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IS THE Z^o OBSERVED IN $p\bar{p}$ COLLISIONS A COMPOSITE OBJECT?*

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ABSTRACT

If the Z^o boson is made of colored subconstituents it can be produced in $p\bar{p}$ (and pp) collisions through the subprocess gluon + gluon $\rightarrow$ Z^o + gluon. Rate is estimated from $Z^o - \gamma$ mixing parameter and found comparable to that of Drell-Yan process. Events with a large p_T Z^o and a large p_T balancing gluon should be observed at $p\bar{p}$ collider.

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The possibility that the weak $W^{\pm}$ and Z^o bosons together with quarks and leptons are composite particles has been considered from various point of views [1]. At low energies with respect to the compositeness scale ($\sqrt{s} \ll \Lambda_H$) the weak interaction is described by an effective theory resulting from a hidden interaction among subconstituents (like low energy strong hadronic interactions are the result of QCD among quarks). Under special constraints (unification [2], good high energy behaviour [3], renormalizability [4], current algebra [5], W boson dominance [6]) this effective theory can at low energy reproduce most of the results of the standard gauge model. The recent discovery of $W^{\pm}$ and Z^o bosons at CERN $p\bar{p}$ collider [7] render particularly exciting the comparison of the predictions of the composite models with those of the standard model. Especially models with low compositeness scale (i.e. $G_F^{-1/2} \lesssim \Lambda_H \lesssim 1$ TeV) are phenomonologically appealing [8-10]. In addition to obvious departures from standard model predictions at moderately high energies ($\sqrt{s} \gtrsim \Lambda_H$) one expects several new couplings should exist as residual interactions. These are for example anomalous multiboson couplings (photon or gluon couplings to weak bosons) or fermion-boson contact interactions [11] as well as 4-fermion contact interactions [12].

In this note we show that Z^o production in $p\bar{p}$ (or pp) collisions offer such a possibility of testing the nature of the weak bosons. In addition to Drell-Yan type of production mechanism ($q\bar{q}$ annihilation and QCD correction terms with q-gluon interactions) [13] effective weak interactions may allow new types of production modes through gluon-gluon collisions (i.e. $gg \to Z^o g$, $Z^o\gamma$, $Z^oH^o \ldots$ as well as $gg \to W^+W^-$, $W^{\pm}H^{\mp}$, $H^+H^- \ldots$). Rates and transverse momentum distributions of $W^{\pm}$, Z^o bosons may also be modified by contact terms like $gq \to Z^o q$ or $gq \to W^{\pm}q'$.

Here we discuss the case of $gg \to Z^o g$ which seems to be particularly promising leaving the other ones for further studies. Let us suppose that subconstituents carry color (and electric) charges so that they couple to gluons (and photons) like quarks do.

As a consequence Z^o-gluons (and Z^o-photons) couplings are induced by annihilation type of diagrams. Examples are $Z^o - \gamma$ mixing [9,14], $Z^o \to 3\gamma$, $Z^o \to 3g$, $Z^o \to 2g + \gamma$ decays [11]; see figs. 1(a) and 1(b). The magnitude of these couplings is controlled by the scale of the binding force and by the nature of the composite particle. In a quarkonium-like picture we have the wave function extension or the value of the wave function at the origin $\phi(0)$ related to the basic "hypercolor" scale Λ_H [14]. However a Goldstone-like particle (like the π meson) can have much smaller couplings controlled by the mass of the particle itself [16]. In ref. [14] it was suggested to use the experimental value of $\sin^2\theta_W$ and the $Z^o\gamma$ mixing formalism [2] in order to get this magnitude:

$$\sin^2\theta_W = \frac{e^2}{g}\cdot\frac{F_W}{M_W}$$

with

$$g^2 = 4M_W^2\,G_F\,\sqrt{2} \quad \text{and} \quad \frac{F_W}{M_W} = \sqrt{n_H\,n_c}\,\left(\frac{2}{m_W^3}\right)^{1/2}\frac{\phi(0)}{\sqrt{4\pi}} \quad ,$$

where n_H and n_c are the numbers of hypercolors and colors among the subconstituents. From $\sin^2\theta_W \simeq 0.22$ and $M_W \simeq 80$ GeV one gets $F_W/M_W \simeq 1.6$. In ref. [11] we derived the subsequent $Z \to 3\gamma,\ 3g,\ 2g+\gamma$ decay widths, for example:

$$\Gamma_{Z^o\to 3g} = \frac{80\alpha_s^3}{243}\,(\pi^2 - 9)\,\frac{F_W^2}{M_W} \quad .$$

