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Searching for a Light Intermediate Mass Higgs at the Large Hadron Collider

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Abstract

Decay channels and event signatures for a light intermediate Higgs boson of mass $m_Z \leq m_H \leq 2m_W$ are reviewed in light of recent CDF limits on the top quark mass . At hadron colliders, LHC and SSC, rare decay channels like $H \to Z^*Z^*$ and $H \to \gamma\gamma$ are necessary in order to disentagle the signal from the background. It is noticed that the very rare process in which a Higgs boson is produced in association with a Z boson could be used to detect a Higgs boson in the 80-100 Gev/c^2 mass range, but only if a very high luminosity option were available.

1 Introduction

The question of the existence of at least one neutral Higgs particle (H^0) is a central problem of electro-weak unification. As well known, although the properties of the Higgs field are rather well constrained, the expectations on its mass, which are crucial when it comes to detecting it, are widely open.

A first systematic search for H^0 is on its way at LEP and it is amongst the main motivations for a further increase of its energy (LEP200). Present measurements [1] have established that the Higgs mass is larger than 48 GeV/c^2. In the next few years it is expected [2] that either H^0 will be found at LEP or such limits will be raised to $80 \div 85$ GeV/c^2.

Any further extensions of this search will require energies and luminosities which are beyond the possibility of the present LEP project and would then need new colliders[3]. It should be pointed out that the energy domain next to the one of LEP, i.e. $80\ GeV/c^2 \leq M_H \leq 2m_Z$ is crucial, since there are many theoretical indications, from minimal supersymmetry [4, 5] to lattice simulations [6], which point to its possible existence in this mass range. In addition, recent studies on radiative corrections to W and Z-boson masses [7] have shown that the most probable value for the top mass is given by $m_{top} = 127 \pm 30\ GeV/c^2$ and that for such value, the minimum of the χ^2 relative to all existing data on the electroweak parameters falls in the region $M_H \approx 100 - 130\ GeV/c^2$. The detection of such an "intermediate mass" H^0 is considered as very difficult and perhaps even impossible [8] with the hadronic colliders presently planned (LHC,SSC) in view of the presence of severe QCD-related backgrounds and in the absence of an appropriate signature. This observation has prompted the interest for an e^+e^- collider of energy beyond the one of LEP - in the range $0.5 \div 1\ TeV$ - in order to extend the search for H^0 to about $200 \div 300\ GeV/c^2$ [9].

In the present paper we would like to show that if a sufficiently high luminosity ($5 x 10^{34} cm^{-2} sec^{-1}$) is made available at a hadron collider, one can find signatures which make such an intermediate Higgs detectable with an appropriate specialized detector, thus closing the mass gap with respect to LEP200 and removing - so to say - the "necessity" of an additional e^+e^- collider. In particular, in this note, we shall address the possibility of detecting a "light intermediate" Higgs boson , in the mass range $80 - 130\ GeV/c^2$, i.e. in a range which is not accessible to the so called "gold plated" signature, $H \rightarrow ZZ^* \rightarrow 4\ leptons$.

We shall start presenting width and production cross-sections for a Higgs boson in this mass range. Next we shall discuss event rates and comparison with the expected background.

2 Decay widths and Branching Fractions

Since the coupling to fermion pairs is proportional to their mass, the physics of the Higgs sector is strongly dominated by the top quark for which there is an upper bound to the mass, m_{top}, from radiative corrections [7], $m_{top} \leq 200\ GeV/c^2$ since $\rho \approx 1$. The present experimental limit reported by the CDF collaboration [10] at FermiLab is $m_{top} \geq 89\ GeV/c^2$.

The fact that m_{top} has exceeded m_W has profund consequences on the H^0 phenomenology :

- the decay channel into $b - \bar{b}$ pairs dominates below the W-pair threshold ($M_H \leq 2m_W$) and correspondingly the decay width of a light Higgs is extremely narrow. Rare decay channels become experimentally accessible, in particular those with one or both IVB propagators off-the-mass-shell, and decay into two photons . The branching fractions into these rare channels become sensitive to higher order QCD corrections[11] to the b-quark mass, a QCD enhancement effect, which may be crucial for detecting a light intermediate Higgs.
- The production of $t - \bar{t}$ pairs is now a QCD driven process of large cross-section in hadronic collisions of sufficiently high energy (many TeV). The new limit on the top mass [10] implies that the dominant decay will be $t \rightarrow Wb$. Hence production of W-pairs occurs at a rate typical of strong interactions, an overwhelming background to the electroweakly produced W-particles from H^0 decay. Fortunately Z^0 channels are free of such background at least in the absence of flavour changing neutral currents in t-decays. Relying on Z^0 leptonic decays introduces a reduction of event rate (with corresponding luminosity requirement) of about one order of magnitude with respect to previous estimates, since (i) the production of Z^0 is less frequent than the one for $W^{\pm}$ and (ii) its leptonic branching ratio is smaller.

