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SEARCHING FOR HIGGS AT PETRA USING THE WILCZEK MECHANISM

by

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Searching for Higgs at PETRA Using the Wilczek Mechanism

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Abstract

We present numerical estimates for the various signatures of a neutral Higgs particle produced in the radiative decays $V \rightarrow H + \gamma$, of a heavy vector onium state $V(\equiv J/\psi, \Upsilon, \Upsilon_t)$. We suggest to enhance the Higgs signal by requiring a correlation with weakly decaying states (τ, charm, bottom) or with strange particles from charm and bottom. Rates for the processes $e^+e^- \rightarrow V \rightarrow H + \gamma \rightarrow$ ≥ 1 lepton $+ \gamma +$ anything, ≥ 2 kaons $+ \gamma +$ anything are presented, and the effects of the lepton energy cuts on the first of the two processes are evaluated.

1. Introduction

Present day electro-weak gauge theories require the existence of fundamental scalar particles (in the sense of quarks and leptons) to incorporate spontaneous symmetry breaking so as to give masses to leptons, quarks and the vector bosons Z, $W^{\pm}$. The simplest scheme of incorporating the Higgs particles in a gauge model is the original version of the Weinberg-Salam theory[1], with only a single complex Higgs doublet

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

and the Higgs potential having the form[2]

$$v(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4 \tag{1}$$

Spontaneous symmetry breaking is incorporated by demanding

$$\langle \phi \rangle_0 = \begin{pmatrix} 0 \\ v/2 \end{pmatrix}$$

Three of the four real fields

$$\phi^+ \quad , \quad \phi^- = \overline{\phi^+} \quad , \quad \mathrm{Im}\ \phi = \frac{1}{i\sqrt{2}} (\phi^0 - \overline{\phi^0})$$

disappear from the theory as physical particles and their associated degrees of freedom reappear as longitudinal polarization components of the vector bosons $W^{\pm}$ and Z.

The only surviving field is Re $\phi = (\phi^0 + \overline{\phi^0})$, and the physical Higgs particle H always appears in the combination

$$\mathrm{Re}\ \phi = H + v$$

It is immediately obvious that the coupling of the Higgs to fermions and bosons will be proportional to their mass, since it is the term v which gives them masses. More specifically, one has, as a result of spontaneous symmetry breaking, the following changes in the Lagrangian

$$\frac{g_{f\phi}}{\sqrt{2}} f\bar{f}\phi + \mathrm{h.c.} \rightarrow g_{f\phi} \bar{f}f(H + v) \equiv g_{fH} \bar{f}fH + m_f \bar{f}f$$

$$\frac{g^2}{2} W_\mu^+ W^{-\mu} |\phi|^2 \rightarrow \frac{g^2}{4} W_\mu^+ W^{-\mu} (H^2 + 2Hv + v^2) \tag{2}$$

$$\equiv \frac{g^2}{4} H^2 W_\mu^+ W^{-\mu} + g_{WH} H W_\mu^+ W^{-\mu} + m_W^2 W_\mu^+ W^{-\mu}$$

so that

$$g_{fH} = m_f / v$$

$$g_{WH} = \frac{g^2 v}{2} = \frac{2 m_W^2}{v}$$

However, the combination $\frac{g^2}{4\sqrt{2}\, m_W^2}$ is identified with the Fermi-Coupling Constant

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 m_W^2}$$

which then fixes v:

$$v^2 = \frac{4 m_W^2}{g^2} = (\sqrt{2}\, G_F)^{-1}$$

This completely determines the coupling of the Higgs in the Weinberg-Salam theory with all other fermions and bosons.

Thus, the Higgs interaction is given by

$$\mathcal{L}_{int}(H) = 2^{1/4}\, G_F^{1/2}\, H\, [m_f \bar{f} f + 2 m_W^2\, W_{+\mu} W_-^{\mu}]$$

Numerically, one has for the coupling[2)]

$3.8\, \frac{m_f}{m_p} \times 10^{-3}$	for fermions
$3.8\, \frac{m_V^2}{m_p} \times 10^{-3}$	for vector mesons

On the other hand, the mass of the Higgs is arbitrary, which can immediately be realised by rewriting the Higgs potential in terms of H

$$V(H) = -\frac{\mu^2}{2}(H+v)^2 + \frac{\lambda}{4}(H+v)^4$$
$$= -\mu^2 \left(H^2 + \frac{1}{v} H^3 + \frac{1}{4v^2} H^4\right) \qquad (4)$$

The Higgs mass

$$m_H^2 = 2\mu^2 = 2\lambda v^2$$

is a free parameter since the quartic coupling λ is not known.

