lp01jjm.tex dias-stp-01-09

Jets signal for Higgs particle detection at LHC

T. Garavagli,*

Institiúid Árd-léinn Bhaile Átha Cliath, Baile Átha Cliath 4, Éire†

A method using jets is investigated for detecting the Higgs boson at LHC in the mass range about 114 GeV/c^2, suggested by LEP experiments. Higgs bosons are produced in association with a $t\bar{t}$ pair, and both t and $\bar{t}$ decay semileptonically to reduce the QCD background. After appropriate cuts, the signal is compared with the main background, $t\bar{t}+2$ jets. This estimate, using a reasonable approximation for the dominant background $t\bar{t}gg$, suggests a 5.1σ effect. This method is seen to be complimentary to the two gamma signal. The $t\bar{t}Z$ channel, with Z decaying to l^+l^-, may be used to reduce theoretical uncertainties in determining the $t\bar{t}H$ signal.

PACS numbers: 14.80.B., 13.85, 12.15

XX International Symposium on Lepton and Photon Interactions at High Energies, Rome 2001. Abstract Number 104.

* Email address: bronco@stp.dias.ie

† Also *Institiúid Teicneolaíochta Bhaile Átha Cliath.*

1. INTRODUCTION

The Standard Model Higgs with mass up to 114 GeV/c^2 has been suggested by fits to electroweak parameters [1] and recent experiments at LEP [2–3]. These results could be confirmed at the LHC where it should be possible to find a Higgs boson with mass near 114 GeV/c^2. For this mass, the rare decay $H \to \gamma\gamma$ was suggested [4], where the Higgs boson H is produced in association with either a $W^{\pm}$ boson or a $t\bar{t}$ pair in pp scattering experiments. A charged hard lepton from $W^{\pm}$ or one of the t quarks is required as a trigger in order to reduce the QCD background. However, since the 2γ mode is a rare decay, it may be difficult to extract this signal from the complicated background. I study the possibility of searching for an intermediate Higgs boson in the two-jet channel by reconstructing its invariant mass. I consider Higgs bosons that are produced in association with $t\bar{t}$ pairs only. This allows both the t and $\bar{t}$ to be tagged using semileptonic decays to cut down on the QCD background. Similar method have been used in top searches at the TEVATRON. Although this method had been suggested for the SSC [5], there has been considerable improvement in b vertex recognition and NLO QCD corrections to the $g\,g \to H$ cross section [6] since then, and the probable success of this search method at the LHC has increased.

2. SIGNAL AND BACKGROUND

The main process of interest is

$$pp \to t\bar{t}H + X, \tag{1}$$

with

$$t \to b + (W^+ \to l^+ + \nu), \tag{2}$$

$$\bar{t} \to \bar{b} + (W^- \to l^- + \bar{\nu}), \tag{3}$$

$$H \to b\bar{b} \quad \text{or} \quad c\bar{c}, \tag{4}$$

where l stands for either an electron or a muon. The final signal searched for is

$$2 \text{ leptons} + 4 \text{ jets} + \text{missing } E_T. \tag{5}$$

It has been know for some time [4] and [7] that $t\bar{t}H$ production at pp colliders can be very well approximated by two-gluon fusion alone. The tree level cross section as a function of the Higgs mass is found using the method of Kunzst [4] for $m_t = 175$ GeV/c^2. As an example, I take $m_H = 114$ GeV/c^2, which gives a cross section of 0.4 pb; our signal (5) has a combined cross section $\times$ branching ratio of

$$\sigma(pp \to t\bar{t}H)B^2(t \to bl^+\nu)B(H \to q\,\bar{q}\, or\, gg) = 0.4 \text{ pb} \times (2/9)^2 \times 0.95 = 18.8 \text{ fb} \tag{6}$$