We shall now look in detail into the Higgs boson decay processes. Since the Higgs boson couples to all the known elementary particles, its branching ratioes are many and varied. In Table 1 we write the expressions for the decay probability in various channels and in **Fig. 1** we show some of the decay widths in the mass range $50 \leq M_H \leq 300\ GeV/c^2$. We have chosen $m_{top} = 90\ GeV/c^2$ and $m_b = 3\ GeV/c^2$, the latter so as to take into account higher order QCD corrections to the direct $H \rightarrow f\bar{f}$ coupling. The choice for the top mass , once it exceeds the W-mass, does not influence appreciably neither the widths nor the branching fractions if , as we do , one is interested in signals for $M_H \leq 2m_W$. Not so , as already mentioned, for the choice of the b-quark mass. Indeed choosing a running quark mass, rather than the value $m_b = 5\ GeV$, roughly doubles all the branching ratioes in this region.

For an accurate prediction, it also very important to include decays into Intermediate Vector Bosons off-the-mass-shell . The Higgs decay width into two lepton pairs

Process	Partial Width
$q\bar{q}$	$\frac{3G_F m_q^2 m_H}{4\pi\sqrt{2}}\left(1-4\lambda_q^2\right)^{\frac{3}{2}}$
l^+l^-	$\frac{G_F m_l^2 m_H}{4\pi\sqrt{2}}\left(1-4\lambda_l m_l\right)^{\frac{3}{2}}$
W^+W^-	$\frac{G_F}{8\pi\sqrt{2}} m_H^3\left(1-4\lambda_W)\right)^{\frac{1}{2}}\left(12\lambda_W^2-4\lambda_W+1\right)$
Z^0Z^0	$\frac{G_F}{16\pi\sqrt{2}} m_H^3\left(1-4\lambda_Z)\right)^{\frac{1}{2}}\left(12\lambda_Z^2-4\lambda_Z+1\right)$
gluon gluon	$\frac{G_F}{36\pi\sqrt{2}} m_H^3\left(\frac{\alpha_s(m_H^2)}{\pi}\right)^2 \lvert\sum_q 3I_q\rvert^2$
$\gamma\gamma$	$\frac{G_F}{8\pi\sqrt{2}} m_h^3\left(\frac{\alpha}{\pi}\right) \lvert 3\sum_q Q_q^2 I_q+\sum_l Q_l^2 I_l-\lvert(3I_W+6\lambda_W)\frac{1-2\lambda_W}{1-4\lambda_W}+3\lambda_W+\frac{1}{2}\rvert\,\rvert^2$

Table 1: Partial Widths of the Higgs decay with $\lambda_k = \left(\frac{m_k}{m_H}\right)^2$ and$I_k = \int_0^1 dx \int_0^{1-x} dy \frac{1-4xy}{1-\frac{xy}{\lambda_q}-i\epsilon}$

through real or virtual Z^0 exchange can be written as follows[12, 13] :

$$\Gamma(H^0 \to 4\mu) = \int_0^{m_H^2} dQ_1^2 \int_0^{(m_H-Q_1)^2} dQ_2^2 \Gamma(H \to Z^* Z^*)\cdot \tag{1}$$

$$\cdot \frac{Q_1 \Gamma(Z^* \to \mu^+\mu^-)}{\pi\left[(Q_1^2-m_Z^2)^2+(m_Z\Gamma_Z^*)^2\right]} \frac{Q_2 \Gamma(Z^* \to \mu^+\mu^-)}{\pi\left[(Q_2^2-m_Z^2)^2+(m_Z\Gamma_Z^*)^2\right]} \tag{2}$$

where Γ_Z^* is the total width of a Z_0 of mass Q and $\Gamma(H \to Z^*Z^*)$ represents the decay of the Higgs boson into a pair of Z_0's of masses Q_1 and Q_2 and it is given by