It has been argued that instead of having a term $-\mu^2\phi^2$ in the Lagrangian with unknown $\mu^2 = \frac{1}{2} m_H^2$. One could set $\mu^2 = 0$ and generate symmetry breaking dynamically through radiative corrections to the effective potential[3)]. In this case the Higgs boson mass is generated due to radiative corrections and is given by the expression

$$m_H^2 = \frac{3\alpha^2}{8\sqrt{2}\,G_F}\left\{\frac{2+\sec^4\theta_w}{\sin^4\theta_w} - o\left(\frac{m_f^4}{m_w^4}\right)\right\} \qquad \text{For } m_F/m_W << 1 \qquad (5)$$

This gives m_H = 10.42 GeV for $\sin^2\theta_w = 0.2$
= 8.58 GeV for $\sin^2\theta_w = 0.25$

The phenomenology of a ~10 GeV Higgs particle has been recently discussed by Ellis et al.[4]. In particular, depending upon m_H, there can be strong mixing between H and η_b, the scalar (0^+) analogue of the $\Upsilon(9.46)$, resulting in the decays η_b $(0^+) \rightarrow c\bar{c}$, $\tau^+\tau^-$. The rates depend very sensitively on the mass difference ($m_H - m_{\eta_b}$) and one has to be extremely lucky to discover Higgs from such induced mixing effects!

In the absence of dynamical symmetry breaking, however, m_H is undetermined. Even in this case m_H is bounded from below. If one takes into account the self interaction of the Higgs as well as its interaction with other fermions and bosons, the self-coupling λ is constrained. The one-loop correction to the Higg potential leads to the bound (5)

$$m_H^2 > \frac{3}{16\pi^2 V^2} \sum_V m_V^4 > 5.2 \text{ GeV}^2 \qquad (6)$$

giving m_H > 2.3 GeV.

The upper bound on the Higgs mass comes by imposing partial wave unitarity. The self coupling λ cannot be arbitrarily large otherwise the perturbative expansion for corrections due to Higgs exchange breaks down. This limit is however not very useful since it gives

$M_H \lesssim 1$ TeV !

All told, the mass of the Higgs lies in the range 1 TeV > m_H > 2.3 GeV if the $-\mu^2\Phi^2$ term is present in the Lagrangian.

It is therefore imperative to search for a neutral Higgs experimentally. With the onset of the high energy e^+e^- machines PETRA and PEP a much bigger mass range has become available for such a search. Unfortunately, the H^0, in the

Weinberg-Salam theory, cannot be pair produced in e^+e^- annihilation due to the Bose symmetry. The only viable way to find a low mass Higgs is in the radiative decays of a heavy vector onium state $V \to H + \gamma$, the so-called Wilczek mechanism[7]. However, the experimental difficulties in finding a monoenergetic photon line with $E_\gamma \lesssim 5$ GeV in a background of multiple π^0s encounter in hadronic final states, are very hard to overcome due to the small branching ratio for the process $(V \to H + \gamma)$. We suggest to enhance the Higgs signal by requiring final states containing the decay products of heavy particles, which are dominantly produced in the H decay. The dominant decay modes of $b\bar{b}$, $c\bar{c}$ and $\tau\bar{\tau}$ pairs contain at least one lepton in the final state, while the dominant decay modes of $b\bar{b}$, $c\bar{c}$ and $s\bar{s}$ pairs contain $K\bar{K}$ pairs in the final states. We have therefore calculated the rates for the processes

$$\begin{aligned} e^+e^- \underset{\gamma}{\to} V \to H + \gamma &\to \geq 1 \text{ lepton} + \gamma + \text{anything} \\ &\to \geq 2 \text{ kaons} + \gamma + \text{anything}. \end{aligned}$$

In order to get a realistic estimate it is necessary to take into account the energy resolution of the machine which obeys $\frac{\Delta\Gamma}{E} \propto E$, thus reducing the height of the peak at $E_{CM} = m_V$. Also important is the effect of the lepton energy cut-off necessary in identifying an electron or a muon. We calculate the entire lepton energy spectra for the processes

$$e^+e^- \to V \to H + \gamma \to (\underset{\lfloor \to \ell^+ \nu_\ell \nu_\tau}{\tau^+\tau^-}, \quad \underset{\lfloor \to s(\ell\nu_\ell,\ u\bar{d})}{c\bar{c}}, \quad \underset{\lfloor \to c(\ell\nu_\ell,\ \bar{u}d,\ \bar{c}s) \;\; \lfloor \to s(\ell\nu_\ell,\ u\bar{d})}{b\bar{b}}) + \gamma$$

This is then used to determine the effect of the lepton energy cut-off on the rates for the process involving leptons. The most promising case is the $T_{t\bar{t}}$ (toponium) decay $T_{t\bar{t}} \to H + \gamma$, where satisfactory counting rates are obtained for a Higgs having a mass $m_H = (m_{T_{t\bar{t}}}$ - a few GeV).

In Section 2 we review the Wilczek mechanism[7]. Rate estimates are presented in Section 3.

2. The Wilczek Mechanism

Presumably, the most promising way of finding the neutral Higgs if $m_{H^0} < m_{\Upsilon t\bar{t}}$ is the one proposed by Wilczek [7]. The basic idea is that since the coupling of the Higgs with the fermions is proportional to the mass of the fermions, one should look for H in the decay products of the heavy $Q\bar{Q}$ systems, for instance in the decays of $\Upsilon(9.4)$ and the toponium $\Upsilon_{t\bar{t}}$.

