CERN-TH.4668/87
PM: 86/21

TESTS OF COMPOSITENESS: $Z\gamma$ PROCESSES AT THE $(\bar{p})_p$ TeV COLLIDERS

J.L. Kneur^{*)} and S. Larbi⁺⁾

Laboratoire de Physique Mathématique
U.S.T.L., Montpellier

and

S. Narison^{")}

CERN - Geneva

A B S T R A C T

Some exotic sources of the $Z\gamma$ processes due to composite or technicolour particles are studied at Tevatron and SSC $(\bar{p})_p$ TeV colliders. We conclude that light composite spinless weak bosons having technicolour-type coupling to gluon-gluon or a weak universal coupling to fermion pairs should be seen at the Tevatron. The SSC should be a good place to see heavy composite bosons with higher spins (e.g., spin two) and to see the effects of contact interactions. The absence of the above signals will provide additional constraints on the spectra and underlying structure of models based on dynamical electroweak breaking.

^{*)} Boursier de Thèse du Ministère de la Recherche et de la Technologie.

⁺⁾ Boursier de Thèse du Gouvernement algérien.

^{")} On leave of absence from LPM, USTL Montpellier, France. Supported in part by the DRCI of the CNRS (France-USA exchange programme: AI 95.03.12).

INTRODUCTION

At the present time, we do not know very well the way in which the breaking of the electroweak $SU(2)_L \times U(1)$ theory is realized. We also do not have any experimental evidence of the Higgs particles. Theories (technicolour¹⁾, composite²⁾) with dynamical symmetry-breaking of the electroweak sector are interesting "per se" though we do not yet have any convincing aspects of such theories. One of the main consequences of such theories is the expectation to have a rich spectrum in the TeV range accessible by the present (Tevatron) and future (LHC, SSC) hadron colliders. In a previous work³⁾, we have studied the possible effects of light composite (pseudo) scalar bosons at the polarized LEP and SLC e^+e^- colliders for the reactions $e^+e^- \rightarrow ZS$, $S\bar{S}$. In this present paper, we extend this search of exotic particles by studying the reaction $(\bar{p})p \rightarrow Z\gamma$ at the TeV colliders. In fact, the $Z\gamma$ process has been noticed in the past⁴⁾ to be among the best and feasible reactions which can reveal the physics beyond the standard model. Contrary to the HZZ and ZW^+W^- vertices which exist at the tree-level in the standard model, the vertex involving $Z\gamma$ occurs only at the loop level. Therefore, once having subtracted the standard T-diagram in the $(\bar{p})p \rightarrow Z\gamma$ process, one could easily conclude that the excess of signals in this process is an indication of new physics. We will study, respectively, the effects of spin zero ($\tilde{\pi}, \tilde{\sigma}, \tilde{\eta}$), spin one (Z', Y), spin two ($\tilde{a}_2$) weak bosons, spin $\frac{1}{2}$ excited quarks (q^*) and contact interactions. We shall limit ourselves to colour singlet particles. The case of coloured particles can be straightforwardly deduced from our results.

1. SPIN ZERO BOSONS

We can have two classes of spin zero bosons P : Goldstone-like bosons ($\tilde{\pi}, \tilde{\sigma}$) with Higgs-type coupling to fermion pairs^{5), 6)} ($g_\pi \simeq g_\sigma \simeq m_\psi / F_\pi$: $F_\pi \simeq (\sqrt{2} G_F)^{-\frac{1}{2}} \simeq 260 \text{ GeV}$) and those $\tilde{\eta}$ with universal coupling to fermions⁶⁾ (we use $g_\eta \simeq g_w \simeq 0.64 \equiv e / \sin \theta_w$ though one would expect also a much larger value $g_\eta^2 \simeq 4\pi$). $\tilde{\pi}, \tilde{\sigma}$ should be associated to a $SU(2)_L$ global symmetry whilst $\tilde{\eta}$ is a $U(1)$ -like particle in much the same way as a gluonium of QCD can have an universal coupling to pion pairs. The $P\gamma\gamma$ vertex can be estimated from a preon triangle anomaly⁷⁾ or from QHD sum rules^{5b)}. In this way, one obtains the range of estimate :

$$G_{\gamma\gamma} \approx \frac{2}{F_\pi} \sim \frac{4}{\alpha} \frac{\sin \theta_w}{M_Z}, \quad (1)$$

which might be expected to give the maximal range of $G_{\gamma\gamma}$ -values. The $P\gamma Z$ coupling can be deduced from (1) by using a Z-boson dominance of the photon propagator⁸⁾. In this way :