We now use the same picture [fig. 1(b)] in order to get the $gg \to Z^o g$ amplitude by just crossing one gluon line. This gives us a kind of residual contact interaction for low energies with respect to Λ_H. For energies just above the $Z^o + g$ threshold the amplitude takes the simple form:

$$R\left(g_a^1\,g_b^2 \to Z^o\,g_c^3\right) = \frac{g_s^3\,d_{abc}}{\sqrt{6n_c}}\cdot\frac{F_W}{M_W}\,\epsilon\cdot T$$

with

$$\epsilon \cdot T \equiv \epsilon \cdot k_1 \Big[2P \cdot k_3 \, \epsilon_1 \cdot \epsilon_2 \, \epsilon_3 \cdot k_1 - M_Z^2 \Big(\epsilon_1 \cdot \epsilon_3 \, \epsilon_2 \cdot k_3 - \epsilon_2 \cdot \epsilon_3 \, \epsilon_1 \cdot k_3 \Big) \Big]$$

$$+ M_Z^2 \Big\{ \epsilon \cdot \epsilon_1 \Big[\epsilon_2 \cdot k_3 \, \epsilon_3 \cdot k_1 - \epsilon_2 \cdot \epsilon_3 \, k_1 \cdot k_3 \Big]$$

$$- \epsilon \cdot \epsilon_2 \Big[\epsilon_1 \cdot k_3 \, \epsilon_3 \cdot k_1 + \epsilon_1 \cdot \epsilon_3 \, k_2 \cdot k_3 \Big] \Big\}$$

where $g_s^2/4\pi = \alpha_s$, d_{abc} is the color octet symmetric tensor and (ϵ, P), (ϵ_i, k_i) are the polarization and momentum 4-vectors of the Z^o boson and of the three gluons.

The basic $gg \to Z^o g$ cross-section is then obtained as

$$\frac{d\hat{\sigma}}{d\Omega} = \frac{160\, \alpha_s^3 \pi}{27\, \hat{s}} \left(\frac{\hat{p}}{\sqrt{\hat{s}}} \right) \frac{F_W^2}{M_W^2} \left(3 + \cos^2 \hat{\theta} \right)$$

in terms of $g - g$ center-of-mass variables (invariant mass $\sqrt{\hat{s}}$, c.m. final momentum $\hat{p} = (\hat{s} - M_Z^2)/2\sqrt{\hat{s}}$, and scattering angle $\hat{\theta}$). Notice that it is almost isotropic. Using $\alpha_s \simeq 0.15$, $F_W/M_W \simeq 1.6$ one gets $\hat{\sigma}$ of the order of 40 nb for $\sqrt{\hat{s}} \gtrsim M_Z$.

We now discuss the process $p\bar{p} \to Z^o + g + \ldots$ and compare it to the Drell-Yan process $p\bar{p} \to Z^o + \ldots$. We write:

$$\sigma = \int\int dx_a \, dx_b \, \frac{1}{32} \, f_g(x_a) \, f_g(x_b) \, \hat{\sigma}$$

with $\tau = \hat{s}/s = x_a x_b$ and we use the gluon distribution inside the nucleons $f_g(x) = 3(1-x)^5/x$. We then easily obtain:

— the $(Z^o + g)$ invariant mass distribution (illustrated in fig. 2):

$$\frac{d\sigma}{d\hat{s}} = \frac{1}{32 s} \int_\tau^1 \frac{dx}{x} \, f_g(x) \, f_g\left(\frac{\tau}{x}\right) \, \hat{\sigma}(\hat{s})$$

