \Upsilon + X)$ and B is the leptonic branching ratio. Here $B(\Upsilon(b\bar{b}))$ is taken from Ref. (2). The total width for the octet quark case is approximately $179\, e_Q^2$ keV (in keV $\Gamma_\ell \sim 16\, e_Q^2$, $\Gamma(\Upsilon \to 3g \to \text{hadrons}) = 0$ $\Gamma(\Upsilon \to 2g + \gamma) \sim 63\, e_Q^2$, $\Gamma(\Upsilon \to \gamma^* \to \text{hadrons}) = 67\, e_Q^2$ and we have included e, μ and τ leptons.) Comparing the octet quark with charm, R_{Qc} is of order 10 e_Q^2. For the $\underline{6}$ quark with $e = 1/3$, $R_{Qb} \sim 1$. Hence we expect the octet quark to give an observable trimuon signal for $W > 1044$ GeV in deep inelastic μp scatterings.

DISCUSSION

As we have shown,the calculations on the heavy quark effects in μp inelastic process prove to be rather complicated and poorly understood; but the consistent ratio of order unity between the signals of charm and an octet quark leads us to expect a signal above threshold while a bottom quark is not expected to be seen at all in such a process.

At kinematic regions way above threshold, ϵ_{Qc} is expected to be large. Since an exotic quark does not couple to the light quarks in standard weak and electromagnetic models, it is not expected to contribute to the structure functions measured in neutrino reactions (unless Q couples to the neutral current and/or there exist other exotic quarks so that Q can couple to charged currents).

In the experimental tests mentioned above, we have compared the octet quark to the b quark. The effect of a t quark ($e = 2/3$) is easily obtained by scaling according to the charge square (i.e. a factor of 4).

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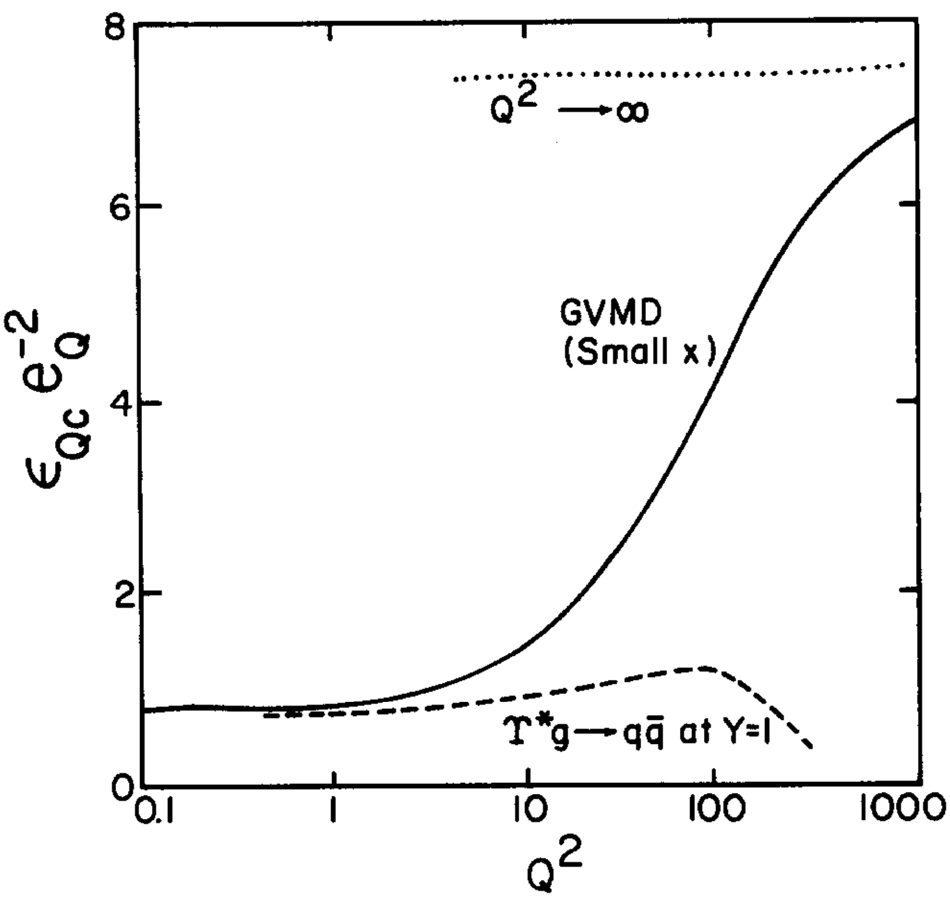
FIGURE CAPTIONS

