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TESTS OF COMPOSITE MODELS WITH Z^0 DECAY MODES

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A B S T R A C T

If Z^0 and $W^\pm$ gauge bosons are composite objects, several multiphoton and multigluon Z^0 decay modes can become well observable and can be used to test the nature of the subconstituents.

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Several models have recently been proposed in which leptons, quarks and intermediate W, Z bosons are composite objects^{1),2)}. At the subconstituent level the dynamics is described by the gauge group³⁾⁻⁵⁾ $U(1)_{EM} \times SU(3)_{Col} \times G_H$ where G_H is some hypercolour gauge group responsible for the binding of the subconstituents inside fermions and weak bosons with a typical scale (confining parameter) Λ_H . The subconstituents interact in a pointlike way with photons and gluons. The standard weak interaction at the quark and lepton level appears as a residual interaction between bound states in the same way as nuclear forces between hadrons are residual interactions due to more fundamental QCD interactions between quarks.

Observability of such a substructure depends upon the value of the scale Λ_H . Constraints on lepton substructure already come from electron and muon $g-2$ measurements and from e^+e^- annihilation data. The result for Λ_H is strongly dependent on the model⁶⁾ and in particular on its chiral symmetry properties, but one finds that Λ_H is at least of a few hundreds of GeV ^{7),8)}.

On the other hand, in several models^{4),9)-11)} the mixing experimentally required between the photon and the W^3 boson [defined in the standard $SU(2)_L \times U(1)$ model] and measured through the value of $\sin^2\theta_W$, gives a relation for the scale of the W boson substructure:

$$\sin^2\theta_W = \frac{e^2}{g^2} \cdot \frac{F_W}{M_W} = \frac{e^2}{g^2} \frac{1}{\sqrt{n_H n_C}} \sqrt{\frac{2}{M_W^3}} \cdot \frac{\phi(0)}{\sqrt{4\pi}} \quad (1)$$

g is the strength of the W couplings to leptons and quarks (of the order of unity and precisely equal to 0.64 in the standard case). F_W is the W decay constant (dynamically related to Λ_H) expressed in terms of the value of the radial W wave function at the origin through Eq. (1) [see Ref. 4)], assuming that W is a 3S_1 fermion-antifermion bound state; n_H and n_C are the number of hypercolours and colours of the W constituents, respectively. Relation (1) is obtained in direct analogy with the $\gamma-\rho^0$ mixing case in QCD and is illustrated in Fig. 1. From the experimental value $\sin^2\theta_W \approx 0.22$ one expects F_W to be of the order of M_W or slightly larger⁴⁾.

Models are constructed in such a way as to give the same effective results as the standard model for weak interactions at low energy. Departures can arise in the 100 GeV energy range and above. Different possibilities have been considered. Masses and widths of W and Z can notably differ from the standard values; new vector bosons with different quantum numbers can appear (isosinglet states, parity doublets, ...); excited bound states $W', W'', \dots$ can exist at higher energies. Such drastic effects on M_Z and Γ_Z would immediately be visible as soon as the Z boson is observed (in $p\bar{p}$ and e^+e^- experiments) and even at lower energies in $\gamma-Z$ interference effects.

However, further constraints such as current algebra and W dominance can be imposed so that the masses and the basic coupling constants of the weak bosons coincide with the standard ones¹¹⁾. This is analogous to the well-known VDM properties of photon-hadron interactions in QCD. In this case strong departure from the standard model predictions (for example due to contribution of excited W states) was expected to only appear at much higher energies (TeV region).

The aim of the present note is to propose tests of these models in order to depart them from the standard gauge model even in the 100 GeV region. We use again the analogy with VDM and QCD in order to look for departure from W dominance due to more fundamental couplings.

One can first think of looking for three-boson or four-boson self-couplings [charged ones¹²⁾⁻¹⁴⁾ or neutral ones¹⁵⁾]; these are indeed interesting tests of the Yang-Mills structure of the gauge bosons but it is surely possible (although this has not been explicitly written) for the composite models to reproduce this structure (i.e., the values of magnetic and quadrupole transitions) by requiring current algebra properties similar to the old vector meson case treated by Kroll, Lee and Zumino¹⁶⁾.