$$\Gamma(H \to Z^* Z^*) = \frac{G_F m_H^3}{16\pi\sqrt{2}} \sqrt{1+\lambda_1^2+\lambda_2^2-2\lambda_1\lambda_2-2\lambda_1-2\lambda_2} \tag{3}$$

$$\cdot \left[1+\lambda_1^2+\lambda_2^2+10\lambda_1\lambda_2-2\lambda_1-2\lambda_2\right] \tag{4}$$

with $\lambda_i = \frac{Q_i^2}{m_H^2}$. It can easily be checked that the above equation reproduces the known expression for $H^0 \to Z^0 Z^0$ when $Q_1 = Q_2 = m_Z$. For Higgs masses near or above the 2 Z^0 threshold , the narrow width approximation in eq.(1) thus reproduces the decay probability of Higgs into 4 muons. Notice that although the above expression has been written for both Z^0's off the mass shell, the favourite kinematical configuration is one in which one Z^0 is on shell. This is the decay configuration which appears in Fig. 1. A formula similar to the above holds also for W-pairs (with a extra factor 2, to compensate for non-identical final state particles) and enters into the calculation for the total width.

In **Fig. 2** we show the branching fractions for a Higgs boson in this mass range, for some purely electromagnetic and leptonic channels : $H^0 \to \gamma\gamma$, $H^0 \to \mu^+\mu^-$ and $H^0 \to Z^*Z^* \to e^+e^-e^+e^-$. Notice that in Fig.2 , we have used eq.(1) for the width, with both Z^0's off-the-mass shell, as appropriate. To evidentiate the dependence upon the running b-quark mass, we have plotted the BR for two different values of m_b.

3 Production of H^0

The production of H^0 is significant in high energy hadron collisions and it is primarily mediated either through its (predicted) coupling to the heaviest quark (top) or the IVB's. The first production mechanism leads to production of an isolated H^0, while the latter implies the production of either a pair $H^0 - Z^0$ or of a pair $H^0 - W^\pm$. Cross-sections for direct or associated production are shown in **Fig.3** together with some typical cross-sections for processes which produce Z^0's. These cross-sections are calculated using parton densities from EHLQ[14], set 2, except for Z^0 inclusive production, for which we have followed the calculation by Altarelli et al. [15].

One can see that the reduction of about a factor 10^2 between direct and associated production cross-section may be compensated by

- the signature of the presence of the Z^0 in the debris of the event and perhaps also
- the more reliable estimate of the cross-section since the properties of the Z^0 (mass, couplings, etc.) are better known than the ones of the top and more immediately related to H^0.

Although higher by about a factor 2 (and more , if branching fractions of the IVB into leptonic channels are taken into account), the cross-section for $H^0 - W^\pm$ has not been shown, since the process $H^0 - Z^0$ is free of t-quark associated backgrounds and thus highly preferable.

The inclusive selection of a Z^0 is an excellent precursory signature toward $H^0 - Z^0$ events as shown in Fig.3 , where one can see that typically $10^{-4} \div 10^{-5}$ of Z^0 events [15] may contain an H^0 depending on its mass. As a comparison, if the isolated H^0 production (in this mass range the cross-section is of the order of few tenths of a nanobarn) is related to the inelastic cross-section, the corresponding ratio is $10^{-8} \div 10^{-9}$!

The production of Z^0 pairs has a cross-section which is approximately ten times larger than the one for $H^0 - Z^0$ events. It therefore follows that this production mode can be useful for H^0 detection only if one where to observe the Higgs boson in a decay mode inaccessible to the Z^0. Such is the decay of Higgs into two photons, since due to Yang's theorem [16] , the mode $Z^0 \to \gamma\gamma$ is forbidden.

4 Event Rates and Background

We can now compare cross-sections for direct Higgs production and decay into two lepton pairs , with and without cuts on the lepton invariant masses, with the cross-section for associated Higgs-Z^0 production and decay into one pair of photons and one lepton pair, respectively. This comparison is shown in **Fig.4**. In this figure we also show cross-section for direct Higgs production and decay into $\gamma\gamma$. From this figure, one can see that the intermediate mass H^0 ($M_H \lesssim 2M_Z$) can be detected by two partially overlapping methods :

