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THE NEEDLE IN THE LARGE p_T HAYSTACK :
HIGGS VERSUS QUARK OR GLUON JETS
TOGETHER WITH Z^0 IN HADRONIC REACTIONS

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ABSTRACT

The possibility of observing a Higgs particle via high p_T bremsstrahlung from a weak Z_0 in $p\bar{p}$ and pp collisions is examined. It appears that, although very weak, some signal might be observed in the future $p\bar{p}$ collision experiments.

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Gauge models have proved to be very successful in describing weak and electromagnetic interactions and are by now considered as "musts". However, in the simplest $SU(2) \times U(1)$ model, there are at least 3 gauge bosons $W^{\pm}, Z^0$ and a scalar particle, the Higgs H , to be discovered¹⁾. Much hope is put in the Isabelle²⁾ and SPS projects³⁾: pp collisions at cm energy $\sqrt{s} = 800$ GeV and $p\bar{p}$ at $\sqrt{s} = 540$ GeV are expected to produce the very massive gauge bosons and maybe the elusive Higgs particle. Indeed many calculations and estimates have already been proposed for weak boson production and signatures [with^{4),5)} or without⁶⁾ QCD corrections] as well as for the Higgs signal^{7),8)}.

The basic mechanism advocated for the gauge bosons production in hadronic collisions is the Drell-Yan one, via quark antiquark annihilation. Here we consider a more general process:

Later on particle C will be identified with $q, \bar{q}, g$ or H , as the case may be. In this note we concentrate on the case of large mass, large transverse momentum^{9),10)} pairs of light leptons ($\ell^+ \ell^-$) from the Z^0 decay, with particular emphasis on the associated H production, through the diagram:

(A)

As pointed out in Ref. (7b), process (A) may be more relevant to an experimental search than the gluon gluon annihilation which, following the authors of Ref. (7a), is the dominant contribution. Considering only light-lepton pairs the H should not confuse the analysis, since due to its coupling to fermion-antifermion it will prefer to decay into the heaviest ones (recall that M_H is expected to be $\gtrsim 10$ GeV). Here we will disregard the predominant decays $Z^0 \rightarrow q\bar{q}$ which produce massive pairs of hadronic jets because of the very

important background of large p_T processes induced by the strong interactions. Hopefully the Z^0 signal in lepton pairs, though weak, will be cleaner. Very much like in hadroproduction of virtual and real photons, a copious source of large p_T dileptons will be given by the lowest order QCD corrections to the bare Drell-Yan $q\bar{q}$ annihilation.

"Annihilation" (B)
(colour average 1/9)

"Compton scattering" (C)
(colour average 1/24)

It is therefore of some interest to compare the relative contribution of process (A) and QCD correction to Drell-Yan.

We are aware of the fact that calculations concerning Z^0 production to first order in quark-gluon couplings in QCD have already been done^{5),6)} using the generalization of the Drell-Yan formula and the p_T variable, as well as some estimate of the Higgs production via bremsstrahlung⁷⁾ although not in the framework of the p_T variable. Nevertheless we think that it is worth while presenting our calculations, because they allow a direct comparison of $\frac{d\sigma}{dp_T}$ for Higgs plus lepton pair production with respect to gluon plus lepton pair production through Z^0 , and it will emerge that such a comparison leads to rather encouraging perspectives.

Now let us give the basic formulae we will use in this letter, just mentioning that we neglect the primordial transverse momentum of the constituents inside the hadrons as well as quark and lepton masses. If p_T is the transverse momentum of the Z^0 relative to the beam direction and m^2 its mass, one can write:

$$\frac{d^2\sigma}{dp_T dm^2} (A+B \rightarrow C+Z+X) = \int_{z_{min}}^1 dz \sum_{a,b} \frac{d^2\sigma}{dp_T dm^2} (a+b \rightarrow C+Z) \int_{z/z}^1 \frac{dx}{x} q_{a/A}(x) q_{b/B}(z/x). \quad (1)$$