One can then look for "anomalous" multiparticle decay modes of the gauge bosons. For example $e^+e^- \rightarrow \gamma \rightarrow \rho \rightarrow 4\pi, 6\pi, \dots$ differ from VDM expectations $\rho \rightarrow \rho^+\rho^- \rightarrow \pi^+\pi^-2\pi^0, \dots$ by non-quasi-two-body modes and jet-like decays. So one can look (Fig. 2) for $Z \rightarrow f\bar{f}f\bar{f}$ (multifermion pairs) which are not due to the mode

$$Z \longrightarrow \begin{array}{c} W^+ W^- \\ \downarrow \quad \downarrow \\ \ell^+ \nu_\ell, \bar{q} q' \end{array}$$

Assuming a contact interaction between the Z boson and two fermion pairs with an effective coupling e/Λ_H^3 one gets:

$$\Gamma_{Z \rightarrow f\bar{f}f\bar{f}} \simeq \frac{\alpha M_Z}{256^2 \pi^5} \left(\frac{M_Z}{\Lambda_H} \right)^6.$$

Even with $\Lambda_H \simeq M_Z$ one gets $\Gamma_{Z \rightarrow f\bar{f}f\bar{f}} \simeq 0.1$ keV very difficult to observe. When $f\bar{f}$ are charged ($\ell^+\ell^-, q\bar{q}$) pairs enhancements due to virtual photons (or gluons) may appear. For example $Z \rightarrow \ell^+\ell^-\ell^+\ell^-$ would also receive contributions from radiative corrections¹⁷⁾ to standard $Z \rightarrow \ell^+\ell^-$ decay and from anomalous

$$Z \longrightarrow \begin{array}{c} \gamma_\nu \gamma_\nu \\ \downarrow \quad \downarrow \\ \ell^+ \ell^- \end{array}$$

transitions¹⁵⁾.

We finally arrive to the direct search of more fundamental couplings. This will be analogous to the case of γ hadron interactions with deviations from vector meson dominance due to direct $\gamma q\bar{q}$ couplings (parton models). We now search for photon and gluon interactions deviating from W or Z dominance due to direct couplings of photons and gluons with the subconstituents as illustrated in Fig. 3a and b.

Deep inelastic scattering and study of W or Z structure functions (deviating from QFD higher order effects) will be difficult; one can for example use the reaction $e^+e^- \rightarrow e^+v_e + X$ and γW collisions (see Fig. 4) but the cross-sections are rather low^{(12), (18)}. However, we have found that multiphoton and multigluon decay modes of the Z boson which are expected to be very rare in standard QFD can become well observable and even rather strong in such composite models.

In Ref. 2) models are separated into two classes: class A in which W and Z subconstituents are colour singlet objects and class B in which they are colour non-singlets. Multiphoton decays will allow to test both classes of models whereas multigluon decays will test only models of class B.

MULTIPHOTON DECAYS

Z^0 decays into two real photons is forbidden by Yang's theorem. We can look to $Z^0 \rightarrow \gamma\gamma\gamma$ and $Z^0 \rightarrow \gamma\ell^+\ell^-$ (through $\gamma + \gamma_{\text{virt.}}$). In standard QFD the process $Z \rightarrow \gamma\gamma\gamma$ is expected to go through lepton, quark and gauge boson loops¹⁹⁾ and to be very weak, with a branching ratio $B_{Z \rightarrow \gamma\gamma\gamma} \approx 7.7 \times 10^{-10}$ ²⁰⁾. In a bound state model described by Fig. 5 one gets:

$$\Gamma_{Z \rightarrow \gamma\gamma\gamma} = \frac{64\alpha^3 \langle Q^3 \rangle^2}{9 M_Z^2} (\pi^2 g) \frac{n_H n_C |\phi(0)|^2}{4\pi} \quad (2)$$

