Detecting the Higgs in Purely Leptonic Decay Modes†

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Abstract

We outline the procedures required in order to detect a high mass, standard model Higgs boson in purely leptonic decay modes. We consider a variety of masses, m_H, above the two-Z threshold, $m_H > 2\ m_Z$, at center of mass energy, $\sqrt{s}$ = 40 TeV. Rough estimates of cross sections, event rates, and errors as a function of luminosity are given. We emphasize the importance of simultaneous measurement of the WZ continuum in order to normalize the background. A high luminosity interaction region would be enormously helpful.

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It has become apparent that backgrounds at a hadron collider, such as the SSC, to Higgs detection and weak boson pair production in purely hadronic and even mixed hadronic/leptonic decay modes may present a real problem.[1] Final agreement on cross sections and optimal cuts in the mixed mode case will be available in the near future.[2] Given this situation it is important to assess the possibility of Higgs detection in purely leptonic modes. It will become obvious that event rates are generally low and that a high luminosity interaction region at the SSC might be required. None-theless it appears feasible and perhaps even desirable to detect the Higgs in this manner.

We focus on Higgs production and decay in the mode

$$pp \to H \to Z_{\hookrightarrow e^+e^- \text{ or } \mu^+\mu^-} + Z_{\hookrightarrow e^+e^- \text{ or } \mu^+\mu^-} . \qquad (1)$$

(The WW pure-leptonic decay mode yields two neutrinos in the final state; in this case, the pair mass cannot be reconstructed and the mode may not be useful.) The primary background to (1) arises from continuum ZZ production

$$pp \to Z_{\hookrightarrow e^+e^- + \mu^+\mu^-} + Z_{\hookrightarrow e^+e^- + \mu^+\mu^-} . \qquad (2)$$

We will also be concerned with the WZ continuum

$$pp \to \begin{cases} W^+_{\hookrightarrow e^+\nu_e \text{ or } \mu^+\nu_\mu} + Z_{\hookrightarrow e^+e^- \text{ or } \mu^+\mu^-} \\ W^-_{\hookrightarrow e^-\bar{\nu}_e \text{ or } \mu^-\bar{\nu}_\mu} + Z_{\hookrightarrow e^+e^- \text{ or } \mu^+\mu^-} . \end{cases} \qquad (3)$$

We remind the reader of the branching ratios involved:

$$[BR\ (Z \to e^+e^- \text{ or } \mu^+\mu^-)]^2 = 3.77 \times 10^{-3} \qquad (4)$$

$$BR\ (Z \to e^+e^- \text{ or } \mu^+\mu^-)\ BR(W \to e\upsilon \text{ or } \mu\upsilon) = 1.02 \times 10^{-2}. \qquad (5)$$

Under some circumstances with appropriate p_T cuts on one Z (decaying in an e^+e^- or $\mu^+\mu^-$ mode) the $\tau\tau$ decay mode for the other Z in (1) or (2) might allow m_H reconstruction. The effective branching ratio in (4) would then be doubled by the addition of

$$2\ BR\ (Z \to e^+e^- \text{ or } \mu^+\mu^-)\ BR\ (Z \to \tau^+\tau^-) = 3.77 \times 10^{-3}. \ (6)$$

However, we will not pursue this further at the moment and will use (4) as the effective branching ratio for ZZ detection in purely leptonic channels.