where $\tau = m^2/\hat{s}$, $\hat{s} = (p_A + p_B)^2$, $\tau_{\min} = (\sqrt{m^2 + p_T^2} + \sqrt{p^2 + p_T^2})/\hat{s}$

where μ^2 is the C mass and $q_{a/A}(x)$ is the probability of finding the constituent a inside the hadron A with momentum xP_A . The cross-section for the subprocess $(a + b \rightarrow C + Z)$ can be expressed in terms of variables relevant to the three-body final state, where a lepton pair of invariant mass m is observed:

$$\frac{d^2\sigma}{dp_T dm^2} (a+b \rightarrow C e^+ e^-) = \frac{m}{\pi} \frac{d\tau}{dp_T} (a+b \rightarrow C+Z) |P(m^2)|^2 \frac{g_{Z\ell\ell}^2 \cdot m}{12\pi} \quad (2)$$

where $|P(m^2)|^2 = [(m^2 - M_Z^2 + \Gamma_Z^2/4)^2 + M_Z^2 \Gamma_Z^2]^{-1}$

is the propagator of the Z^0 and $g_{Z\ell\ell}$ its coupling to $\ell^+ \ell^-$. For the evaluation of the subprocesses for the p_T distribution we need to define some couplings like $g_{Zf\bar{f}}$ and $g_{ZH\bar{f}f}$. $g_{Zf\bar{f}}$ can be obtained from the interaction Lagrangian

$$\mathcal{L}_{Zf\bar{f}} = - \frac{\sqrt{G_F M_Z^2}}{\sqrt{2}} Z_\mu (C_L \bar{f}_L \gamma^\mu f_L + C_R \bar{f}_R \gamma^\mu f_R)$$

where $f_{L,R} = \frac{1}{2}(1 \pm \gamma_5)f$ stands for a left-handed or right-handed fermion field. In the minimal Weinberg-Salam model one has

$$C_{L,R} = 2\sqrt{2} (t_{L,R}^3 - e \sin^2 \theta_w)$$

where $t_{L,R}^3$ is the third component of the weak SU(2) and e the charge of the electron. With an analogous definition the Higgs coupling to the Z^0 is

$$g_{HZZ} = 2M_Z^2 / \sqrt{G_F \sqrt{2}}$$

Then the squared matrix element of the subprocess $q + \bar{q} \rightarrow H(m^2) + Z(m^2)$, in terms of the usual invariants s, t, u , is given by

$$\sum_{i,f} \left| \mathcal{M}(q + \bar{q} \rightarrow H(p^2) + Z(m^2)) \right|^2 = G_F^2 M_Z^6 (C_L^2 + C_R^2)^q \left(2s - p_T^2 + \frac{t u}{m^2} \right) |P(s, M_Z, p_T)|^2 \quad (3)$$

where the superscript q denotes the quark coupled to the Z . The transverse momentum of the Z^0 is such that

$$s p_T^2 = t u - m^2 p^2 \quad (4)$$

Now using (1), (2) and (3) it is an easy matter to obtain the hadronic p_T distribution for the whole hadronic process (A):

$$\frac{d\sigma^A}{dp_T} = \frac{G_F^3 M^8}{\sqrt{2} 16\pi^3} (1 - 4\sin^2\theta_W + 8\sin^4\theta_W) \int dm^2 p_T (2m^2 + p_T^2) |P(m^2)|^2 \cdot \int_{\tau_{\min}}^1 d\tau \int_0^1 \frac{dx_a}{x_a} \frac{\zeta(q\bar{q}) |P(\tau\hat{s})|^2}{[(m^2 + p_T^2 - \tau\hat{s})^2 - 4(p_T^2 \tau\hat{s} + m^2 p_T^2)]^{1/2}} \quad (5)$$

with

$$\begin{aligned} \zeta(q\bar{q}) = & \frac{1}{9} \left\{ (C_L^2 + C_R^2)^u \left[u(x_a) u(\tau/x_a) + \bar{u}(x_a) \bar{u}(\tau/x_a) + 2c(x_a) c(\tau/x_a) \right] \right. \\ & \left. + (C_L^2 + C_R^2)^d \left[d(x_a) d(\tau/x_a) + 2s(x_a) s(\tau/x_a) + \bar{d}(x_a) \bar{d}(\tau/x_a) \right] \right\} \quad (6) \end{aligned}$$