$$G_{\gamma Z} \approx \frac{1}{\sin \theta_w} G_{\gamma\gamma}. \quad (2)$$

One can also deduce from Eq. (1) the Pgg coupling using a trivial rescaling of the charge of the colored preons circulating inside the triangle anomaly. Therefore :

$$G_{gg} \approx \frac{\sqrt{2}}{3} \frac{1}{Q_\alpha^2 + Q_\beta^2} G_{\gamma\gamma}, \quad (3)$$

where we take (as usual) $Q_\alpha = |Q_\beta| = \frac{1}{2}$ for the values of the preon charge²⁾. The lowest value of the coupling in Eq. (3) is very similar with the colour-singlet π_H technipion coupling to gluon-gluon^{1)*} :

$$G_{gg} \approx (2\sqrt{\frac{2}{3}}) \frac{N_T}{F_\pi} \quad (4)$$

for $SU(N_T)$. Therefore, we shall use as a representative lowest value the technicolour type coupling in Eq. (4) for our numerical analysis. We estimate the total width of these bosons as the sum of their fermion pairs, gluon-gluon and WW decay widths, which are given by :

$$\begin{aligned} \Gamma_{P \rightarrow gg} &\approx \alpha_s^2 \frac{M_P^3}{64\pi} (G_{gg})^2, \\ \Gamma_{P \rightarrow \bar{\psi}\psi} &\approx N_c \frac{g_P^2}{8\pi} M_P \left(1 - \frac{4m_\psi^2}{M_P^2}\right)^{3/2}, \end{aligned} \quad (5)$$

* One should notice that, contrary to the gluon-gluon-Higgs G_H -coupling which is obtained at high-momentum transfer, Eq. (4) is a low energy result. Therefore G_H behaves as $(m_t/M_H)^2$ which explains why the production cross-section of $\tilde{\pi}$, $\tilde{\sigma}$ is higher for $M \gg F$. One should also notice that Higgs production through longitudinal $\tilde{W}$, Z fusions is one to two orders of magnitudes smaller than the $\tilde{\pi}$ one though larger than the Higgs production. In addition, the fact that the standard Higgs couples only to $Z\gamma$ through one loop, really justifies the neglect of this effect in the forthcoming analysis.

where $N_c = 3(1)$ for quarks (leptons) and we take $m_t \approx 70$ GeV and three families of fermions. In order to have a general result, we consider :

- a) The case of narrow bosons with a technicolour coupling ($\tilde{\pi}$) which has a total width dominated by gg and $\tilde{\pi}\psi\psi$ decays.
- b) The case of large width bosons ($\tilde{\sigma}$) which also decay into W and Z pairs like the standard Higgs and which have a technicolour type coupling or a much larger coupling of the order of :

$$G_{\gamma\gamma} \approx 0.1 (0.03) \text{GeV}^{-1}, \quad (6)$$

for $M_{\tilde{\sigma}} \approx 3M_Z (1 \text{ TeV})$.

- c) The case of $\tilde{\eta}$ -boson which decays into W and Z pairs like the standard Higgs and which has a universal coupling to fermion pairs.

In the Table we give the Feynman rules for the different vertices and the resulting differential cross-sections, which should be compared with the standard $Z\gamma$ process occurring from $\bar{q}q$ -T diagram, to which corresponds the differential cross-section :

$$\frac{d\sigma}{d\Omega} [\text{standard}] \approx \frac{\alpha^2}{3} Q_i^2 [(g_A^i)^2 + (g_V^i)^2] \frac{1}{\hat{s} - M_Z^2} \cdot \left\{ \frac{2(1 + M_Z^4/\hat{s}^2)}{\sin^2 \theta} - (1 - M_Z^2/\hat{s})^2 \right\} \quad (7)$$

where Q_i is the quark charge ; $g_A^u = -g_A^d = 1/2 \sin 2\theta_W$; $g_V^i = g_A^i - Q_i \tan \theta_W$. We have not taken into account the QCD corrections to Eq. (7) due to our leading order analysis and to the inaccuracy of various models considered here.