at the LHC. This is still significantly larger than the $H \to \gamma\gamma$ signal with a single lepton tag. Although a b-tagging efficiency of 50% is suggested to likely at the TEVATRON and at LHC, I assume only a 40% efficiency, and I assume a lepton recognition efficiency of 90%, which has been achieved at LEP. To reduce most of the QCD background, I put a 15 GeV cut on the minimum p_T of each of the leptons and jets and place a 30 GeV minimum on the total missing E_T. An isolation cut is then applied to each lepton, requiring it to be at least $\sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ units away from any of the four jets. This has the effect of guaranteeing that almost all remaining events are of the type $t\bar{t} + 2$ hard jets. The same amount of separation is also applied to e^+e^- and $\mu^+\mu^-$ pairs to avoid QED background.

I now consider possible sources of background to the signal. There are three major types of background events:

(1) Sources of background other than $t\bar{t}$ that produce l^+l^- pairs are suppressed by at least two factors of either α_{weak} or α_{em}. These events do not have intrinsic missing E_T and will probably not pass the missing E_T cut. Thus, non $t\bar{t}$ contributions to the background are likely to be small.

(2) By far, the most important background is the QCD process

$$pp \to t\bar{t} + 2 \text{ jets}, \tag{7}$$

where the jets come mostly from initial state radiation. Both the t and $\bar{t}$ decay, as before, semileptonically to give the required signature.

Experience shows that $t\bar{t}$ pairs produced at the LHC are almost always accompanied by extra high p_T jets, and I make the ansatz that there will be an average of 2.0 jets with $p_T > 15$ GeV in every $t\bar{t}$ event. By assuming a Poisson distribution for the number of extra jets, the $t\bar{t}$ cross section with two and only two accompanying jets with $p_T > 15$ GeV is found to be 0.41 nb. Folding in the leptonic branching ratio for top quarks reduces this number to 0.02 nb. The Poisson distribution peaks at the average value, and I take this to be a conservative estimate.

There is also a combinatorial factor for forming two-jet pairs from the four jets in each event, and this enhances the background by a factor of 6. Compared to 18.8 fb for the signal, the background is larger by a factor of 2×10^3. As seen later this will be suppressed severely by additional cuts (see Table I). In addition, the background events will not have any special feature in the two-jet invariant mass spectrum while the signal will show a prominent peak around the mass of the Higgs boson.

(3) In addition to $t\bar{t}H$, there are also $t\bar{t}W^{\pm}$ and $t\bar{t}Z$ events in which the $W^{\pm}$ and Z decay to two jets, thus producing the same signature. The production cross section for $W^{\pm}$ is about one-tenth of that for the Z. This together with a smaller mass makes the $W^{\pm}$ events less important. The $t\bar{t}Z$ signal is an exact analogue of $t\bar{t}H$ for m_H close to the Z mass. With m_H near 114 GeV/c^2, I expect the two to have very similar cross sections; however, they should have no significant overlap. The estimated cross section for $t\bar{t}Z$ is roughly 0.3–0.4 pb for $m_t = 175$. The mass resolution for $Z \to 2$ jets at the LHC was estimated to be roughly ± 5 GeV in a similar energy dependent situation.

This signal not only turns out to be benign, it actually works to our advantage. Unlike the Higgs, the Z also decays to charged lepton pairs with a large branching ratio (6%). In my case, this gives a signature of 4 leptons and 2 jets, which has very little background if I further require two of the leptons to reconstruct to a Z. Therefore, the $t\bar{t}Z$ cross section can be measured by reconstructing the two-lepton invariant mass in the 4 leptons + 2 jets events. I expect that most of the theoretical uncertainty in the ratio of the two cross sections, $pp \to t\bar{t}H$ and $pp \to t\bar{t}Z$, cancels, and the cross section for $t\bar{t}H$ can then be reliably inferred from that of the $t\bar{t}Z$. Finally, this calibration from the Z is absent in the $\gamma\gamma$ channel because $Z \to \gamma\gamma$ is forbidden on account of anomaly cancellation.