The rate for the decay

$$V \to H + \gamma \tag{7}$$

can be calculated from Fig. (1) and is conveniently expressed in terms of the leptonic rate of V as [4,7]:

$$\frac{\Gamma(V \to H\gamma)}{\Gamma(V \to e^+e^-)} = \frac{G_F m_V^2}{4\sqrt{2}\pi\alpha}\left[1 - \frac{m_H^2}{m_V^2}\right] \tag{8}$$

If $\frac{m_V - m_H}{m_V} \ll 1$, then the rate for the decay (7) should be corrected to incorporate the characteristic dipole k^3 behaviour [4]:

$$\frac{\Gamma(V \to H\gamma)}{\Gamma(V \to e^+e^-)} = \frac{G_F m_V^2}{4\sqrt{2}\pi\alpha}\left[1 - \frac{m_H^2}{m_V^2}\right] \frac{\left[\frac{m_V}{2}\left(1 - \frac{m_H^2}{m_V^2}\right)\right]}{\left[\frac{m_V}{2}\left(1 - \frac{m_H^2}{m_V^2}\right) + \Delta\right]} \tag{9}$$

where Δ is an onium potential dependent parameter typically $\sim$ 1 GeV. The branching ratio for $V \to H + \gamma$ can then be obtained by measuring the leptonic branching ratio.

The decays of H are governed again by its preferential coupling to the heaviest available fermion pair. Thus

$$\Gamma(H \to Q\bar{Q}) = \frac{3 G_F m_Q^2 m_H}{4\sqrt{2}\pi}\left[1 - \frac{4 m_Q^2}{m_H^2}\right]^{3/2}$$

$$\Gamma(H \to \ell^+\ell^-) = \frac{G_F^2 m_\ell^2 m_H}{4\sqrt{2}\pi}\left[1 - \frac{4 m_\ell^2}{m_H^2}\right]^{3/2} \tag{10}$$

The factor 3 in $\Gamma(H \to Q\bar{Q})$ is due to colour. There is another decay mode, $H \to 2$ gluons, which is potentially useful for a very massive Higgs $\left(\frac{m_H}{m_t} \sim \left(\frac{\alpha_s}{\pi}\right)^{-1}\right)$ The $H \to 2$ gluons width is:

$$\Gamma(H \to gg) = \frac{G_F N^2}{36\sqrt{2}\pi}\left(\frac{\alpha_s}{\pi}\right)^2 m_H^3 \tag{11}$$

where N is the number of heavy fermion pairs.

However, if $m_H < m_{\Upsilon t\bar{t}}$ then the branching ratio $\frac{\Gamma(H \to gg)}{\Gamma(H \to all)}$ is miniscule.

This in some sense helps to distinguish the decay (7) from the normal radiative decays

$$\Upsilon, \Upsilon_t \to (\eta_b, \eta_t) + \gamma$$
$$\hookrightarrow 2g$$

This is also the reason why we emphasize the leptonic final states, which necessarily involve weak decays.

3. Rate Estimates

In table 1 we have presented the product branching ratios $\frac{\Gamma(V \to H\gamma)}{\Gamma(V \to all)} \frac{\Gamma(H \to Q\bar{Q}, \ell\bar{\ell})}{\Gamma(H \to all)}$ for some representative values of m_H. For $m_{\Upsilon t\bar{t}}$ we have used the values 30.0 GeV [8], 40.0 GeV [9] and 55.0 GeV [10] covering most theoretical predictions about m_t.

For numerical estimates in this note we have used the following masses

$$m_u = m_d = 0.3 \text{ GeV}$$
$$m_s = 0.5 \text{ GeV}$$
$$m_c = 1.65 \text{ GeV}$$
$$m_b = 5.0 \text{ GeV}$$
$$m_{\tau^\pm} = 1.78 \text{ GeV}$$

A glance at table 1 shows that the search of a low mass Higgs in the decays of J/ψ and $\Upsilon(9.46)$ is beset by frustratingly small branching ratios. However, because of the m_V^2 behaviour of $\frac{\Gamma(V \to H\gamma)}{\Gamma(V \to e^+e^-)}$, the Higgs search appears much more promising in the decays of $\Upsilon_{t\bar{t}}$. In what follows we concentrate on the decays $\Upsilon_{t\bar{t}} \to H + \gamma$.

If $m_H > 2m_D$, then the most prominent channels for Higgs search are

$$V \to H\gamma \to (\geq 1 \text{ lepton}) + \gamma + \text{anything} \qquad (12)$$
$$\to (K^+K^-, K^\pm K^0_s, 2K^0_s) + \gamma + \text{anything}$$

In this section, we estimate the rates for the processes (12) and calculate the effect of lepton energy cut on the various lepton associated signals of the Higgs decay. The semi-leptonic branching ratios as well as the lepton energy spectra of the $\tau^{\pm}$ [11] and charm [12] are now known sufficiently precisely and are in good agreement with QCD calculations [13]. For the bottom quark (meson) decays we assume the dominance of the $b \to c$ transition, which is expected theoretically[14]. The most important bottom decays then are

$$b \to c\ (\ell \bar{\nu}_\ell\ ,\ \bar{u} d\ ,\ \bar{c} s) \qquad \ell = e, \mu, \tau$$
$$\hookrightarrow s\ (e^+ \nu_e\ ,\ \mu^+ \nu_\mu\ ,\ u \bar{d})$$