2. SPIN ONE BOSONS

Bosons which can couple to $Z\gamma$ are the Z' -excitation and the isoscalar Y partner¹⁰⁾ of the "composite" Z-boson. The general Lorentz-invariant and CP-conserving couplings are given in the Table¹¹⁾. These couplings are normalized by the weak breaking scale F_π in such a way that they become dimensionless. We use for our numerical analysis $g_1 = g_2 \approx \sqrt{4\pi}$. The coupling of the Z' to fermion pairs is assumed to be $(M_Z/M_{Z'})$ times the Z-fermion pair coupling. The $Y\psi\psi$ couplings used here are those given in Ref. (12) (their model A) where we take $\sin^2 \theta_Y \approx 0.03$ resulting from the maximal allowed value from the analysis of neutral current data. The $Z\gamma$ processes due to the Z' and Y should interfere with the standard T-diagram process, which is not the case of the spin zero bosons discussed previously. The differential

cross-sections which take into account such interferences are given in the Table. We assume that the Y, Z' coupling to W^+W^- are like the ZWW coupling. Therefore, we assume in our numerical analysis that the Y, Z' total width is given by its decays into $\bar{\psi}\psi$ and WW pairs where :

$$\Gamma(Z' \rightarrow W^+W^-) = \frac{\pi\alpha}{4} \cot^2\theta_W \cdot \frac{M_{Z'}}{12\pi} (M_{Z'}/M_W)^2 (1 - 4 \frac{M_W^2}{M_{Z'}^2})^{3/2} \cdot \{1 + 20 \frac{M_W^2}{M_{Z'}^2} + 12 \frac{M_W^4}{M_{Z'}^4}\} \quad (8)$$

and we have used for the Z' coupling the rescaling factor $M_Z/M_{Z'}$, but not for the Y .

3. SPIN TWO BOSONS

If the Z -boson is a composite particle, it is natural to expect composite partners having higher spins. We learn from QCD that properties of tensor mesons are accurately measured in contrast to the case of spin zero mesons. We also know that the features of the 2^{++} mesons are very similar to the case of spin 1 (ρ, ω, ϕ) mesons. Therefore, we might expect that such similarities will be also reproduced for the electroweak sector if Z is a composite boson. For the present analysis, we are concerned with the $2^{++} \tilde{a}_2$ bosons which couple to fermion and boson pairs with the Lorentz-invariant structure given in the Table. The couplings are normalized in such a way that they are dimensionless. The values of g_V and g_A are supposed to be the same as the one of Z to fermion pairs, whilst we take $g_1^2 \simeq 4\pi$ and $g_2^2 \simeq g_1^2 (M_{a_2}/F_\pi)^4$ *. We assume that the total width of the $\tilde{a}_2$ is given by the sum of its decay into $gg, \bar{\psi}\psi$ and W pairs which are :

$$\Gamma_{\tilde{a}_2 \rightarrow gg} \simeq \left(\frac{\alpha_s}{F_\pi}\right)^2 \left\{ 6g_2^2 + \left(\frac{M_{a_2}}{F_\pi}\right)^4 g_1^2 \frac{M_{a_2}^3}{1920\pi} \right\}, \quad (9)$$

$$\Gamma_{\tilde{a}_2 \rightarrow \psi\psi} \simeq \frac{4\pi\alpha N_c}{(F_\pi)^2} \frac{M_{a_2}^3}{10\pi} \left\{ (g_V^2 + g_A^2) \left(1 - \frac{4m_\psi^2}{M_{a_2}^2}\right) + \frac{20}{3} g_V^2 \frac{m_\psi^2}{M_{a_2}^2} \right\}, \quad (10)$$

with $N_c = 3(1)$ for quarks (leptons). We could

* We plan to study low-energy constraints on the parameters of the $\tilde{a}_2$ hypothetical bosons.

estimate its width into W pairs as being given by Eq. (9) by changing α_s into α and by using a double vector boson dominance of the type used in Eq. (2). Therefore, we find that the $\tilde{a}_2$ total width is large even in the case where we neglect its WW width. This width is about 150 GeV for $3M_Z$ and of the order of its mass for $M_{a_2} \approx 1$ TeV. The differential cross-section for the $Z\gamma$ processes due to the $\tilde{a}_2$ is given in the Table.

4. CONTACT INTERACTIONS.

a) $ggZ\gamma$ contact interaction is expected to have an important effect at the TeV collider due to the enhancement of the gluon structure functions. Unlike Ref. (4), which uses a non-relativistic treatment of the preon-bound state, we parametrize the $ggZ\gamma$ vertex by an effective interaction which gives the correct low-energy behaviour of the $\gamma\gamma$ into $\gamma\gamma$ fermion box diagram¹³⁾. Therefore the lowest dimension gauge-invariant operators for one flavour preon is the one given in the Table where F , Z , G are gauge field strengths of the γ , Z and g . We have taken into account combinatorics involved with the different types of gauge-fields. We have not taken into account parity-violating terms which do not contribute to leading order of the preon chiral symmetry-breaking. The compositeness scale Λ_H should be interpreted as the effective mass of the preon which forms the box diagrams. However, in the absence of any dynamical information on its value, we take Λ_H larger than $F_\pi \approx (\sqrt{2} G_F)^{-\frac{1}{2}}$ and more probably $\Lambda_H \approx 1$ TeV as suggested by the QHD sum rule analysis¹⁴⁾ where Λ_H corresponds to the continuum preon (haplon) threshold in the models where the W and Z are composite. We give in the Table the differential cross-section due to the $ggZ\gamma$ contact interaction. If one compares such expressions with the ones obtained in Ref. (4), one should remark that the s -behaviour is not the same. This is due to the fact that gauge-invariant amplitude is described by higher dimension operators. One can also notice that the numerical factors induced by integrals over Feynman parameters of the preon box calculation relatively suppress the cross-section obtained here compared to the one in Ref. (4).