— the longitudinal and transverse momentum distributions of the Z^o with respect to the $p\bar{p}$ colliding axis [figs. 3(a) and 4(a)]:

$$\frac{d\sigma}{dp_L} = \int\int dx_a \, dx_b \, f_g(x_a) f_g(x_b) \, \frac{4\pi\sqrt{\hat{s}}}{32(x_a + x_b)\, \hat{p}\, \sqrt{s}} \cdot \frac{d\hat{\sigma}}{d\Omega}$$

$$\frac{d\sigma}{dp_T^2} = \int\int dx_a \, dx_b \, f_g(x_a) \, f_g(x_b) \, \frac{4\pi\sqrt{\hat{s}}}{32\,\hat{p} \left[\left(M_Z^2 + \hat{s} \right)^2 - 4\hat{s} \left(p_T^2 + M_Z^2 \right) \right]^{1/2}} \cdot \frac{d\hat{\sigma}}{d\Omega} \, .$$

Using $F_W/M_W = 1.6$ we obtain at $\sqrt{s} = 540$ GeV a total cross-section $\sigma(p\bar{p} \rightarrow Z^o + g + \ldots) \simeq 0.8$ nb.

Results are compared to the standard Drell-Yan calculations (including QCD corrections with $q\bar{q}$ and qg collisions) [13,15]. Depending upon the choice of quark distributions and the estimations of QCD corrections the expected rate for $\sqrt{s} = 540$ GeV falls around 1.0 to 3.0 nb. So considering also the uncertainties in the gluon distributions inside nucleons we can conclude that if the relation $F_W/M_W = 1.6$ is valid one should observe at least one Z^o event among 3 or 4 as due to the "anomalous" $gg \rightarrow Z^o g$ mode.

The most striking feature (illustrated in fig. 4) is the fact that these anomalous events should appear with a large p_T Z^o balanced by a corresponding large p_T gluon jet. This is the direct consequence of the contact term $gg \rightarrow Z^o g$ as being approximately isotropic as opposed to the Drell-Yan $q\bar{q} \rightarrow Z^o$ process which is concentrated at low p_T apart from a tail due to QCD corrections [fig. 4(b)].

A first test for the existence of such modes may consist in looking for an anomalously large number of large p_T Z^o's identified by their decay into lepton pairs. If some candidates were found further checks could be done and related processes could be searched. These anomalous Z^o production modes should be Parity conserving so no forward-backward asymmetry should be observed in $Z^o \rightarrow \ell^+\ell^-$ decays. However the Drell-Yan process itself gives only a weak (7%) asymmetry because of the small vector $Z^o \ell^+\ell^-$ coupling following from $\sin^2\theta_W \simeq 0.22$. So this will be a difficult test. Another way would be to directly look for anomalous Z^o decay modes like $Z^o \rightarrow 3\gamma,\ 3g,\ 2g+\gamma$ and for other types of anomalous boson pair production ($gg \rightarrow W^+W^-,\ W^\pm H^\mp,\ H^+H^-, \ldots$). If no signal were found then assuming some gluon and quark distribution inside the nucleon an upper limit could be given for the composite W decay coupling constant F_W.

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FIGURE CAPTIONS

Fig. 1. Z^o-photons and Z^o-gluons couplings in a compose picture.

Fig. 2. Shape of $d\sigma/d\hat{s}$ for $p\bar{p} \rightarrow Z^o + g + \ldots$; $\hat{s}$ is the $(Z^o + g)$ invariant mass squared; $\sqrt{s} = 540$ GeV.

Fig. 3. Longitudinal Z^o momentum distributions (for $\sqrt{s} = 540$ GeV):

(a) in $p\bar{p} \rightarrow Z^o + g + \ldots$ from $gg \rightarrow Z^o g$ subprocess (solid).

(b) in $p\bar{p} \rightarrow Z^o + \ldots$ from Drell-Yan subprocess subprocess (dashed).

Fig. 4. Transverse Z^o momentum distributions (for $\sqrt{s} = 540$ GeV):

(a) in $p\bar{p} \rightarrow Z^o + g + \ldots$ from $gg \rightarrow Z^o g$ subprocess (solid).

(b) in $p\bar{p} \rightarrow Z^o + \ldots$ from Drell-Yan subprocess and QCD corrections (dashed).