- In the alternative that the mass of H^0 falls below threshold for a pair of real particles, it is possible to attempt detection - still based on inclusive H^0 production - with the reaction $H \to Z_1^0 + Z_2^* \to e_1^+ + e_1^- + e_2^+ + e_2^-$ but with Z_2^* off-the-mass-shell. An appropriate cut ($M_2 \geq 0.6M_Z$) must be introduced in the invariant mass of M_2 of the $e_2^+ + e_2^-$ pair in order to remove events in which a virtual photon γ_2^* is exchanged in the place of Z_2^* [17, 18, 19]. On the other hand, the presence of the Z^0 propagator makes the distribution of M_2 peak sharply toward its highest possible value. This is method is valid, but it runs out of rate when $M_H \leq 140\ GeV/c^2$.
- The decay channel $H \to \gamma\gamma$ is of considerable interest since (i) it is sizeable for all H^0-masses below the IVB threshold (ii) it cannot be masked by Z^0's. However, unless an extraordinarily sharp mass resolution is ensured, the H^0-mass peak from inclusive production will remain buried within the QCD continuum primarily due to $q\bar{q} \to \gamma\gamma$.

From the above considerations we conclude that in order to have a clearly identifiable signal for a Higgs boson in the Z^0mass region, one must make use of the associated $H^0 - Z^0$ production, because of the far greater probability of finding an $H \to \gamma\gamma$ event when in coincidence with a $Z^0 \to e^+ + e^-$ signature. However, in order to be able to collect an acceptable number of events, the integrated luminosity must be correspondingly larger. In addition, use must be made of events from $Z^0 \to \mu^+\mu^-$. In Table 2, we show the expected number of events for this production channel, assuming an integrated luminosity of 5x10^5 pb^{-1} at the LHC, for all Higgs bosons produced within $\pm$ 2.5 units of rapidity, and with two different cuts on the photon transverse momentum (see later discussion).

Before concluding that the number of events, although not large, could be adequate, we must examine resolution and intrinsic background problems. There is in fact a potentially dangerous background constituted by γ pairs emitted,through QED bremsstrahlung, from the initial quark-antiquark legs. To eliminate some of this background, one must introduce appropriate cuts on the photon transverse momentum. One can impose a generic cut $p_t^\gamma \geq 30\ GeV$ on the photons , and assume that a

M_{Higgs}	# *Events* $p_t^\gamma \geq 30 GeV$	# *Events* $p_t^\gamma \geq 20 GeV$
80 GeV	19	31
100 GeV	25	34
120 GeV	25	30
140 GeV	16	17

Table 2: **Table 2 : HZ**$\rightarrow \gamma\gamma l^+ l^-$

resolution $\Delta M = 1\ GeV/c^2$ can be achieved. With these values of the parameters, we see from **Fig.5a** that the signal is well visible above the background[20]. To increase the statistical significance, one might try to adopt a less stringent cut. This was done in **Fig. 5b** where the cut on the photon transverse momentum is $p_t^\gamma \geq 20\ GeV/c^2$. The number of events from the signal increases , as shown in Table 2, and so does the background[20]. The signal however remains well visible.

5 Conclusions

We have examined the rare decay processes $H^0 \rightarrow Z^*Z^*$ and $H \rightarrow \gamma\gamma$ for an intermediate mass Higgs produced directly and in association with a Z^0 . Upon imposing some reasonable cuts to eliminate part of the intrinsic background from $Z\gamma^*$ for one process and $Z^0\gamma\gamma$ for the other, it appears that for a Higgs boson such that $M_H \approx m_Z$, the process $pp \rightarrow Z^0 H \rightarrow l^+l^-\gamma\gamma + X$ has a good signal to noise ratio and a number of events which is rather small, but adequate provided a very high luminosity is available, i.e. L=5x10$^{34} cm^{-2} sec^{-1}$. We notice that the cross-section for direct Higgs production and decay into $\gamma\gamma$ is much larger (and so it is for the event rate), but given the large background which accompanis this process, we believe the signature discusses here to be, if not competitive, at least complementary with $H \rightarrow \gamma\gamma$. We think that the process $pp \rightarrow Z^0 H \rightarrow l^+l^-\gamma\gamma + X$ should be seriously considered at the LHC, as a mean to discover the Higgs boson or to exclude its existence in the mass range just above the region accessible to LEP200, i.e . $80 \leq M_H \leq 130 GeV/c^2$.