for $p\bar{p}$ collisions, assuming that $q_{a/\bar{p}} \equiv q_{\bar{a}/p}$. The corresponding expression for proton-proton is obtained by obvious changes [i.e. replacing $q(x_1) q(\tau/x_1) + \bar{q}(x_1) \bar{q}(\tau/x_1)$ by $q(x_1) \bar{q}(\tau/x_1) + \bar{q}(x_1) q(\tau/x_1)$].

Let us now turn to the QCD induced process, for which we have taken the running coupling constant to depend on m^2 , $\alpha_s(m^2)$; the result is

$$\frac{d\sigma^{B+C}}{dp_T} = \left(\frac{G_F M^2}{8\pi} \right)^2 \frac{(1 - 4 \sin^2 \theta_W + 8 \sin^4 \theta_W)}{3 \hat{s}^2} \int dm^2 \cdot m^2 \alpha(m^2) \int_{z_{\min}}^1 \frac{dz}{z^2} \cdot \int_z^1 \frac{dx_a}{x_a} |L(m^2)|^2 [\gamma(q\bar{q}) Q(p_T, m^2) + \gamma(qq) R(p_T, m^2)] \quad (7)$$

In this equation we kept the separation between "annihilation" and "Compton" terms. $\gamma(q\bar{q})$ is defined in (6), while

$$\begin{aligned} \gamma(qq) = \frac{G(x_a)}{24} \left\{ (C_L^2 + C_R^2)^u [u(z/x_a) + \bar{u}(z/x_a) + 2c(z/x_a)] \right. \\ \left. + (C_L^2 + C_R^2)^d [d(z/x_a) + \bar{d}(z/x_a) + 2s(z/x_a)] + \{x_a \leftrightarrow z/x_a\} \right\} \quad (8) \end{aligned}$$

is valid both in $p\bar{p}$ and pp cases.

$Q(p_T, m^2)$ and $R(p_T, m^2)$ represent the matrix elements contribution from diagrams (B) and (C) respectively.

$$Q(p_T, m^2) = \frac{32}{p_T} \frac{m^4 + s^2 - 2s p_T^2}{\sqrt{(m^2 - s)^2 - 4p_T^2 s}} \quad (9)$$

$$R(p_T, m^2) = -\frac{16}{p_T} \frac{(m^2 - s)(2m^4 - 2m^2 s + s p_T^2 + s^2) - 4m^2 s p_T^2}{\sqrt{(m^2 - s)^2 - 4p_T^2 s}} \quad (10)$$

The factor $1/p_T$ reflects an infra-red divergence due to the masslessness of the quarks and the gluon; more precisely it is a collinear divergence. This makes the cross-section ill-defined in the small p_T region and a careful analysis would require a regularization procedure -see Ref. 9) and references therein. As far as we are concerned, we are safe once we consider only the large p_T (say $\gtrsim 5$ GeV/c) region. This situation has to be contrasted with

the Higgs bremsstrahlung where the p_T factor is upstairs [Eq. (5)] making the cross-section well-defined everywhere.

In fact, in the diagrams (B) and (C) the Z could be as well a γ , and we have calculated the contributions of the $\gamma\gamma$ and γZ interference; they are negligible with respect to the ZZ terms in the cross-section.

Concerning the structure functions we have used the Buras-Gaemers parametrization¹¹⁾. This is not in contradiction with Politzer's theorem, since scaling violations are related to soft QCD processes which sum up, while here we just pick up a hard one. As for α_s we have taken m^2 as the evolution parameter, with the scale parameter $\Lambda = 0.300 \text{ GeV}/c$ ¹¹⁾. At this point we should mention that the results for proton-proton collisions are less solid than those for proton-antiproton because of the prominent role of the sea quarks, which are not accurately known. What is more important, as one sees from Eq. (7) is that the lower limit of the x_a integral is τ , roughly varying $1/\hat{s}$ at fixed p_T around the Z_0 peak; then, the higher the $\hat{s}$ is, the smaller are the values of x we probe. In the small x region, different parametrizations can yield drastically different results. For instance, with the quark distributions of Buras and Gaemers, which are steeply rising near $x = 0$, the pp cross-sections will be somewhat high with respect to $p\bar{p}$. Owing to the p_T dependence on τ , this effect will be less pronounced at large transverse momentum. Keeping that in mind we will therefore discuss in more detail the $p\bar{p}$ case which, in that respect, looks safer.