b) $\bar{q}qZ\gamma$ contact interaction is parametrized by the effective term in the Table. The compositeness scale Λ_q is not necessarily the same as Λ_H . We use $\Lambda_q \approx F_\pi$ for our numerical analysis. We give the

differential cross-section in the Table.

5. EXCITED QUARKS.

In order to complete our analysis, we also study the effects of spin 1/2 excited quarks with the coupling given in the Table.¹⁵⁾

NUMERICAL CONCLUSIONS.

The $\bar{q}q \rightarrow Z\gamma$ and $gg \rightarrow Z\gamma$ subprocesses given in the Table are transformed into the proton processes using the standard parametrization of the invariant mass distribution of $Z\gamma$:

$$\frac{d\sigma}{dM} = \frac{2M}{s} \int_{-Y}^Y dy_{\text{Boost}} \int_{\cos \theta_1}^{\cos \theta_2} d(\cos \theta) F(x_1)F(x_2) \frac{d\sigma}{d(\cos \theta)} \quad (11)$$

where $F(x_i)$ are gluon or quarks distribution functions which we take from Duke and Owens¹⁶⁾. The collider energy s is related to the parton one as $\hat{s} = x_1 x_2 s \equiv \tau s$ where x_i are the fraction of parton inside the proton [$x_1 = \sqrt{\tau} \exp(Y_{\text{Boost}})$, $x_2 = \sqrt{\tau} \exp(-Y_{\text{Boost}})$]. The invariant mass M is equal to $\sqrt{\hat{s}}$. We evaluate the structure functions at $Q^2 = M_Z^2$ and for $\Lambda \approx 0.2$ GeV. We have checked the accuracy of our numerical program based on VEGAS subroutine integration¹⁷⁾ by comparing our results of the standard model with the existing ones in the literature. Our expressions of the amplitude have been obtained by the REDUCE algebraic programm. Our results are shown in Figs 1 (resp.2) for Tevatron (resp. SSC) hadron colliders.

a) Tevatron : Fig.1

We show in Fig.1 the effects of light composite particles having a mass of $3M_Z$ at Tevatron collider. The spin zero $\tilde{\pi}$ and $\tilde{\sigma}$ having a technicolour coupling at the gg and $Z\gamma$ vertices have a total width of 2.4 and 7.9 GeV. Their identification can be easily done as they appear as narrow resonances. The $\tilde{\sigma}$ having a larger coupling $G_{\gamma\gamma} = 0.1$ at the $Z\gamma$ and gg vertices is wider with a total width of 24 GeV. It is not surprising that in this case the rate of production is important. Spin zero boson $\tilde{\eta}$ having a weak universal coupling to $\bar{q}q$ pairs is shown for two different values of the $Z\gamma$ couplings. Its effects exceed only the SM ones in the case of the large coupling $G_{\gamma\gamma} = 0.1$,

where the $\tilde{\eta}$ gives a characteristic signal for wide resonance. The spin two $\tilde{a}_2^g$ boson produced through gluon gluon fusion has negligible effects for the couplings normalized by the weak break scale $F_\pi = 260$ GeV. Spin two $\tilde{a}_2^q$ from $\bar{q}q$ pairs interferes with the standard T-diagram. There is a destructive interference effect below threshold for the choice $g_1, g_2 > 0$ used for the plot given in Fig. 1. Above threshold the interference term adds to the diagonal one. With the coupling normalized to F_π , the $\tilde{a}_2^q$ effects are smaller than the SM process.