where $\langle Q \rangle$ means the average constituent charge inside the bound state. The use of the non-relativistic approximation may be questionable. However, this case may be similar to the one of light $q\bar{q}$ bound states ($\pi, \rho, \dots$) where this approximation nevertheless gives a good order of magnitude. Using Eq. (1) one gets:

$$\Gamma_{Z \rightarrow \gamma\gamma\gamma} \approx O(100 \text{ keV}) \quad \text{i.e.} \quad B_{Z \rightarrow \gamma\gamma\gamma} \approx O(0.3 \times 10^{-4})$$

much larger values than the QFD ones and well observable at the Z peak in $e^+e^- \rightarrow \gamma\gamma\gamma$ [i.e., much larger than the QED contribution to this reaction and with a different (hard photon) kinematical distribution].

The process $Z \rightarrow \gamma\ell^+\ell^-$ can go through the three diagrams of Fig. 6. We shall estimate the "composite model" contribution 6a supposing that parity breaking leads to a $^3S_1 - ^3P_1$ configuration mixing because it is only the 1^{++} component of the Z^0 which can undergo this decay. As above the high order QFD contribution 6b [see Ref. 15)] will be about 10^{-3} smaller. The dangerous background comes from the lowest order QFD contribution 6c. However, it is peaked for low real γ momenta, i.e., high $\ell^+\ell^-$ masses whereas the interesting process 6a is peaked for low $\ell^+\ell^-$ masses. So let us look at the $\ell^+\ell^-$ mass spectrum for $z = (k^2/M_Z^2) \ll 1$:

$$\frac{dB^{(a)}}{dz} = \frac{256 \alpha^3 \langle Q^2 \rangle^2 M_Z}{2 \Gamma_Z} n_H n_C \frac{|\phi'(0)|^2}{4\pi M_Z^5} \quad (3)$$

Assuming for the derivative of the P wave function a behaviour similar to the ones known for heavy quarkonia, in comparison with S wave functions, i.e.,

$$\frac{|\phi'(0)|^2}{M_Z^5} \simeq \frac{|\phi(0)|^2}{M_Z^3} \quad (4)$$

and using Eq. (1) one gets

$$\frac{dB^{(a)}}{dz} \simeq O(10^{-3}) \quad \text{for } z \ll 1.$$

On the other hand one gets [see Ref. 21)] the radiative emission background:

$$\frac{dB^{(c)}}{dz} = \frac{\alpha B_{\ell^+\ell^-}}{2\pi} \int_{\epsilon}^{1-z-\epsilon} \frac{(x+z)^2 + (x-1)^2}{x(1-x-z)} dx \quad (5)$$

where ϵ is some cut-off to avoid collinear singularities. For $z \ll 1$ with $B_{\ell^+\ell^-} \simeq 3\%$ (the usual branching ratio for $Z \rightarrow \ell^+\ell^-$) one gets

$$\frac{dB^{(c)}}{dz} \simeq 3 \times 10^{-5}.$$

One may notice another way of looking at these vertices in inelastic e^+e^- scattering $e^+e^- \rightarrow e^+e^- + Z$ or in direct $\gamma e^\pm$ collisions where process 7a will also compete with the standard "Compton-like" process 7b [see Ref. 22)]

MULTIGLUON DECAYS

One has just to replace photons by gluons in the above discussions. For $Z \rightarrow ggg$ one gets from Fig. 5:

$$\Gamma_{Z \rightarrow ggg} = \frac{160 \alpha_s^3}{243 M_Z^2} (\pi^2 - 9) \eta_H \eta_C \frac{|\phi(0)|^2}{4\pi} \quad (6)$$

i.e.,

$$\Gamma_{Z \rightarrow ggg} \approx \mathcal{O}(0.3 \text{ GeV}) \quad , \quad B_{Z \rightarrow ggg} \approx \mathcal{O}(10\%) .$$