3. SIMULATION

Both the signal and background are simulated using Monte Carlo methods at the parton level. As a preliminary study, simplified distributions in phase space are used for each scattering and decay process. The total cross sections are then normalized to published values.

For my signal, the parton cross section is given on purely dimensional ground by

$$d\sigma(gg \to t\bar{t}H) \propto \frac{1}{\hat{s}^2}\, d\Phi_3 \ , \tag{8}$$

where $d\Phi_n$ is the n-body Lorentz invariant phase space:

$$d\Phi_n = \delta^{(4)}(P - \textstyle\sum p_i) \displaystyle\prod_{i=1}^{n} \frac{d^3 p_i}{2E_i} \ , \tag{9}$$

where $\hat{s}$ is the center of mass energy of the partons and P is their total momentum. Each of t, $\bar{t}$ and H is then decayed independently to $b\,l^+\nu$, $\bar{b}\,l^-\bar{\nu}$ and $b\bar{b}$ respectively to give us the signature of 4 jets + 2 leptons + missing E_T. I take $m_t = 175$, $m_H = 114$ GeV/c^2 and 0.4 pb for the total cross section.

For the background, I first take

$$d\sigma(gg \to t\bar{t}gg) \propto \frac{1}{\hat{s}^3}\, d\Phi_4 \ , \tag{10}$$

and normalize it to the $t\bar{t}gg$ cross section. Just as in the case of $t\bar{t}H$, I assume that the dominant contribution to the $t\bar{t}$ cross section comes from gluon fusion. Since the top quarks are heavy and hardly radiate, I next assume that the two extra jets are gluons coming from initial state radiation only. The angular and energy distributions of the gluons, in addition to Eq. (10), are assumed to follow the Altarelli-Parisi function

$$P_{gg}(z) = c_{gg} \left(\frac{z}{1-z} + \frac{1-z}{z} + z(1-z) \right) , \tag{11}$$

where z is the fractional momentum of the initial gluon after radiation:

$$z = \frac{E_i - p_{L_i}}{E_{i-1} - p_{L_{i-1}}} , \tag{12}$$

where the subscripts $i-1$ and i refer to the initial gluon before and after radiation. I also use the approximation where the further splitting of a radiated virtual gluon is replaced by two sequential radiations from the same initial gluon. The t and $\bar{t}$ are decayed as before to give us the required signature.

To mimic a real experimental situation, the energy of each parton is smeared to reproduce the proposed detector resolution for jets and leptons, and I impose an isolation cut on each of the hadronic partons (jets) in η-ϕ space so that no two jets are within a distance of 0.5 units from each other:

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.5 .$$

A rapidity cut of $\eta < 2.5$ is also applied to each of the jets and leptons.

4. RESULTS

I generate the number of events for the signal and background that corresponds to an integrated luminosity of 100 fb^{-1} with an LHC luminosity of 10^{33} cm^{-2}s^{-1}. The following cuts are then performed on both types of events: (1) A 15 GeV minimum p_T cut is first applied to all jets and leptons. (2) A second p_T cut is then applied to the four hadronic jets: For each of the six pairs of jets, I form the scalar sum of the two individual p_T and require it to be larger than 60 GeV. This will severely suppresses the background while keeping the signal almost unchanged. (3) To try to guarantee that the two leptons originate from top quark decays, I require each lepton to be at least a distance $\Delta R = 0.4$ away from any jet in η-ϕ space. The two leptons are required to be separated by the same amount. (4) The missing transverse energy in each event must be larger than 30 GeV.

There are many less important sources of background such as $Z + 4$ jets + missing E_T and $b\bar{b} + 2g$, etc. To ensure that they do not significantly affect our result, I also apply the following cut: The invariant mass of all the observed particles should be larger than $2m_t + m_H$. This greatly enhancing the probability of having heavy particles in the final state. The results of all the cuts are shown in Table I in the order of their applications.

Table I.