The effects of excited quarks with the coupling normalized to Λ_H are smaller than the SM process. They are comparable in magnitude with the $\tilde{\eta}$ effect except that the later presents a wide peak at $3 M_Z$. Contact terms normalized by a low scale F_π are still negligible compared to resonance effects though they tend to increase for high values of M . Only the $\bar{q}q Z\gamma$ contact term C_q can be drawn in the scale of our figure. Finally, we show the effects of spin one composite Z' and Y bosons with the couplings given in the Table and discussed in the text. We have not considered in our figures the longitudinal part $|M|^2_{//}$ of the cross-section which has a bad high-energy behaviour and which can be cancelled by some other contributions in a realistic complete theory. One should notice that the Z' appears as a narrow resonance with a total width of 4 GeV. The isoscalar Y with the parameters used here is a wide resonance with a width of 150 GeV. The effects of the above spin one bosons exceed the SM process around the resonance peak. The number of events expected from the spin one bosons is comparable with the one from spinless $\tilde{\pi}$ and $\tilde{\sigma}$ bosons.

b) SSC : Fig.2

We show in Fig.2, the effects of heavy particles of masses 1 TeV. In order to illustrate the spin zero bosons, we have only considered the cases of technicolour-type couplings at the gg and $Z\gamma$ vertices. In this case, the widths of the $\tilde{\pi}$, $\tilde{\sigma}$, $\tilde{\eta}$ are respectively 52, 500 and 1000 GeV. For large values of the invariant mass, all of them exceed the SM process. However, the $\tilde{\pi}$ is the only one which remains as a "true" resonance. It gives the dominant signal at the peak. Spin two $\tilde{a}_2$ bosons with the couplings normalized by F_π give an important signal but this effect vanishes rapidly if one uses instead a normalization of such couplings by the compositeness scale $\Lambda_H = 1$ TeV. One should notice that due to the s-behaviour

of the cross-sections characteristic for nonrenormalizable couplings, the $\tilde{a}_2$ mass distribution only starts to decrease for high values of M not shown in this figure. The relative importance of the excited quark effects increases as the excited quark mass is now equal to Λ_H while in the case of light particles, this mass has been much smaller than Λ_H . The effects of left handed couplings both at the γ and Z vertices are more favoured at small invariant mass than the ones with left (resp. right) handed couplings at the γ (resp. Z) vertices. The difference between these two cases can be attributed to the different energy behaviour of the cross-sections as well as to the presence of interference terms with SM for the later. It can be difficult to separate the excited quarks and spin two $\tilde{a}_2^q$ bosons for the values of the invariant mass above thresholds, while below thresholds, such effects can be confused with other ones, $\tilde{\sigma}$, q^* , $\tilde{\pi}$. The relative strengths of the effects of contact interactions have increased at SSC. These effects are important at high M and for low values of the normalization scale. (The curves shown in Fig. 2 correspond to the couplings normalized by F_π). Spin one bosons Z' and Y have now a total width of 110 GeV and 1 TeV. At Tevatron, their effects are comparable to the $\tilde{\pi}$ one. At SSC, the relative role of the $\tilde{\pi}$ has increased due to the small x -behaviour of the gluon structure functions. The maximal effect of the Z' is smaller than the one of the $\tilde{\sigma}$ having a technicolour-type coupling. The distinction of the Y with the $\tilde{\sigma}$ can be done above threshold as the $\tilde{\sigma}$ effect is much higher in this case. One can really notice that various exotic effects can be much higher than the SM process at SSC. This is a further support for having high energy collider in order to probe physics beyond the standard model.

ACKNOWLEDGEMENTS

We have enjoyed conversations with L. Ametller, M.S. Chanowitz, H. Fritzsch, H. Harari, I. Hinchliffe, G. Martinelli, M. Perrottet, F.M. Renard, J. Soffer and G. Veneziano. One of us (S.N.) would like to thank Prof. M.K. Gaillard for her kind invitation to LBL (Berkeley) and Prof. M. Jacob for the kind hospitality offered to him at the CERN Theory Division.

FIGURE CAPTIONS

Fig. 1 : Invariant mass distribution at the Tevatron energy

for a resonance mass of $3M_Z$:

a) gluon-gluon fusion

b) $\bar{q}q$ processes

for a rapidity cut $Y = 1.5$ and $P_{T\gamma}$ cut of 10 GeV.

Fig. 2 : The same as in Fig. 1 at SSC energy for a resonance

mass of 1 TeV and for a rapidity cut $Y = 2.5$ and $P_{T\gamma}$
cut of 50 GeV.