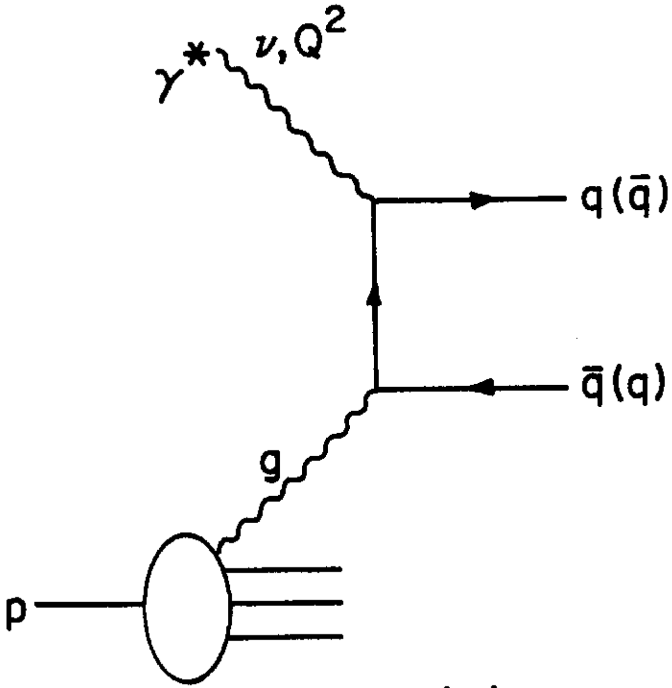
Fig. 1: The ratio $\epsilon_{Qc}(x, Q^2)\, e_Q^{-2}$ for various deep inelastic processes. The solid curve is the GVMD prediction (including the threshold effect) while the dashed curve is $\epsilon_{Qc}\, e_Q^{-2}$ for the process $\gamma^* g \rightarrow q\bar{q}$ at $Y = 1$, at $E_\mu = 300$ GeV.

Fig. 2: a. The diagram of the process $\gamma^* g \rightarrow q\bar{q}$.

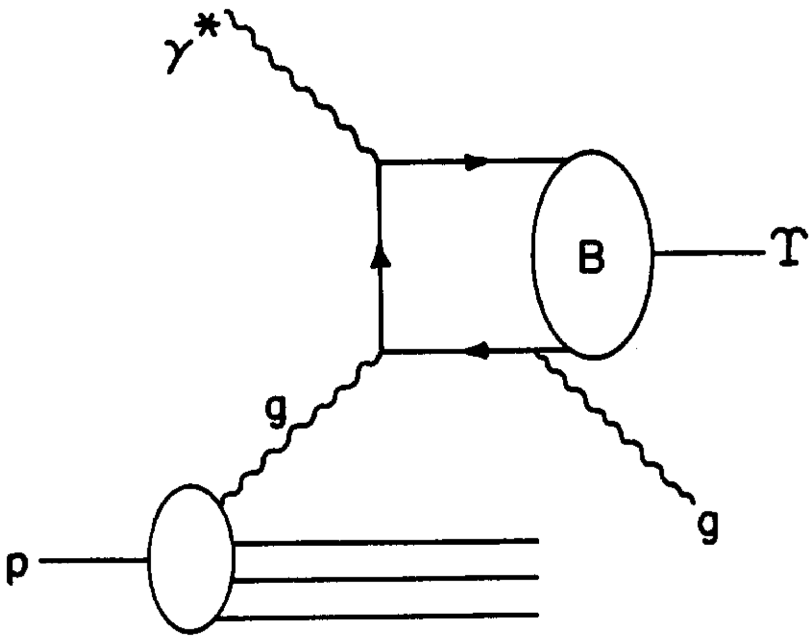
b. The process $\gamma^* g \rightarrow \Upsilon\, g$. B is the bound state wave function.