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Figure Captions

Fig.1 Decay width for an intermediate mass Higgs boson decaying into : WW^* and ZZ^* with both charges included for the W's (dot-dashes), W^+W^- and Z^0Z^0 pairs (dashes), $b\bar{b}$-pairs of mass $m_b = 3\ GeV$ (dots), two photons (dashes) with $m_{top} = 90\ GeV$, $\mu^+\mu^-$-pairs (dots). Full line is the total width.

Fig. 2 Decay fractions for an intermediate mass Higgs into two photons (dots), $\mu^+\mu^-$pairs (dashes) and 4 electrons (full line) from all , on and off-shell, Z^0Z^0 pairs, with $m_{top} = 90\ GeV/c^2$ and $m_b = 3$ and $5\ GeV/c^2$.

Fig. 3 Total cross-section in proton-proton collisions at $\sqrt{s} = 16\ TeV$ for the following processes : (1) inclusive Z^0 production to order α_s as from ref. 15, varying between indicated limits (dots) because of theoretical errors from QCD,(3) production of an isolated Higgs boson from gluon-gluon fusion with different top mass values (full line) and $|y_{Higgs}| \leq 2.5$, (4) production of Z^0 pairs from quark-antiquark annihilation (dashes) with $|y_Z| \leq 2.5$, (5) associated production of Higgs and Z^0 boson (full line) with $|y_{H,z}| \leq 2.5$.Parton densities are from ref.14, mode 2.

Fig.4 Total production cross-section for the processes :

$pp \to HZ + X \to \gamma\gamma e^+e^- + X$ (full line)

$pp \to H + X \to \gamma\gamma + X$ (dots)

$pp \to Z^*Z^* + X \to e_1^+e_1^- + e_2^+e_2^- + X$ with

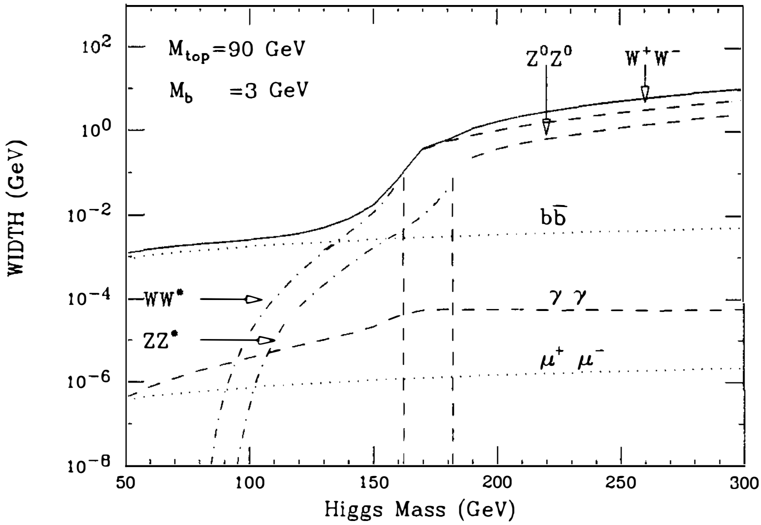
(i) no special selection (dashes)

(ii) one lepton pair such that $|M_{e^+e^-} - m_Z| \leq \Gamma_Z$ and the other such that $M_{e^+e^-} \geq 20\ GEV$ (dotdashes)

(iii) one lepton pair such that $|M_{e^+e^-} - m_Z| \leq \Gamma_Z$ and the other such that $M_{e^+e^-} \geq 50\ GeV$ (dotdashes).