REFERENCES

- 1) For reviews on technicolour models, see e.g. :
G. Barbiellini et al, ECFA/LEP specialized group 9, Desy report 81-064 (1981) ; E. Farhi and L. Susskind, Phys. Rep. 3(1981) 277.
- 2) For reviews on composite models, see e.g. :
H. Fritzsch MPI/PAE, Pth 85/84 ; H Harari, WIS 85/7 Feb. (SLAC summerschool 1984) ; R.D. Peccei, MPI-PAE/Pth 35/84 (1984) ;
W. Buchmüller, CERN preprint Th 4189/85 (1985) ; M. Peskin, SLAC pub 3852 (1985) ; L. Lyons, Oxford Univ. preprint (1982).
- 3) S. Narison and C. Wallet, Phys. Lett. 158B (1985) 355.
- 4) F.M. Renard, Phys. Lett. 132B (1983) 450 ; H. Harari, M. Leurer and R. Barbieri, Phys. Lett. 141B (1984) 455. For a review, see e.g. : E. Eichten, I. Hinchliffe, K. Lane and C. Quigg, Rev. Mod. Phys. 56 (1984) 579, Errata, FNAL Pub 86/75T (1986).
- 5) G. Girardi et al, Phys. Lett. 133B (1983) 234 ;
S. Narison and M. Perrottet, Nuov. Cim. 90A (1985) 49.
- 6) U. Baur, H. Fritzsch and H. Faissner, Phys. Lett. 135B (1984) 313
R.D. Peccei, Phys. Lett. 136B (1984) 121 ; F.M. Renard, Phys. Lett. 139B (1984) 449 ; W. Hollik, B. and F. Schrempp, Phys. Lett. 140B (1984) 424 ; D. Düsedau, D. Lüst and D. Zeppenfeld, MPI-PAE/Pth 24/84 ; P. di Vecchia and G. Veneziano, Phys. Lett. 95B (1980) 247 ;
K. Yamawaki, M. Bando and K. Matumoto, DPNU preprint 85-47 (1985).
- 7) H. Fritzsch and G. Mandelbaum, Phys. Lett. 150B (1985) 395.
- 8) For reviews see e.g. : J.J. Sakurai, Acta Phys. Austriaca, Suppl. 24 (1982) 275 ; D. Schildknecht, MPI-PAE/Pth 23/83 (1983).
- 9) R.N. Cahn and S. Dawson, Phys. Lett. 136B (1984) 196 ;
M.S. Chanowitz and M.K. Gaillard, Nucl. Phys. B261 (1985) 379.
- 10) H. Fritzsch, R. Kögerler and D. Schildknecht, Phys. Lett. 114B (1982) 157.
- 11) M. Perrottet (private communication) ; see also G. Gounaris, R. Kögerler and D. Schildknecht, Phys. Lett. 137B (1984) 261, K. Hagiwara et al, Nuclear Phys. 282B (1987) 253.
- 12) M. Kuroda, D. Schildknecht and K.H. Schwarzer, Nucl. Phys. 261B (1985) 432.
- 13) H. Euler, Ann. Phys. 26 (1936) 398.
- 14) For a review, see e.g. : S. Narison, talk given at the EPS conference, Bari (1985) edited by L. Nitti and G. Preparata.

- 15) Phenomenology of excited quarks at $(\bar{p}p)$ has been discussed by A. de Rújula, L. Maiani and R. Petronzio. Phys. Lett. 140B (1984) 253 and references therein. Low-energy constraints on excited leptons have been discussed by F.M. Renard, Phys. Lett. 116B (1982) 264 ; see also S. Narison, Phys. Lett. 167B (1986) 214 ; QHD sum rules constraints on excited leptons are in S. Narison and P. Pascual, Phys. Lett. 150B (1985) 363.
- 16) D.W. Duke and J.F. Owens, Phys. Rev. D7 (1984) 508. For alternative parametrization, see e.g. : M. Glück, E. Hoffmann and E.Reya, Z. Phys. C13 (1982) 119 and Ref. 4c). The parametrization of Ref. 15b) tends to underestimate the cross sections at large momentum transfer.
- 17) We thank L. Ametller for providing us with the numerical program of the Trieste QCD group.

T A B L E

Vertices and Differential cross-section $\frac{d\hat{\sigma}}{d\Omega}$

1. SPIN ZERO

$g_{\eta} \gamma_5$
 $\alpha_s G_{\sigma} (g^{\mu\nu} p_1 p_2 - p_1^{\nu} p_2^{\mu})$
 $\alpha_s G_{\pi} \epsilon^{\mu\nu\rho\sigma} p_{1\rho} p_{2\sigma}$
 $\alpha G_{Z\gamma} \epsilon^{\mu\nu\rho\sigma} p_{3\rho} p_{4\sigma}$
 $\frac{1}{8} \frac{1}{256\pi^2} \frac{1}{4} \alpha_s^2 \alpha_{\gamma Z}^2 G_{\gamma Z}^2 G_{\sigma}^2 \frac{(s-M_Z^2)^3}{|D(s)|^2}$
 $\frac{1}{3} \frac{1}{256\pi^2} \alpha_s^2 G_{\gamma Z}^2 g_{\eta}^2 \frac{(s-M_Z^2)^3}{s |D(s)|^2}$