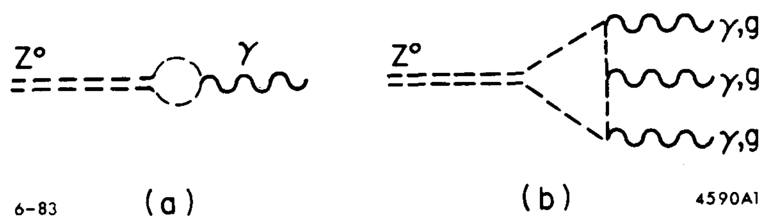
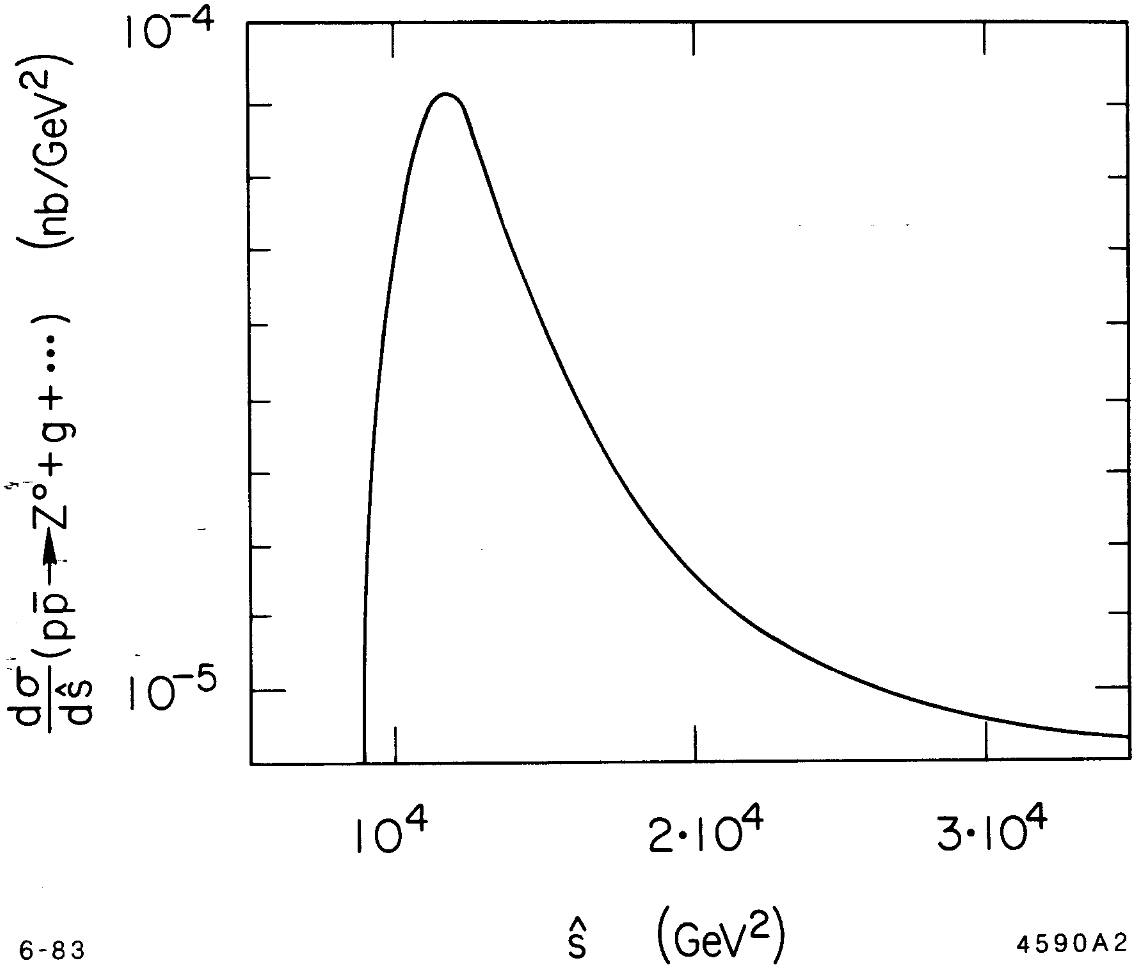