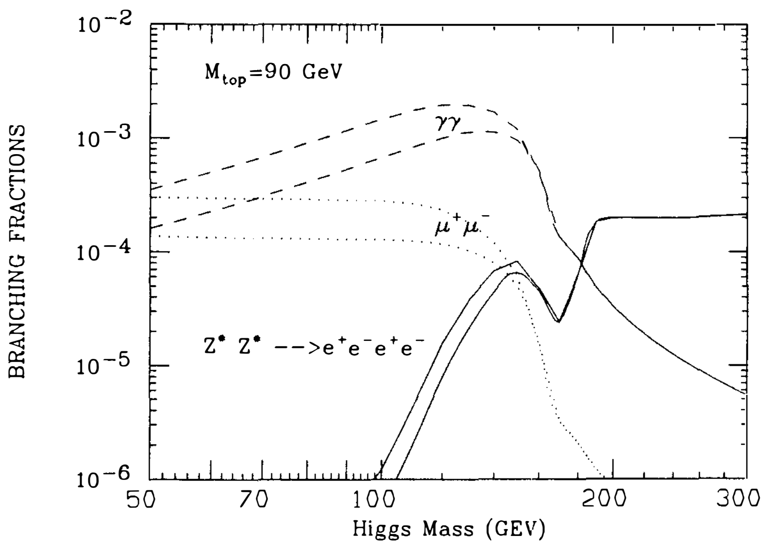
Everywhere is $|y_Z| \leq 2.5$

Fig.5 Differential cross-section for $pp \to Z\gamma\gamma + X$ vs. the invariant mass of the $\gamma\gamma$ system at $\sqrt{s} = 16\ GeV$. Histograms are for the purely QED process, i.e. Z^0 production and double bremsstrahlung from initial quark legs , and for production of a Higgs boson of mass $M_{Higgs} = 80, 100, 120, 140\ GeV/C^2$. In Fig.5a the cut on each single photon is $p_t^\gamma \geq 30\ GeV$, while in Fig.5b is $p_t^\gamma \geq 20\ GeV$.In both figures, $|y_Z| \leq 2.5$.



M_{top}=90 GeV
M_b =3 GeV
Z^0Z^0
W^+W^-
$b\bar{b}$
WW*
ZZ*
$\gamma\ \gamma$
$\mu^+\ \mu^-$
WIDTH (GeV)
Higgs Mass (GeV)

Fig. 1



M_{top}=90 GeV
$\gamma\gamma$
$\mu^+\mu^-$
Z* Z* -->e+e-e+e-
BRANCHING FRACTIONS
Higgs Mass (GEV)

Fig. 2

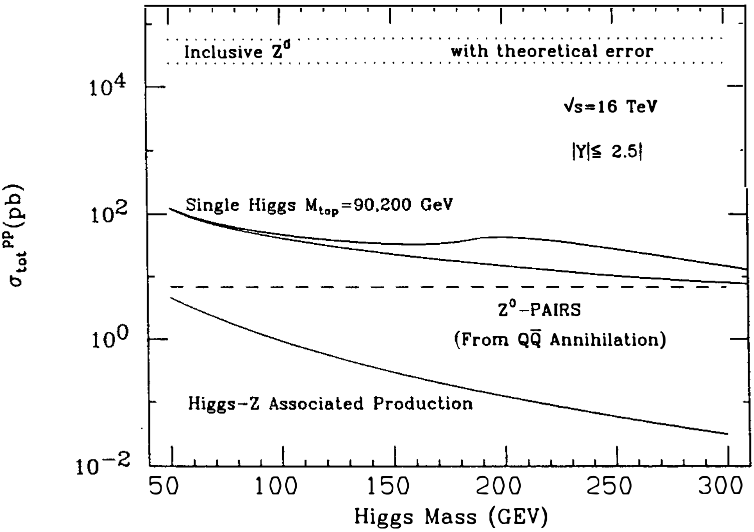

Inclusive Z^0 with theoretical error
$\sqrt{s}$=16 TeV
|Y|≤ 2.5|
Single Higgs M_{top}=90,200 GeV
Z^0-PAIRS
(From $Q\bar{Q}$ Annihilation)
Higgs-Z Associated Production
σ_{tot}^{PP}(pb)
10^4
10^2
10^0
10^{-2}
50
100
150
200
250
300
Higgs Mass (GEV)