Numerical estimates of the differential cross-sections $\frac{d\sigma^A}{dp_T}, \frac{d\sigma^{B+C}}{dp_T}$ as defined previously in Eqs. (5) and (7) are given in Figs. (1) and (2) for $p\bar{p}$ collisions ($\sqrt{s} = 540 \text{ GeV}$) and pp collisions ($\sqrt{s} = 800 \text{ GeV}$) for $\sin^2\theta_w = 0.20$ and 0.23 . The Higgs mass is a priori a free parameter, but in the case where the symmetry breaking is generated by radiative corrections¹²⁾ it is given by the following formula¹³⁾:

$$m_H^2 \simeq \frac{3\alpha^2}{8\sqrt{2}G_F} \cdot \frac{2 + \sec^4\theta_w}{\sin^4\theta_w}$$

namely $m_H = 10.4$ and 9.2 GeV for the two values of $\sin^2\theta$ we take. Due to the strong peaking of $|P(m^2)|^2$ around M_Z^2 we have calculated $\frac{d\sigma^{B+C}}{dp_T}$ using the narrow width approximation (NWA) replacing $|P(m^2)|^2$ by $\pi\delta(m^2 - M_Z^2)/M_Z\Gamma_Z$ in Eq. (7). Then one observes that the cross-sections are at the level of the

picobarn or less, with a very long tail in p_T . Actually we calculated¹⁴⁾ the average squared transverse momentum of the lepton pair in $p\bar{p}$ which comes out to be about $45(\text{GeV}/c)^2$. Specifically, we did the calculations at $y = 0$ and obtained $\langle p_T^2 \rangle \sim 92(\text{GeV}/c)^2$ comparable to the value quoted in Ref. 4); the discrepancy between the two calculations are due to phase space effects. As noted earlier the cross-sections are not integrable; nevertheless, one can have a rough estimate by imposing a plateau below $p_T = 1 \text{ GeV}/c$ to simulate smearing effects. Using this procedure we obtain $\sigma^{(B+C)}(p\bar{p}) \sim 18 \text{ pb}$. This value for the first order contribution is very sizeable if one compares with the zeroth order contribution coming from the pure Drell-Yan quark-antiquark annihilation $\sigma^{(0)}(p\bar{p}) = 28.5 \text{ pb}$. To say whether this is accidental or is related to the inadequacy of perturbative QCD would require higher order calculations. If we are correct, this means that for lepton pairs with $p_T > 5 \text{ GeV}/c$, a region where the zeroth order contribution, even with primordial motion included, is negligible, there will still be a detectable Z^0 signal (about 10% of all lepton pairs).

Now we turn to the estimates for the associated H product labelled as process (A) where unlike in the preceding (B + C) case we did not use the narrow width approximation, even for $|P(m^2)|^2$ in (5). The NWA is good only if one wants to observe lepton pairs close to the peak, but because of the peculiar kinematics, the m^2 distribution is strongly smeared out. Whether or not the peak of $|P(s)|^2$ is within the τ range of integration depends on the value of m^2 one is observing. The peak is just at the edge of phase space $\tau = \tau_{\min}$ for $m^2 = M^2 + \mu^2 - 2\sqrt{\mu^2 + p_T^2}$. It is within phase space for smaller m^2 and outside for larger ones. This means that especially for the combination of high p_T and m^2 smaller than M^2 one will pick out the enhanced part of $\frac{d\sigma^A}{dp_T}$.