We first outline the problems associated with Higgs detection in a purely leptonic mode and then a possible strategy. The Higgs will appear as a fluctuation in the number of purely leptonic events above the expected continuum rate due to (2). At low m_H ($\lesssim$ 500 GeV) the Higgs width is narrow, $\Gamma_H \lesssim 60$ GeV, and this fluctuation will appear in a relatively well defined bin of the effective mass of the four lepton final state. The background is then effectively determined by the surrounding bins. In this case the significance of a fluctuation can be computed on a purely statistical basis in the appropriate mass bin. At high m_H values Γ_H becomes very large and the Higgs will appear only as a broad enhancement in the number of purely leptonic events above the predicted continuum level. The lack of a clear peak means that this continuum level must be fairly precisely computable in order for the Higgs to be detectable. However knowledge of this continuum rate is theoretically elusive. Let us assume that the required higher order QCD corrections to continuum ZZ production have been computed. It is still possible to imagine a factor of two uncertainty in the predictions for continuum ZZ production due to uncertainties in the quark-antiquark luminosity functions. Jet cross sections at relevant jet pair masses are dominated by gluon processes and, in any case, are sensitive only to a gross sum over all types of quark jets and associated distribution functions, and thus do not help significantly to normalize the required $q\bar{q}$ luminosities. In contrast, purely electroweak final state processes, in particular WZ continuum production (which has no Higgs signal in the standard model), can in principle be used to normalize the $q\bar{q}$ luminosities over a wide range of subprocess energies. We will, in the following, assume that an exact measurement of the WZ continuum at a given WZ pair mass implies exact knowledge of the ZZ continuum at the same pair mass even though the luminosities involved are not exactly the same. Of course, there are other electroweak subprocesses than can be used to normalize $q\bar{q}$ luminosities. For simplicity we trace through only the WZ case; in practice a variety of channels should be experimentally examined in order to reduce this source of error.

However, observation of the WZ continuum is plagued by the same background problems as Higgs production itself. Let us again be pessimistic and assume that WZ continuum production can only be clearly observed in its purely leptonic modes, i.e., as in eq. (3). A crucial point is that these modes still allow complete reconstruction (up to the usual two-fold ambiguity for the neutrino) of the WZ pair mass and final state configuration.

Our strategy is then the following. Consider a value of m_H. Measure the WZ pair cross section at this value of m_H in the production/decay mode (3). Use this rate to predict the ZZ pair cross section at the same m_H value (up to systematic errors coming from statistical errors in the WZ measurement). Finally assess the statistical significance of a possible Higgs signal at m_H in view of statistical uncertainties in the continuum ZZ rate and the WZ induced systematic uncertainties in the predicted ZZ continuum rate. We shall integrate cross sections over a mass bin about m_H of size Γ_H. As stressed earlier, at low m_H, where Γ_H is small, this single bin need not be considered in isolation and the systematic error introduced by inaccuracy in knowledge of the background can be greatly reduced. However at high m_H values the study of a single broad bin of size Γ_H becomes appropriate. We shall separately track the systematic and purely statistical errors in the following. As m_H increases a correct estimate of the significance of a Higgs signal must include an increasing amount of the former.

We consider cross sections for WZ or ZZ pair production with the restriction $|y_{pair}| < 2.5$. We employ fig. 155 of EHLQ[3] which plots

$$\Sigma_{ZZ}(m_H) = \int_{\Gamma_H} \frac{d\sigma}{dm_H} (pp \to ZZ)\, dm_H \tag{7}$$

for both ZZ continuum, $\Sigma^C_{ZZ}(m_H)$ and $H \to ZZ$, $\Sigma^H_{ZZ}(m_H)$ processes. We consider $m_H \gtrsim 400$ GeV so that vector boson fusion dominates the H production process. We also require

$$\Sigma^C_{WZ}(m_H) = \int_{\Gamma_H} \frac{d\sigma}{dm_H} (pp \to WZ)\, dm_H . \tag{8}$$

To compute (8) we have estimated the ratio

$$R(m_H) = \Sigma^C_{WZ}(m_H)/\Sigma^C_{ZZ}(m_H) \tag{9}$$

using the EHLQ continuum plots fig. 128 and 133 for $d\sigma/dM_{WZ}$ and $d\sigma/dM_{ZZ}$ respectively (also restricted by $|y_{pair}| < 2.5$) and approximating

$$R(m_H) \sim [d\sigma/dM_{WZ}/d\sigma/dM_{ZZ}]_{M_{pair}=m_H} . \tag{10}$$

In this way we find the following values of $R(m_H)$.