The relative rates $\dfrac{b \to (\geq 1\, \ell) + \text{anything}}{b \to \text{all}}$ can be calculated using the free quark decay model[15]. However, since experimentally[16]

$$\frac{\Gamma(c \to \ell + \text{anything})}{\Gamma(c \to \text{all})} \simeq 0.1 \qquad \ell = e, \mu$$

as compared to the free quark model result 0.2 it appears that there is some non-leptonic enhancement. To lowest order in α_S, these enhancement factors are [17]:

$$\begin{aligned} A_c &= 1.8 \\ A_b &= 1.4 \\ A_t &= 1.2 \end{aligned} \qquad (13)$$

This suggests that the non-leptonic enhancement in bottom decays is smaller compared to charm. Since there are more decay channels available to the bottom quark as opposed to charm we believe that the two effects compensate each other to give [18]:

$$\frac{\Gamma(b \to c + e \nu_e)}{\Gamma(b \to \text{all})} \approx \frac{\Gamma(c \to s + e^+ \nu_e)}{\Gamma(c \to \text{all})} \gtrsim 0.1 \qquad (14)$$

We have combined (14) with the phase space to get the following branching ratios:

$\dfrac{b \to c +}{b \to \text{all}}$	$e^- \bar{\nu}_e$	$\mu^- \bar{\nu}_\mu$	$\tau^- \bar{\nu}_\tau$	$\bar{c} s$	$\bar{u} d$	(15)
	0.1	0.1	0.03	0.2	0.57	

The estimates of (15) are then combined with the measured leptonic branching ratio of $\tau^{\pm}$ 11)

$$\frac{\Gamma(\tau^{\pm} \to \ell^{\pm} \nu_\ell \nu_\tau)}{\Gamma(\tau^{\pm} \to \text{all})} \simeq 0.16 \qquad \ell = e, \mu$$

and the semi-leptonic branching ratio for charm.

The resulting rates for the multileptonic rates are presented in table 2
This leads to the estimates

$$\begin{aligned} \frac{\tau^+\tau^- \to \geq 1\ell}{\tau^+\tau^- \to \text{all}} &= 0.54 \\ \frac{c\bar{c} \to \geq 1\ell}{c\bar{c} \to \text{all}} &= 0.36 \\ \frac{b\bar{b} \to \geq 1\ell}{b\bar{b} \to \text{all}} &= 0.64 \end{aligned} \tag{16}$$

To estimate the rates for the process

$$V \to H\gamma \to \gamma + (K^+K^-, K^{\pm}K^0_s, 2K^0_s) + \text{anything}$$

we have assumed

$$s\bar{s} \to \left(\frac{4}{3}\right)^2 (K^+K^-, K^{\pm}K^0_s, 2K^0_s)$$

and, depending on m_H, have added the various components from the decays H →

$$s\bar{s}, \quad c\bar{c} \to s\bar{s}, \quad b\bar{b} \to c\bar{c} \to s\bar{s}$$

Having determined the branching ratios, all we need to calculate the counting rates is the production cross section for $e^+e^- \to \Upsilon_{t\bar{t}}$. We estimate this by scaling the energy resolution (ΔE) and the height of the resonance (h) using the scaling relation

$$\frac{(\Delta E)_{\Upsilon}}{(\Delta E)_{J/\psi}} = \frac{\sqrt{\rho_{DORIS}}\; m^2_{\Upsilon_{t\bar{t}}}}{\sqrt{\rho_{PETRA}}\; m^2_{J/\psi}} \tag{17}$$

where $\rho_{DORIS,\ PETRA}$ are the radii of the DORIS and PETRA rings, respectively.
The height of the peak can then be determined by using

$$\frac{(h\,\Delta E)_{\Upsilon_{t\bar{t}}}}{(h\,\Delta E)_{J/\psi}} = \frac{m^2_{J/\psi}}{m^2_{\Upsilon_{t\bar{t}}}} \tag{18}$$

This gives the height of $\Upsilon_{t\bar{t}}$ in units of the height of the J/ψ peak (measured in terms of R at $\sqrt{s} = m_{J/\psi}$). Using[19])

$$\begin{aligned} \text{PETRA} &= 192 \text{ m} \\ \text{DORIS} &= 12 \text{ m} \\ (J/\psi) &= 2300 \text{ nb} \end{aligned} \tag{19}$$

we get for example $h(m_{\Upsilon t\bar{t}} = 30 \text{ GeV}) = 1.06$ nb. For other values of $m_{\Upsilon t\bar{t}}$, h can be obtained using the relations (17) and (18).