with : $D_p(s) = s - M_p^2 + i M_p \Gamma_p$

2. SPIN ONE

$e \gamma^{\mu} (g_V + g_A \gamma_5)$
 $e \{ g_1 \epsilon^{\rho\mu\nu\tau} \epsilon_{1\mu} \epsilon_{2\nu} p_{1\tau} + \frac{g_2}{M_Z^2} \epsilon^{\rho\mu\tau\sigma} \epsilon_{1\mu} (\epsilon_2 \cdot p_1) p_{2\tau} p_{1\sigma} \}$
 $\frac{d\hat{\sigma}}{d\Omega} = \frac{1}{3} \frac{(4\pi\alpha)^2}{64\pi^2 \hat{s}} \frac{B_Z}{\hat{s}} \{ |M|_T^2 + |M|_{//}^2 + M_{Z'}^+ M_{SM} \}$
 with
 $|M|_T^2 = g_1^2 (v_{Z'}^2 + a_{Z'}^2) \cdot B_Z^2 (1-z^2)/4 |D_{Z'}(s)|^2$
 $|M|_{//}^2 = (g_2 B_Z + 2g_1 M_Z^2)^2 (v_{Z'}^2 + a_{Z'}^2) \cdot B_Z^2 (1+z^2) \cdot \frac{\hat{s}}{32 M_Z^6 |D_{Z'}(s)|^2}$
 $M_{Z'}^+ M_{SM} = \frac{\text{Im } D_{Z'}}{|D_{Z'}|^2} (g_V^{\phi} a_{Z'} + g_A^{\phi} v_{Z'}) \frac{1}{M_Z^2} [g_2 \hat{s} B_Z + 2g_1 M_Z^2 (\hat{s} + M_Z^2)]$

3. SPIN TWO

with :

$$(\gamma_\psi - a_\psi \gamma_5) \{ \gamma^\mu p^\nu + \gamma^\nu p^\mu + \frac{2}{3} (\frac{q^\mu q^\nu}{2} - g^{\mu\nu}) \} \frac{1}{F_\pi}$$

$$(\alpha_s) \frac{1}{F_\pi} \{ g_2 F_1^{\rho\mu} F_{2\mu}^\sigma + \frac{g_1}{F_\pi^2} F_{\mu\nu}^1 F_{\mu\nu}^2 p_1^\rho p_2^\sigma \} T_{\rho\sigma}$$

$$p \equiv p_1 - p_2 \quad q \equiv p_1 + p_2 \quad \eta^{\mu\nu} \equiv (-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2})$$

$$\sum_{\lambda} T^{\rho\sigma} T^{\alpha\beta} = \frac{1}{2} (\eta^{\rho\alpha} \eta^{\sigma\beta} + \eta^{\rho\beta} \eta^{\sigma\alpha} - \frac{2}{3} \eta^{\rho\sigma} \eta^{\alpha\beta})$$

$$\frac{d\hat{\sigma}}{d\Omega} = \frac{\alpha^2}{3.64\pi^2} \hat{s}^2 \frac{B_Z^2}{\sin\theta_W} \{ \frac{B_Z^2}{|D(\hat{s})|^2} \frac{(v_\psi^2 + a_\psi^2)}{\sin\theta_W} \frac{1}{F_\pi^4}$$

$$[2 B_Z^2 (\frac{g_1^2}{F_\pi^4} B_Z^2 - 2 \frac{g_1 g_2}{F_\pi^2} M_Z^2) z^2 (1-z^2) + g_2^2 [2(B_Z^2(1+z^2) + M_Z^2 B_Z^2) \cdot (1-z^2) + M_Z^2 \hat{s} (3-z^2)]] +$$

$$\frac{\text{Re}(D)}{|D(s)|^2} 8\pi Q_i (g_V^i v_i + g_A^i a_i) \cdot [\frac{g_1}{F_\pi^2} B_Z^2 M_Z^2 z^2$$

$$- g_2 [B_Z^2 (1+z^2) + M_Z^2 B_Z^2 + 2 M_Z^2 \hat{s}] \}$$

$$\frac{d\hat{\sigma}}{d\Omega} = \frac{1}{8} \cdot \frac{1}{64\pi^2} \frac{B_Z^2}{\hat{s}^2} \cdot \frac{(\alpha_s \cdot \alpha)^2}{9 \times 2^8} \cdot \frac{1}{F_\pi^4} \frac{1}{|D(\hat{s})|^2}$$