$$R(m_H) \sim \begin{cases} 2.6 & m_H = .4 \text{ TeV} \\ 2.4 & m_H = .65 \text{ TeV} \\ 2.3 & m_H = 1 \text{ TeV} \end{cases} . \tag{11}$$

Computing $\Sigma^C_{WZ}(m_H) = R(m_H)\, \Sigma^C_{ZZ}(m_H)$ with (from EHLQ fig. 155)

$$\Sigma^C_{ZZ}(m_H) \sim \begin{cases} .4 \text{ pb} & m_H = .4 \text{ TeV} \\ .3 \text{ pb} & m_H = .65 \text{ TeV} \\ .2 \text{ pb} & m_H = 1 \text{ TeV} \end{cases} \tag{12}$$

and using the purely leptonic branching ratio (5), combined with an integrated (yearly) luminosity of

$$L = 10^4 \ \mathrm{pb}^{-1} \lambda \ , \tag{13}$$

we obtain the number of purely leptonic events, $N^C_{WZ}(m_H)$, from reaction (3) within Γ_H of a given value of m_H. These are (for the same three m_H values)

$$N^C_{WZ}(m_H) \sim \begin{cases} 100 \ \lambda \\ 77 \ \lambda \\ 46 \ \lambda \end{cases} \tag{14}$$

with associated statistical errors (to be used as systematic errors for the ZZ continuum prediction) of

$$\Delta^C_{ZZ} \sim \begin{cases} 10\%/\sqrt{\lambda} \\ 11\%/\sqrt{\lambda} \\ 14\%/\sqrt{\lambda} \end{cases} . \tag{15}$$

Combining (12), (13) and the branching ratio (4) we obtain the number of purely leptonic events from ZZ continuum production,

$$N^C_{ZZ} \sim \begin{cases} 15 \ \lambda \pm (1.5\sqrt{\lambda})_{\text{systematic}} \pm (4 \sqrt{\lambda})_{\text{statistical}} \\ 11 \ \lambda \pm (1 \sqrt{\lambda})_{\text{systematic}} \pm (3.4 \sqrt{\lambda})_{\text{statistical}} \\ 7 \ \lambda \pm (1 \sqrt{\lambda})_{\text{systematic}} \pm (2.7 \sqrt{\lambda})_{\text{statistical}} \end{cases} , \tag{16}$$

where the systematic errors arise from (15).

Finally, including the Higgs to ZZ cross sections (from fig. 155 of EHLQ, including a factor of $\frac{1}{2}$ for the restricted integral defined in eq. (7))

$$\Sigma^H_{ZZ}(m_H) \sim \frac{1}{2} \begin{cases} 2 \ \mathrm{pb} \\ .75 \ \mathrm{pb} \\ .4 \ \mathrm{pb} \end{cases} , \tag{17}$$

we can obtain yearly event rates for the sum of Higgs and continuum production in the purely leptonic ZZ decay modes. In doing so we will arbitrarily assume that the systematic errors in Σ^H_{ZZ} and Σ^C_{ZZ} are completely correlated. In practice the WW/ZZ fusion production mechanism for the Higgs is sensitive to a different combination of quark luminosities than is the ZZ continuum. The results are:

$$N^C_{ZZ} + N^H_{ZZ} \sim \begin{cases} 50\,\lambda \pm (5\,\sqrt{\lambda})_{\text{systematic}} \pm (7\,\sqrt{\lambda})_{\text{statistical}} \\ 25\,\lambda \pm (2.5\sqrt{\lambda})_{\text{systematic}} \pm (5\,\sqrt{\lambda})_{\text{statistical}} \\ 13\,\lambda \pm (2\,\sqrt{\lambda})_{\text{systematic}} \pm (3.5\,\sqrt{\lambda})_{\text{statistical}} \end{cases} \tag{18}$$

Of course in eqs. (16) and (18) the "systematic" and statistical errors are independent, having arisen from the measurement of two different cross sections, and should be added in quadrature to obtain the total error in cases where both must be incorporated (see below).