The counting rates for the processes

$$e^+e^- \to \Upsilon_{t\bar{t}} \to H\gamma \to \begin{array}{l} \geq 1 \text{ lepton} + \gamma + \text{anything} \\ \geq (K^+K^-, K^\pm K^0_S, 2K^0_S) + \gamma + \text{anything} \end{array}$$

are plotted in Fig. (2) assuming an integrated luminosity of $2 \times 10^4 \text{nb}^{-1}$. This corresponds to ~4 weeks effective running time with $\mathcal{L} = 10^{31}/\text{cm}^2\text{sec}$ ($T = 4 \times 6 \times 24 \times 3600$ sec).

In table 4 we present the fraction of events surviving an assumed lepton energy cut-off. In Fig. (3) we plot the number of events for the process $e^+e^- \to \Upsilon_{t\bar{t}} \to H + \gamma \to (\geq 1 \ell^\pm + \gamma + \text{anything})$ taking into account the effect of the lepton energy cut, as indicated. We remark that the counting rates are still manageable, and allow a search for Higgs up to a mass very close to $m_{\Upsilon t\bar{t}}$.

Discussion

The calculations presented in this report are motivated by the need to check the hypothesis that $m_{H0} < m_{\Upsilon t\bar{t}}$ and can be used to find an H^0 at PETRA and PEP if such a low mass Higgs exists or else to set a limit on m_{H0}. The only unknown in the calculations is the mass of $\Upsilon_{t\bar{t}}$. The numerical estimates could be made much more precise once the toponium is discovered. However, we have calculated the effects of a Higgs using a rather large range for $m_{\Upsilon t\bar{t}}$. This then also makes the calculations useful if there is yet another Onium beyond $\Upsilon_{t\bar{t}}$. It is clear from Figs.(2) and (3) that because of the behaviour $\sigma(e^+e^- \xrightarrow[\gamma]{} V) \sim 1/E^2_{c.m.}$ and $\frac{\Delta E}{E_{c.m}} \sim E_{c.m.}$

the counting rates plunge down very fast as the mass of the Onium increases. Curiously, the best signature of H^0 are in the decays of a $\Upsilon_{t\bar{t}}$ having a mass of about 30 GeV.

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Table Captions

Table 1: Product branching ratio $\frac{\Gamma(V \to H^\circ \gamma)}{\Gamma(V \to all)} \frac{\Gamma(H^\circ \to q\bar{q}, \ell^+\ell^-)}{\Gamma(H^\circ \to all)}$

for the various assumed values of the Higgs mass

a) $V = J/\psi$

b) $V = \Upsilon(9.46)$

c) $V = \Upsilon_{t\bar{t}}$ with $m_{\Upsilon t\bar{t}} = 30.0$, 40.0 and 55.0 GeV

Table 2: Hadronic and Leptonic branching ratios for the decay $H^0 \to \tau^+\tau^-$, $c\bar{c}$, $b\bar{b}$. The ratios $\sigma_{i\ell}$ are defined as

$\sigma_{i\ell} \equiv \frac{H^\circ \to \tau^+\tau^- \to i\ell + \text{anything}}{H^\circ \to \tau^+\tau^-}$ for example for $\tau^+\tau^-$ mode.

Table 3: Fraction of leptonic events surviving a cut of 0.25, 0.5 and 1.0 GeV in the decays $H \to \tau^+\tau^-$, $c\bar{c}$, $b\bar{b} \to i\ell$ + anything for the various assumed values of m_H.

Figure Captions

Fig. 1 The radiative decay of a heavy vector meson $V \to H + \gamma$

Fig. 2 Expected number of events for the processes

$e^+e^- \to V \to H + \gamma \to \geqslant 2(K^\pm, K_S^0) + \gamma +$ anything and

$e^+e^- \to V \to H + \gamma \to \geqslant 1$ lepton $+ \gamma +$ anything

for a fixed integrated luminosity = $2. \times 10^4$ nb^{-1}.
For energy resolution and height of the peak at $\sqrt{s} = m_V$ see text.

Fig. 3 The effect of lepton energy cut-off on the cross-section for the process $e^+e^- \to V \to H + \gamma \to 1$ lepton $+ \gamma +$ anything. We have assumed $E_e^{cut}=0.5$ GeV and $E_\mu^{cut}=1.0$ GeV. For details about the lepton energy spectra see text.

$V = J/\psi(3.1)$

m_H(GeV) \ Mode	$\mu^+\mu^-$	$u\bar{u} + d\bar{d}$	$s\bar{s}$
2.5	$< 2.3 \times 10^{-7}$	$< 9.2 \times 10^{-6}$	$< 1. \times 10^{-5}$
3.0	$< 4.1 \times 10^{-8}$	$< 9.7 \times 10^{-6}$	$< 2 \times 10^{-6}$

(a)