8
6
4
2
0
$\epsilon_{Qc}\, e_Q^{-2}$
$Q^2 \longrightarrow \infty$
GVMD
(Small x)
$\Upsilon^* g \longrightarrow q\bar{q}$ at Y=1
0.1
1
10
100
1000
Q^2



(a)



(b)

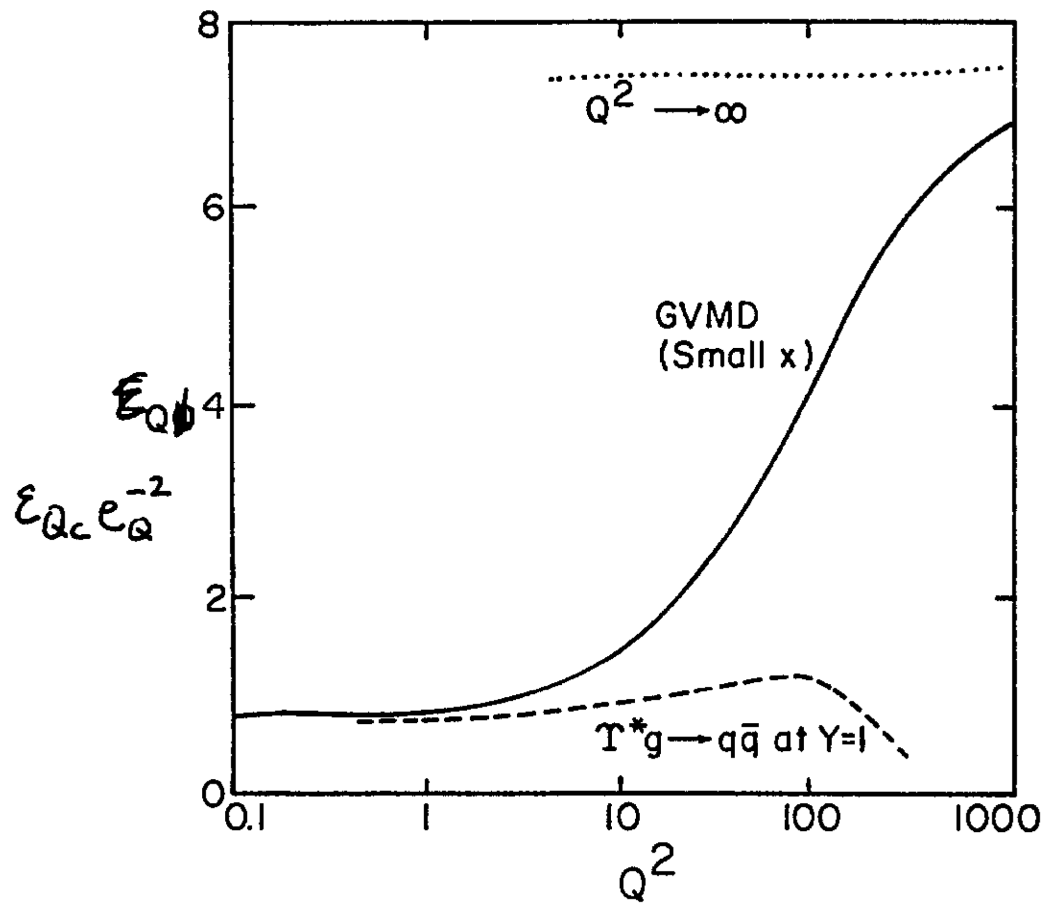

$Q^2 \longrightarrow \infty$
GVMD
(Small x)
$\Upsilon^* g \longrightarrow q\bar{q}$ at Y=1
$\mathcal{E}_{Q\phi}$
$\mathcal{E}_{Qc}\, e_Q^{-2}$
Q^2
0
2
4
6
8
0.1
1
10
100
1000

Fig 2