Fig. 3

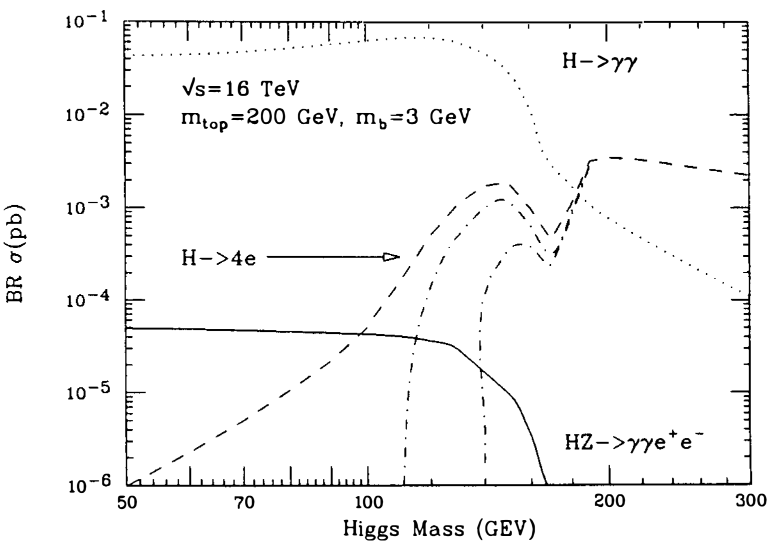

$\sqrt{s}$=16 TeV
m_{top}=200 GeV, m_b=3 GeV
H->$\gamma\gamma$
H->4e
HZ->$\gamma\gamma e^+e^-$
BR σ(pb)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
50
70
100
200
300
Higgs Mass (GEV)

Fig. 4

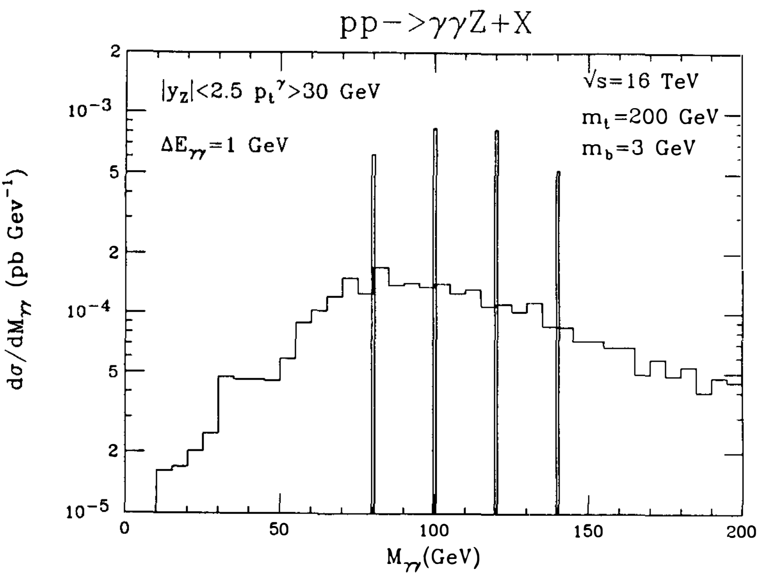

pp->γγZ+X
|y_Z|<2.5 p_t^γ>30 GeV
ΔE_γγ=1 GeV
√s=16 TeV
m_t=200 GeV
m_b=3 GeV
dσ/dM_γγ (pb Gev^-1)
M_γγ(GeV)
2
10^-3
5
2
10^-4
5
2
10^-5
0
50
100
150
200

Fig.5A

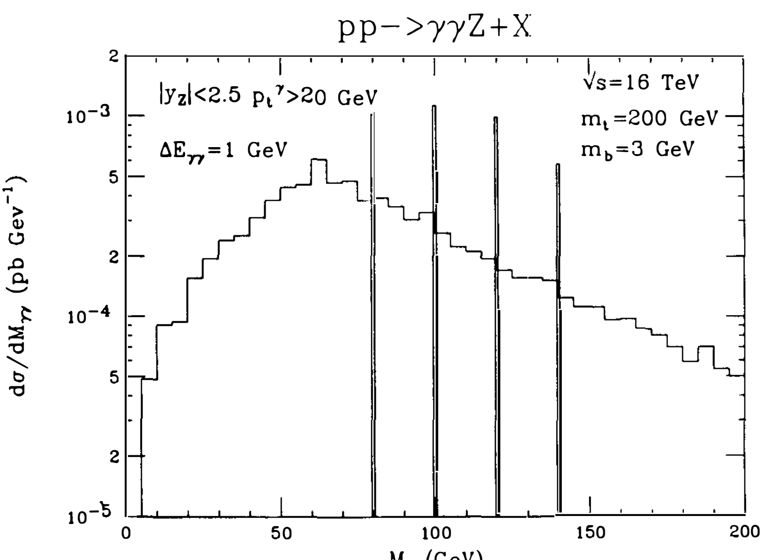

pp->γγZ+X
|y_Z|<2.5 p_t^γ>20 GeV
ΔE_γγ=1 GeV
√s=16 TeV
m_t=200 GeV
m_b=3 GeV
dσ/dM_γγ (pb Gev^-1)
M_γγ(GeV)
2
10^-3
5
2
10^-4
5
2
10^-5
0
50
100
150
200

Fig.5B