$V = \Upsilon(9.46)$

m_H(GeV) \ Mode	$\mu^+\mu^-$	$\tau^+\tau^-$	$u\bar{u} + d\bar{d}$	$s\bar{s}$	$c\bar{c}$
2.5	2.9×10^{-6}	-	1.4×10^{-4}	1.4×10^{-4}	-
3.0	2.4×10^{-6}	-	1.1×10^{-4}	1.35×10^{-4}	-
3.6	2.2×10^{-6}	2×10^{-6}	1.0×10^{-4}	1.3×10^{-4}	-
4.0	1.35×10^{-6}	3.6×10^{-5}	6.2×10^{-5}	8.2×10^{-5}	4.3×10^{-5}
8.0	$\lesssim 1 \times 10^{-7}$	1.9×10^{-5}	4.4×10^{-6}	6.2×10^{-6}	4.6×10^{-5}

(b)

$V = \Upsilon(t\bar{t})$

m_H (GeV) \ Mode, $m_{\Upsilon t\bar{t}}$	$\mu^+\mu^-$			$\tau^+\tau^-$						$s\bar{s}$			$c\bar{c}$			$b\bar{b}$		
	30	40	55	30	40	55	30	40	55	30	40	55	30	40	55	30	40	55
2.5	6.7×10^{-5}	1.3×10^{-4}	2.3×10^{-4}	-	-	-	2.5×10^{-3}	5.1×10^{-3}	9.6×10^{-3}	3.5×10^{-3}	6.2×10^{-3}	2.3×10^{-2}	-	-	-	-	-	-
4.0	3.8×10^{-5}	6.8×10^{-5}	1.3×10^{-4}	1×10^{-3}	1.8×10^{-3}	3.4×10^{-3}	1.7×10^{-3}	3.1×10^{-3}	6.0×10^{-3}	2.3×10^{-3}	4.1×10^{-3}	7.8×10^{-2}	1.2×10^{-3}	2.2×10^{-3}	4.1×10^{-3}	-	-	-
10.0	6.1×10^{-6}	1.1×10^{-5}	2.25×10^{-4}	1.4×10^{-3}	2.7×10^{-3}	5.2×10^{-3}	3.0×10^{-4}	5.5×10^{-4}	1.1×10^{-3}	4.1×10^{-4}	7.7×10^{-4}	1.5×10^{-3}	3.5×10^{-3}	6.7×10^{-3}	1.3×10^{-2}	-	-	-
15.0	1.25×10^{-6}	2.6×10^{-6}	5.2×10^{-6}	3.3×10^{-4}	6.7×10^{-4}	1.4×10^{-3}	6.0×10^{-5}	1.2×10^{-4}	2.5×10^{-4}	8.5×10^{-5}	1.7×10^{-4}	3.5×10^{-4}	8.3×10^{-4}	1.7×10^{-3}	3.5×10^{-3}	3.5×10^{-3}	7.1×10^{-2}	1.45×10^{-2}
20.0	6.5×10^{-7}	1.6×10^{-6}	3.4×10^{-6}	1.85×10^{-4}	4.4×10^{-4}	9.6×10^{-4}	3.2×10^{-5}	7.6×10^{-5}	1.7×10^{-4}	4.4×10^{-5}	1.05×10^{-4}	2.3×10^{-4}	4.8×10^{-4}	1.1×10^{-3}	2.5×10^{-3}	2.9×10^{-3}	6.8×10^{-3}	1.5×10^{-2}
25.0	-	1.1×10^{-6}	2.7×10^{-6}	9×10^{-5}	3.1×10^{-4}	7.7×10^{-4}	1.5×10^{-5}	5.3×10^{-5}	1.3×10^{-4}	2.1×10^{-5}	7.4×10^{-5}	1.8×10^{-4}	2.3×10^{-4}	8.1×10^{-4}	2.0×10^{-3}	1.6×10^{-3}	5.7×10^{-3}	1.4×10^{-2}
30.0	-	7.5×10^{-7}	2.2×10^{-6}	-	2.1×10^{-4}	6.3×10^{-4}	-	3.6×10^{-5}	1.1×10^{-4}	-	5.0×10^{-5}	1.5×10^{-4}	-	5.4×10^{-4}	1.6×10^{-3}	-	4.2×10^{-3}	1.3×10^{-2}
45.0	-	-	9.7×10^{-7}	-	-	2.7×10^{-4}	-	-	4.7×10^{-5}	-	-	6.5×10^{-5}	-	-	7.1×10^{-4}	-	-	6.0×10^{-3}
50.0	-	-	5.5×10^{-7}	-	-	1.6×10^{-4}	-	-	2.7×10^{-5}	-	-	3.8×10^{-5}	-	-	4.0×10^{-4}	-	-	3.1×10^{-3}

(c)

Production mode	$\sigma_{0\ell}$	$\sigma_{1\ell}$	$\sigma_{2\ell}$	$\sigma_{3\ell}$	$\sigma_{4\ell}$
$\tau^+\tau^-$	0.46	0.44	0.1	-	-
$c\bar{c}$	0.64	0.32	0.04	-	-
$b\bar{b}$	0.36	0.42	0.18	3.5×10^{-2}	2.5×10^{-3}