$$\{ (1-3z^2)^2 B_Z^4 \hat{s}^2 (\frac{g_1^2}{F_\pi^4} B_Z^2 - 2g_1 g_2 M_Z^2) - 18 \frac{g_1^3}{F_\pi^2} B_Z^4 M_Z^2 (1-z^2)^2 + \frac{g_1^2}{F_\pi^4} \cdot g_2^2 \{ 18 B_Z^5 [(1-z^2)^2 \hat{s} + M_Z^2 (1-z^2)] + M_Z^4 B_Z^2 [(55-60z^2+9z^4) B_Z^2 + (38-30z^2) M_Z^2 B_Z^2 + (10-6z^2) M_Z^4] \} + 9 g_2^4 B_Z^2 [(\hat{s} + M_Z^2)^2 + 2z^2 [(\hat{s} + M_Z^2) B_Z^2 + 2\hat{s}^2] + z^4 B_Z^2] \}$$

$$\text{with } B_Z \equiv \hat{s} - M_Z^2, \quad z \equiv \cos \theta$$

4. SPIN 1/2

$$g_W \frac{m_*}{F_\pi^2} \bar{q} \sigma^{\mu\nu} (1 \pm \gamma_5) q F^{\mu\nu}$$

$$\text{with } g_W \equiv e/\sin \theta_W$$

$$\frac{d\hat{\sigma}}{d\Omega} \Big|_{LL} = \frac{1}{3} \cdot \frac{1}{64\pi^2} \frac{B_Z}{\hat{s}^2} \cdot 128 m_*^2$$

$$\left\{ \frac{\hat{u}(2\hat{u}\hat{s} + \hat{t} M_Z^2)}{(\hat{u} - m_*^2)^2} + \frac{1}{(\hat{t} - m_*^2)^2} \hat{t} (2\hat{t}\hat{s} + \hat{u} M_Z^2) + \right.$$

$$\left. + \frac{1}{(\hat{t} - m_*^2)(\hat{u} - m_*^2)} 2\hat{u}\hat{t} (2\hat{s} - M_Z^2) \right\}$$

(no interference with standard model)

$$\frac{d\hat{\sigma}}{d\Omega} \Big|_{LR} = \frac{1}{3} \frac{1}{64\pi^2} \frac{B_Z}{\hat{s}^2} \cdot \{ |M|_{q*}^2 + M_{q*} M_q^+ \}$$

with

$$|M_{q*}|^2 = \left(\frac{m_*}{F_\pi^2} \right)^2 g_W^4 128 (2\hat{u}\hat{t} + \hat{s} M_Z^2) \left(\frac{\hat{u}^2}{(\hat{u} - m_*^2)^2} + \frac{\hat{t}^2}{(\hat{t} - m_*^2)^2} \right)$$

$$M_{q*} M_q = Q i 4\pi\alpha g_W^2 \cdot \left(\frac{m_*}{F_\pi^2} \right) \cdot$$

$$8 \left\{ \frac{4\hat{u}}{\hat{u} - m_*^2} (g_A^\psi - g_V^\psi) (\hat{u} - M_Z^2) - \frac{4\hat{t}}{\hat{t} - m_*^2} (\hat{t} - M_Z^2) (g_A^\psi + g_V^\psi) \right\}$$

5. CONTACT INTERACTIONS

$$\frac{\alpha}{\Lambda_q^3} F^{\mu\nu} Z_{\mu\nu} \bar{\psi}\psi$$

$$\frac{d\hat{\sigma}}{d\Omega} = \frac{\alpha^2}{\Lambda_q^6} \frac{1}{3} \cdot \frac{1}{64\pi^2} \cdot \frac{1}{2} \cdot \frac{B_Z^3}{\hat{s}}$$

(no interference with standard model)

$$\frac{\alpha_s}{180 \Lambda_H^4} \{ 28 \textcircled{GGZF} + 28 \textcircled{GGFZ} + 28 \textcircled{GZGF} - 10 \widehat{GG} \widehat{ZF} - 20 \widehat{GZ} \widehat{GF} \}$$

⊖ means order of tensorial contractions.

$$\begin{aligned} \frac{d\hat{\sigma}}{d\Omega} &= \frac{1}{4} \cdot \frac{1}{8} \cdot \frac{1}{256\pi^2} (\alpha_s \alpha)^2 \frac{139}{(90\Lambda_H^4)^2} B_Z^3 \cdot \\ &\cdot \{ (3+z^2)^2 + \frac{M_Z^4}{\hat{s}^2} (1-z^2)^2 + \frac{M_Z^2}{\hat{s}} (1-z^2) \cdot \\ &\cdot (\frac{121}{139} + z^2) \} \cdot \end{aligned}$$

Fig. 1

Fig. 2