Therefore we present in the figures the p_T distribution for different m^2 integration ranges (dashed curves) together with their sum (solid line A)*). From these figures it is clear that the best chance to find a Higgs signal is in events where the dilepton mass is below the Z^0 mass. Of course the cross-sections are still tiny, about 1/10 of a picobarn, but these are the configurations where the relative signal is larger. For a $p\bar{p}$ collider working at a luminosity of $10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ for 1000 hours this would mean only 1 event (with 3 lepton doublets). It is also fair to point out that this is an optimistic number because our Higgs mass is only 10 GeV; a heavier Higgs would be more or

*) Note that all these curves have been multiplied by 100 to make them appear on the same plot as (B + C).

less undetectable. It would be of considerable interest to gain one factor in the initial luminosity because 10 events is a good sample to work on. As far as the pp collider is concerned, we said earlier that the estimates are less reliable, but are expected to be a factor 5 lower, which is highly compensated by the available luminosity $10^{32 \pm 1} \text{ cm}^{-2} \text{ sec}^{-1}$. With such a machine one can therefore reasonably hope to see an "abundant" signal from a light Higgs.

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REFERENCES

- 1) In this note we will be concerned with the most economical Weinberg-Salam theory involving only one $I = \frac{1}{2}$ Higgs multiplet $H = (H^+, H^0)$. For a phenomenological study concerning the Higgs particle see for example: J. Ellis, M.K. Gaillard and D.V. Nanopoulos, Nucl. Phys. B106 (1976) 292, and more recently: M.K. Gaillard in Comments on Nuclear and Particle Physics 8 (1978) 31.
- 2) BNL report No. BNL 20161 (1975).
- 3) CERN/SPSC/78-06 SPSC/92
- 4) F. Halzen and D.M. Scott, Phys. Lett. 78B (1978) 318;
F. Halzen and D.M. Scott, Phys. Rev. D18 (1978) 3378.
- 5) M. Chaichian et al., University of Helsinki preprint HU-TFT 78.42 (1978).
- 6) R.B. Palmer et al., Phys. Rev. D14 (1976) 118;
R.F. Peierls et al., Phys. Rev. D16 (1977) 1397;
C. Quigg Reviews of Mod. Phys. 49 (1977) 297 and references therein;
M. Perrotet, Annals of Phys. 115 (1978) 107;
J. Finjord, Nucl. Phys. B131 (1978) 507.
- 7) a) M.M. Georgi et al., Phys. Rev. Lett. 40 (1978) 692;
b) S.L. Glashow et al., Harvard preprint HUTP 78/A012 (1978).
- 8) D.R.T. Jones and S.T. Petcov, CERN Preprint TH. 2661 (1979);
J. Finjord, CERN Preprint TH. 2663 (1979);
E. Ma and J. Okada, University of Hawai preprint UH-511-344 (1979).
- 9) R.D. Field, Proc. 19th Int. Conf. High Energy Physics, Tokyo 1978.
- 10) J.F. Owens, XIVth Rencontre de Moriond, Les Arcs, March 1979, Tran Thanh Van Editor.
- 11) A.J. Buras and K.J.F. Gaemers, Nucl. Phys. B132 (1978) 249.
- 12) S. Coleman and E. Weinberg, Phys. Rev. D7 (1973) 1888.
- 13) J. Ellis, M.K. Gaillard, D.V. Nanopoulos and C.T. Sachrajda, Phys. Lett. B, 83B (1979) 339.
- 14) J. Finjord, G. Girardi, P. Sorba, in preparation.

Figure captions

Fig. 1 : Dilepton transverse momentum distribution for $\sqrt{s} = 540$ GeV ($p\bar{p}$ collider) (a) $\sin^2\Theta_w = 0.2$, (b) $\sin^2\Theta_w = 0.23$. The Higgs distribution (H) has been rescaled by a factor 10^2 . The QCD contribution refers to the diagrams (B) and (C) defined in the text. The dashed curves are relative to different m^2 integration ranges of the Higgs distribution.

Fig. 2 : Same as Fig. 1 for pp collisions for $\sqrt{s} = 800$ GeV.

FIG. 1a

FIG. 1 b

FIG. 2a

FIG. 2 b