Table 2

E_ℓ cut	$E_\ell \geq$ 0.25 GeV				$E_\ell \geq$ 0.5 GeV				$E_\ell \geq$ 1.0 GeV			
m_H (GeV) \ mode	$\tau^+\tau^-$	$c\bar{c}$			$\tau^+\tau^-$	$c\bar{c}$			$\tau^+\tau^-$	$c\bar{c}$		
4.0	0.95	0.9	-	-	0.74	0.48	-	-	0.16	6×10^{-3}	-	-
10.0	0.95	0.9	-	-	0.86	0.64	-	-	0.68	0.27	-	-
15.0	0.95	0.91	0.99	0.89	0.90	0.71	0.96	0.55	0.78	0.4	0.78	0.11
20.0	0.96	0.92	0.99	0.90	0.92	0.75	0.96	0.58	0.84	0.5	0.8	0.17
25.0	0.97	0.92	0.99	0.90	0.93	0.78	0.96	0.6	0.87	0.56	0.81	0.21
30.0	0.97	0.93	0.99	0.90	0.95	0.81	0.96	0.63	0.89	0.61	0.83	0.26
45.0	0.98	0.95	0.99	0.91	0.97	0.85	0.96	0.68	0.93	0.7	0.87	0.37

Table 3

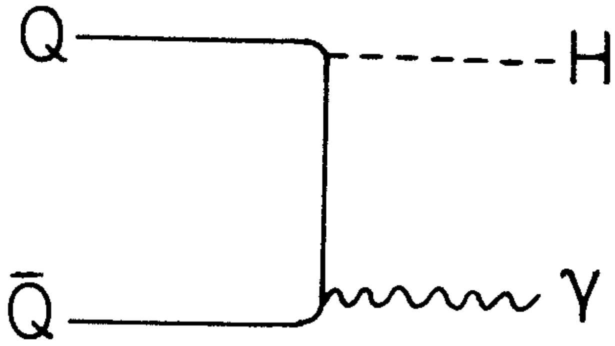


Fig. 1

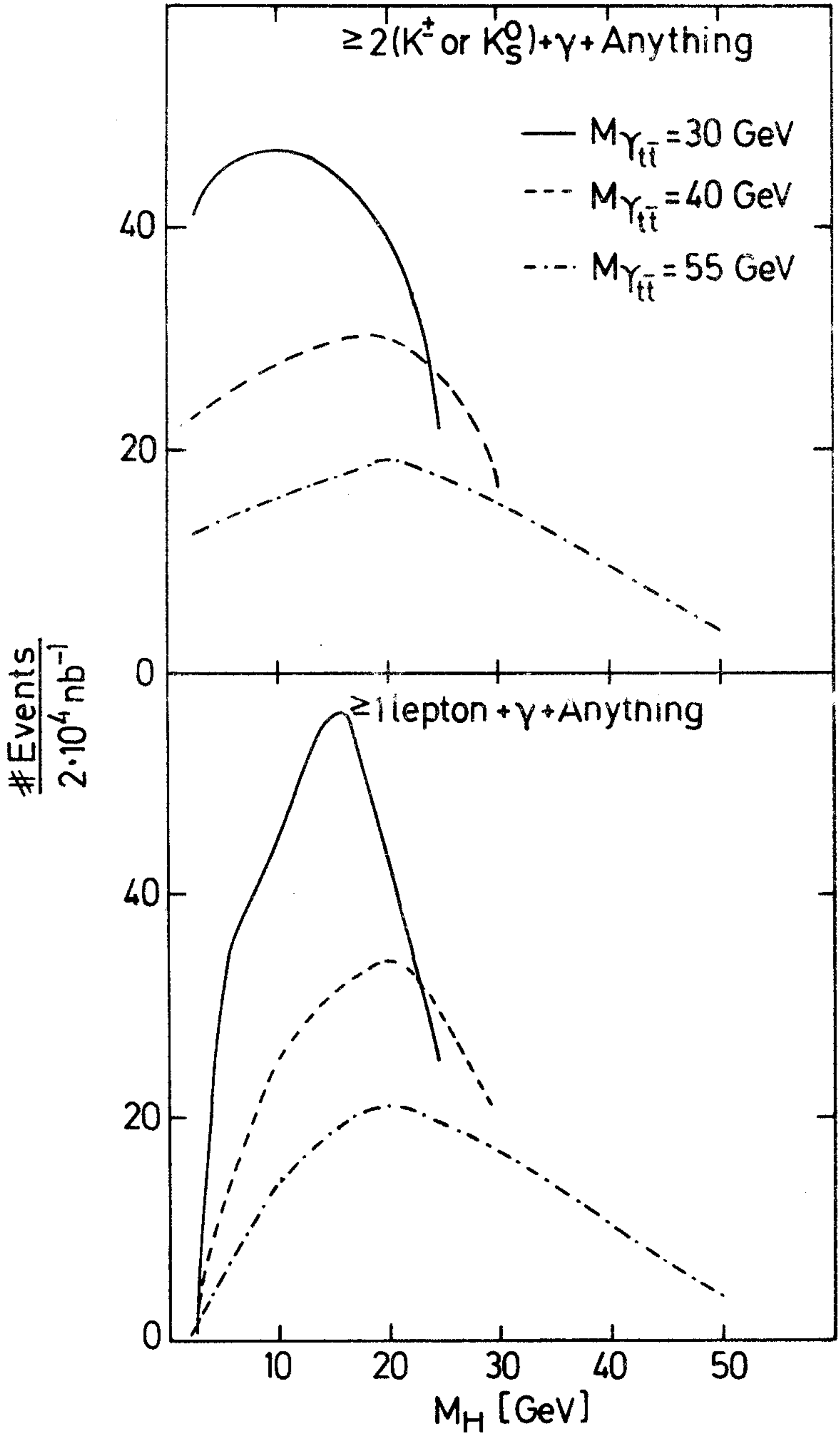
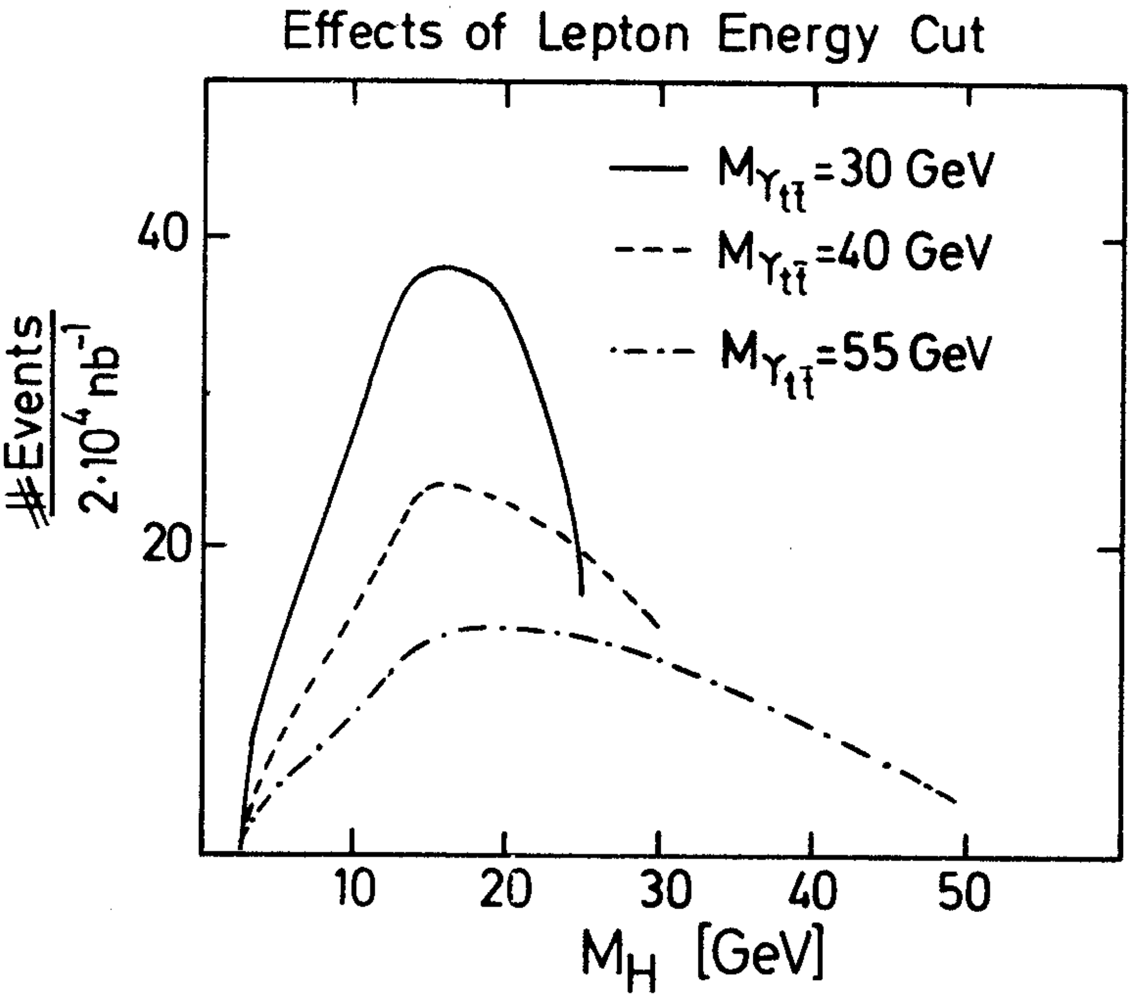

≥ 2(K± or K0S)+γ+ Anything
Mϒtt̄ = 30 GeV
Mϒtt̄ = 40 GeV
Mϒtt̄ = 55 GeV
≥1 lepton + γ + Anything
Events / 2·10⁴ nb⁻¹
MH [GeV]
0
20
40
10
20
30
40
50

Fig. 2



Effects of Lepton Energy Cut
$M_{\Upsilon_{t\bar{t}}}$=30 GeV
$M_{\Upsilon_{t\bar{t}}}$=40 GeV
$M_{\Upsilon_{t\bar{t}}}$=55 GeV
40
20
$\frac{\#\text{Events}}{2\cdot 10^4\,\text{nb}^{-1}}$
10
20
30
40
50
M_H [GeV]

Fig. 3