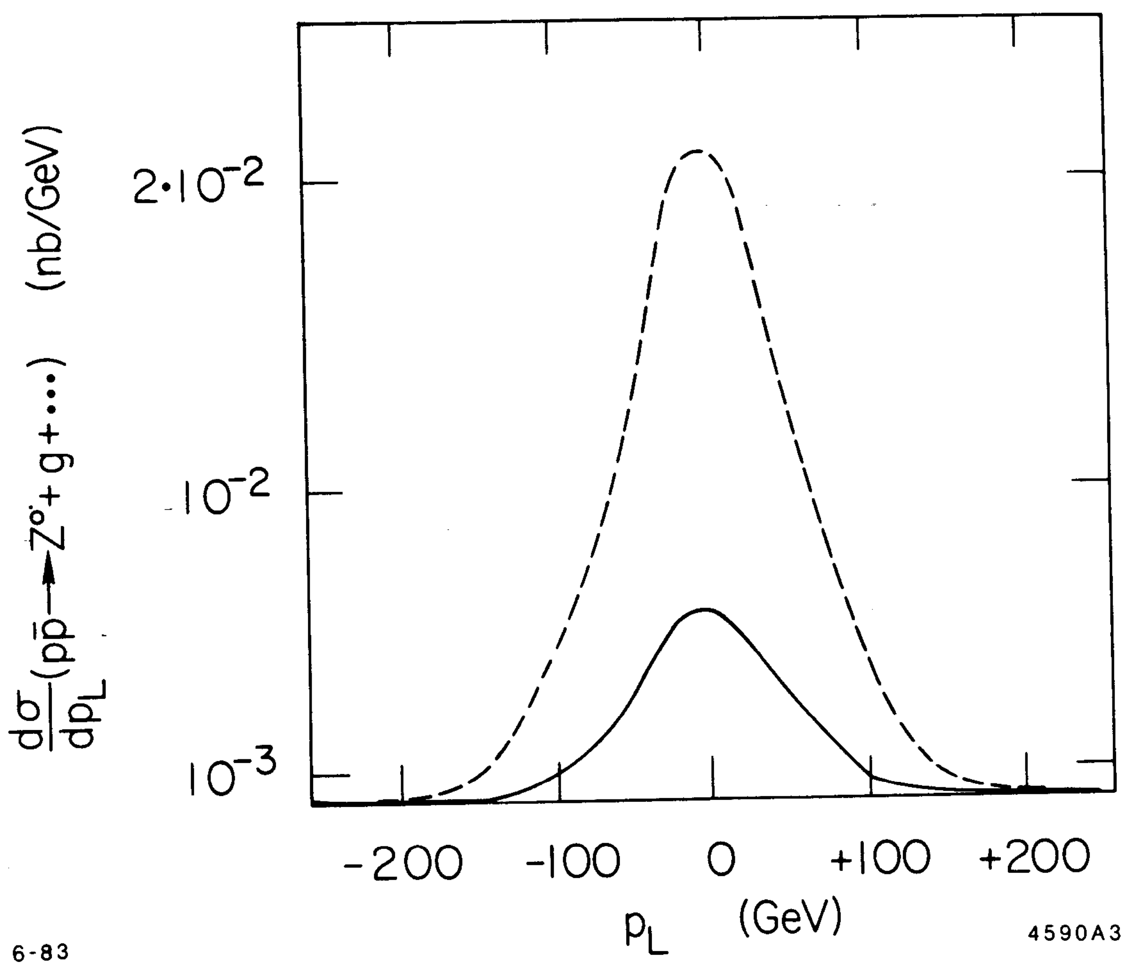