We can crudely characterize the ability to see the Higgs plus continuum event rates of eq. (18) by computing the number of standard deviations by which the predicted central values exceed the purely continuum rates (with associated errors) obtained in eq. (16). At m_H = .4 TeV Γ_H is small and the systematic errors need not be incorporated to first approximation. An $\sim 9\sigma$ effect is obtained at nominal luminosity, $\lambda = 1$. At m_H = 1 TeV $\Gamma_H \sim 450$ GeV and the systematic errors should be incorporated. An $\sim 2\sigma$ effect is likely at $\lambda = 1$ while $\lambda = 10$ would yield an $\sim 6\sigma$ effect. At m_H = .65 TeV $\Gamma_H \sim 120$ GeV; whether this is too large a width for accurate assessment of background level using bins neighboring on the enhancement is not clear.

In practice the statistical uncertainty dominates the systematic and an $\sim 4\sigma$ effect is possible at $\lambda = 1$.

Thus we conclude that Higgs observation at the SSC in the charged leptonic final states of the $H \to ZZ$ decay mode is nontrivial. The above predictions have not incorporated the effects of trigger efficiencies which could be significantly less than 100%. Realistically, an interaction region with increased luminosity, $\lambda > 1$ in eq. (13), will be required. The higher event rates associated with an increased luminosity might also allow the study of various distributions that distinguish between ZZ continuum background and the Higgs signal. However $\lambda > 1$ would imply many more interactions per beam crossing and a higher trigger rate than is currently being planned for. A detector, which focuses on energetic leptons and vetoes against accompanying hadrons of significant energy would be required.

The cross sections associated with inclusive leptonic processes of various types are illustrated in Fig. 1. We exhibit three curves.

a) The single lepton inclusive trigger rate (including $e^{\pm}$ and $\mu^{\pm}$) from all sources as a function of p_T^{min} - a minimum transverse momentum cut on the lepton; the dominant source for the single leptons is heavy quark decay.[4]

b) The same quantity but with the $e^{\pm}$ or $\mu^{\pm}$ coming from continuum $pp \to WW$ production - one W decays to the observed e or μ and the other is allowed to decay in any channel. This would be the appropriate cross section to consider if mixed hadronic/leptonic mode backgrounds can be overcome.

c) The same integrated inclusive spectrum but with the $e^{\pm}$ or $\mu^{\pm}$ coming from the decay of a 650 GeV Higgs in the purely leptonic modes of eq. (1).

Obviously it is a nontrivial task to isolate curve c) which has an inclusive trigger rate between 10^{-5} and 10^{-6} times that of a). Certainly it would be far better if further analysis demonstrates that the backgrounds to the mixed hadronic/leptonic modes for WW/ZZ continuum processes and Higgs production can be controlled. Then nominal SSC luminosity (λ=1) would probably be adequate and the processes of interest occur at a level of 10^{-3} times the inclusive trigger rate, as illustrated by curve b).

References

1. J.F. Gunion, Z. Kunszt, and M. Soldate, Phys. Lett. B163,389 (1985), and erratum thereto.
   S.D. Ellis, R. Kleiss, and J. Stirling, Phys. Lett. B163,261 (1985).

2. The two groups of Ref. 1 are working together to obtain agreement.

3. E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, Rev. Mod. Phys. 56,579 (1984).

4. This curve is taken from F. Paige, "SSC Trigger Rate Estimates" BNL report, to appear in these proceedings.

FIGURE CAPTION

FIGURE 1 Inclusive single lepton cross sections ($e^{\pm} + \mu^{\pm}$) at $\sqrt{s}$ = 40 TeV integrated above a particular p_T^{min}

$$\sigma = \int_{p_T^{min}}^{\infty} \frac{d\sigma}{dp_T} (e^{\pm} \text{ or } \mu^{\pm})\, dp_T .$$

The three curves are described in the text.