This is again much larger than the high order QFD contribution going through quark loops²⁰⁾ ($B_{Z \rightarrow ggg} \approx 10^{-5}$). Such a strong three gluon jet decay should be well observable, having a distribution very similar to the one of a heavy quarkonium decay. For $Z \rightarrow gg\gamma$ one gets:

$$\Gamma_{Z \rightarrow gg\gamma} = \frac{128 \alpha_s^2 \alpha \langle Q \rangle^2}{81 M_Z^2} (\pi^2 - 9) \eta_H \eta_C \frac{|\phi(0)|^2}{4\pi} \quad (7)$$

i.e.,

$$\Gamma_{Z \rightarrow gg\gamma} \approx \mathcal{O}(20 \text{ MeV}) \quad , \quad B_{Z \rightarrow gg\gamma} \approx \mathcal{O}(0.7\%) .$$

much larger than the QFD contribution [4×10^{-6} 20)]. Incidentally this mode can also be an interesting source of (gg) glueball production at the Z peak.

One can also look at the process $Z \rightarrow gq\bar{q}$ going through the three diagrams of Fig. 6 replacing photons by gluons and leptons by quarks. One gets for $z = (k^2/M_Z^2) \ll 1$:

$$\frac{dB^{(a)}}{dz} = \frac{256\alpha_s^3 M_Z}{3\Gamma_Z} n_H n_C \frac{|\phi'(0)|^2}{4\pi M_Z^5} \quad (8)$$

which can approach unity if (4) and (1) are correct and then even modify the total Z width.

$$\frac{dB^{(c)}}{dz} = \frac{2\alpha_s B_{q\bar{q}}}{3\pi} \int_{\epsilon}^{1-z-\epsilon} \frac{(x+z)^2 + (x-1)^2}{x(1-x-z)} dx \quad (9)$$

describes the usual $q\bar{q}g$ jets distribution and is only of the order of a few per cent.

The appearance of strong couplings of the Z to gluons could also modify the Z production rates in hadronic ($pp, p\bar{p}$) collisions; the new processes (like in the case of heavy quarkonia) would compete with the usual Drell-Yan process.

Finally, we would like to notice the possible reaction $e^+e^- \rightarrow gg$ in models of class B where electron subconstituents are colour non-singlets. The reaction would proceed through diagrams of Fig. 8. As compared with the reaction $e^+e^- \rightarrow \gamma\gamma$ (which contributes for a few units of R in e^+e^- annihilation at high energy) one expects for $e^+e^- \rightarrow gg$:

$$R \simeq \left(\frac{\alpha_s}{\alpha}\right)^2 \frac{\Lambda^3}{\Lambda_H^6} \quad (10)$$

where Λ_H is again the scale of electron substructure (or the mass of excited bosonic or fermionic states coupled to the electron). One would get $R \simeq 1$ for $\sqrt{s} \simeq 100$ GeV if $\Lambda_H = 250$ GeV. At such a level two gluon jets (with an angular distribution different from $1 + \cos^2\theta$) could surely be quickly distinguished from the usual $q\bar{q}$ jets.

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FIGURE CAPTIONS

- Fig. 1 : γ - W^3 mixing amplitude in composite models.
- Fig. 2 : Anomalous $Z \rightarrow$ multifermion pair decays.
- Fig. 3 : a) W dominant photon couplings;
b) pointlike photon couplings.
- Fig. 4 : Deep inelastic eW scattering.
- Fig. 5 : Diagram for $Z \rightarrow \gamma\gamma\gamma$ in composite models.
- Fig. 6 : Diagrams for $Z \rightarrow \gamma\ell^+\ell^-$:
a) due to Z composite structure
b) due to standard Z couplings in QFD
c) radiative correction to $Z \rightarrow \ell^+\ell^-$.
- Fig. 7 : Diagrams for $e^+e^- \rightarrow e^+e^-Z$:
a) due to Z composite structure;
b) due to standard $\gamma e \rightarrow Ze$ diagrams in QFD.
- Fig. 8 : Diagrams for $e^+e^- \rightarrow gg$ in composite models.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig.8