Fig. 1



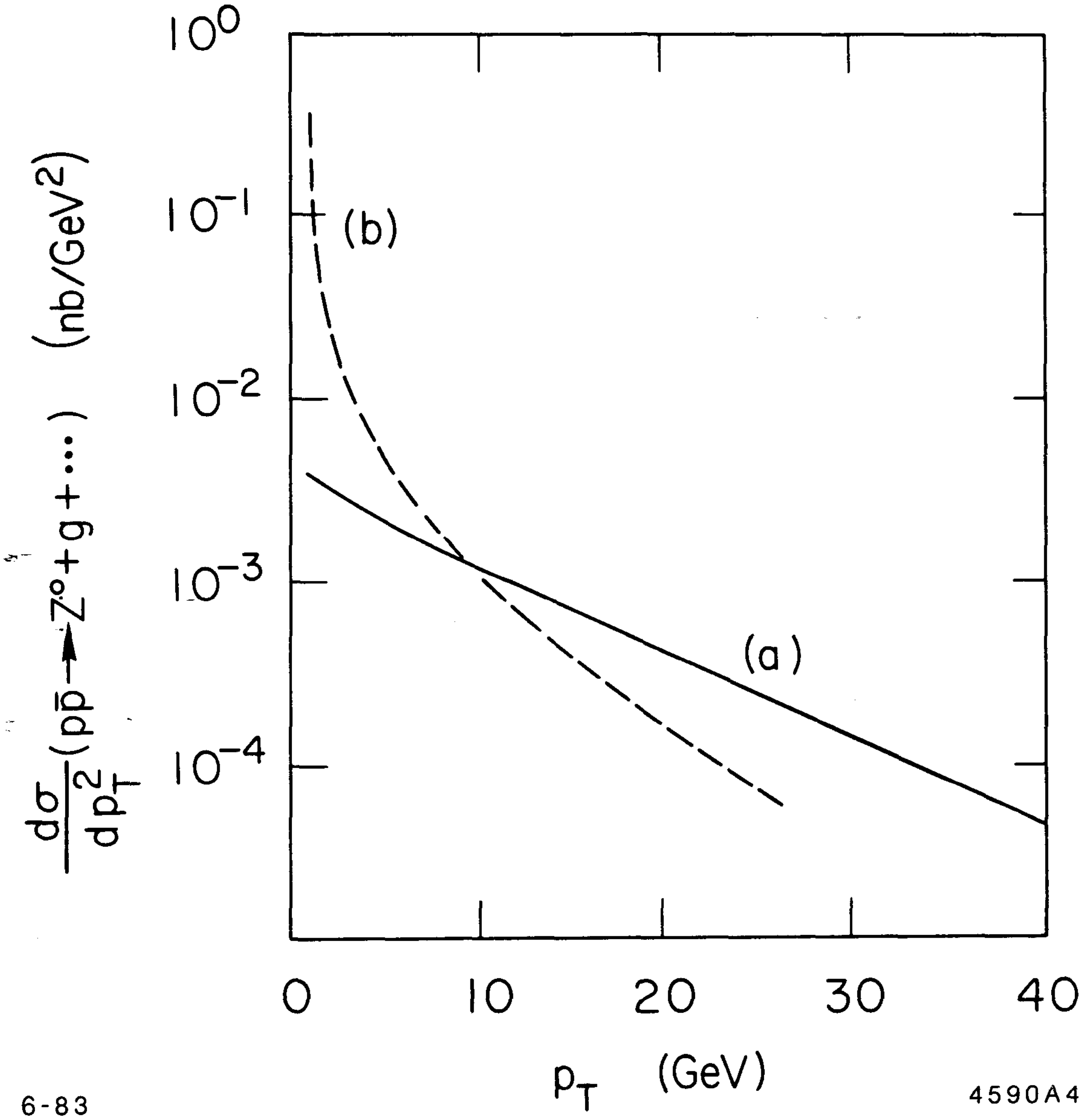
$\frac{d\sigma}{d\hat{s}}(p\bar{p}\to Z^0+g+\cdots)$ (nb/GeV^2)
10^{-4}
10^{-5}
10^4
$2\cdot10^4$
$3\cdot10^4$
$\hat{s}$ (GeV^2)
6-83
4590A2

Fig. 2



$\frac{d\sigma}{dp_L}(p\bar{p} \to Z^0 + g + \cdots)$ (nb/GeV)
$2 \cdot 10^{-2}$
10^{-2}
10^{-3}
-200
-100
0
+100
+200
p_L (GeV)
6-83
4590A3

Fig. 3



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
(b)
(a)
0
10
20
30
40
$\frac{d\sigma}{dp_T^2}(p\bar{p} \rightarrow Z^0 + g + \cdots)$ (nb/GeV^2)
p_T (GeV)
6-83
4590A4

Fig. 4