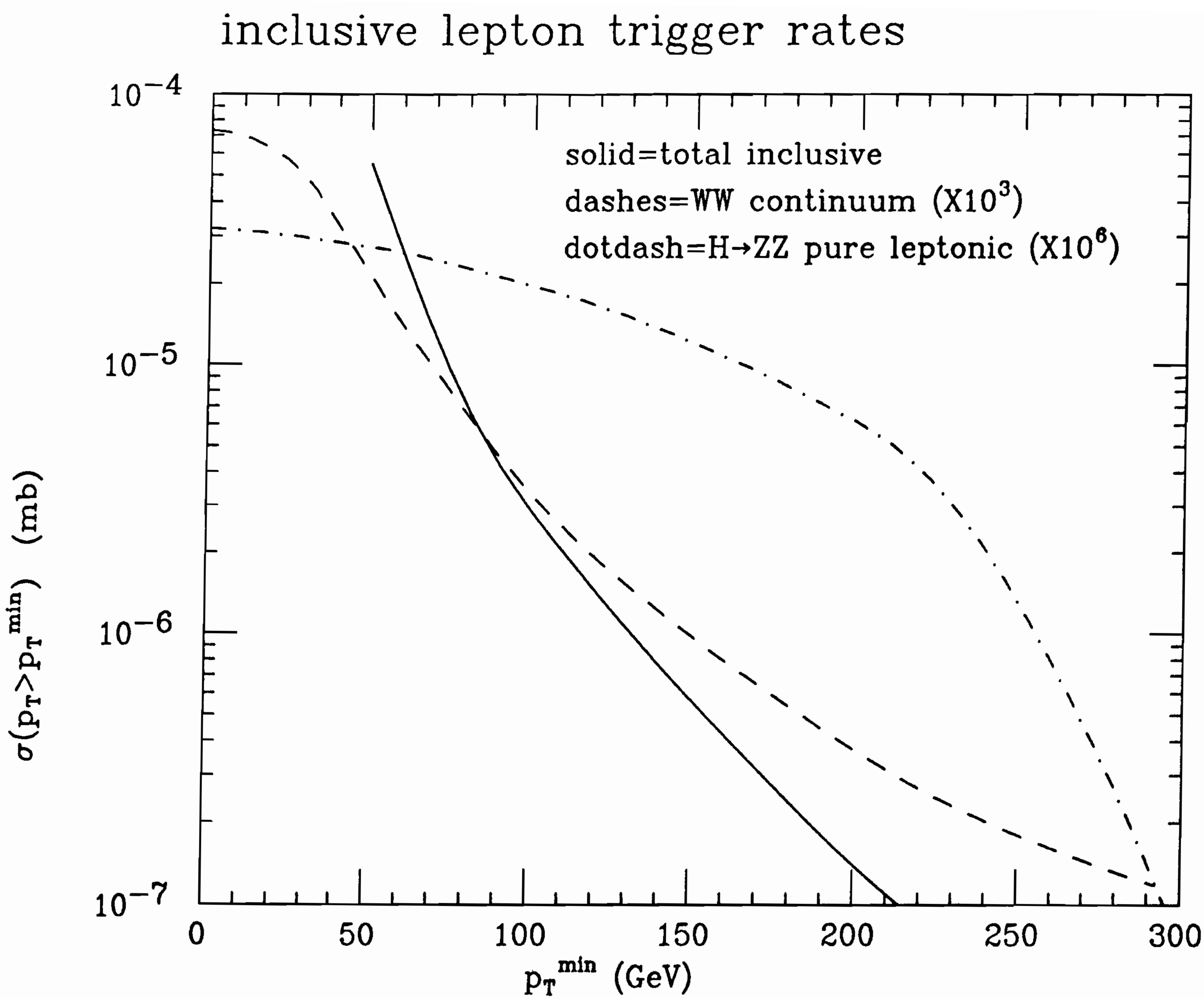
inclusive lepton trigger rates
solid=total inclusive
dashes=WW continuum (X10^3)
dotdash=H→ZZ pure leptonic (X10^6)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$\sigma(p_T > p_T^{min})$ (mb)
0
50
100
150
200
250
300
p_T^{min} (GeV)

Figure 1