Cuts	Signal ($t\bar{t}H$) 100% ≈ 18.8 fb	Background ($t\bar{t}gg$) 100% ≈ 2.0 pb
All $p_T > 15$ GeV	51%	64%
All $p_{T1} + p_{T2} > 60$ GeV	49%	11%
Missing $E_T > 40$ GeV	48%	11%
Observed invariant mass > 464 GeV	33%	3.2%
Isolation cuts (j-j, l-j and l-l)	17%	1.3%

To extract the signal from this background, I need to reconstruct the Higgs mass from two-jet pairs. Figure 1a shows the distribution of the two-jet invariant mass of the signal and the Z peak. It has a prominent peak about $m_H = 114$ GeV/c^2 containing 208 counts in the 8 GeV/c^2 or so region under the peak. The width of the resonance matches roughly the two-jet resolution of 8 GeV achievable at the LHC. The $t\bar{t}gg$ background is shown in Fig. 1b. Over the same 8 GeV range under the Higgs peak, the background contains roughly 1680 counts. Thus, I obtain a significance, signal/$\sqrt{\text{background}}$ = 5.1. The combined result is shown in Fig. 1c. This figure shows with our approximations a recognizable signal over the QCD background despite the fact that the cuts applied have not been fully optimized. In view of all the approximations I have made, the background in the region of interest can easily be off by a factor of two or three. For example, the Altarelli-Parisi splitting function I used in Eq. (11) tends to generate gluons softer and closer to the beam line than would occur in real background events. However, I have been generous in normalizing the overall cross section for the background. If more optimal cuts are also used, I believe the signal could still be measured over a slightly higher background. I believe that reconstruction from jets is a promising technique in the detection of the Higgs boson, and, used in conjunction with related methods [8–9], it should give definitive evidence for Higgs detection. QCD NLO corrections [6] to the process $g\,g \rightarrow H$ indicate a K factor of ≈ 2.2, and this could improve the signal recognition. Although jet smearing has been used to give a more realistic representation of the jet and lepton signals, the actual fragmentation of jets is hard to simulate [9], and this could cancel the NLO effect. Finally, these results can be used in conjunction with other signals, and this should lead to Higgs detection within the first two years of LHC operation.

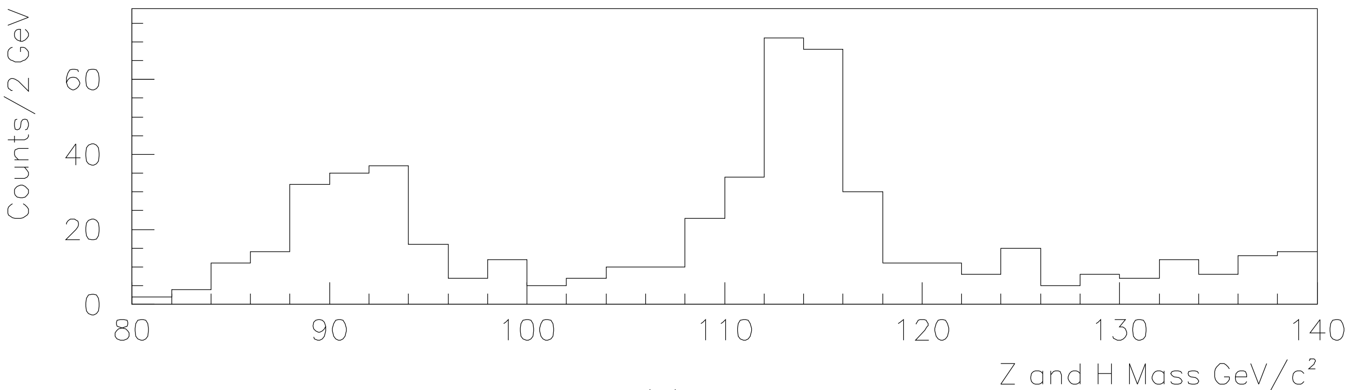
The author has benefited from the use of the Queen's University Belfast and Dublin University parallel processor.

REFERENCES

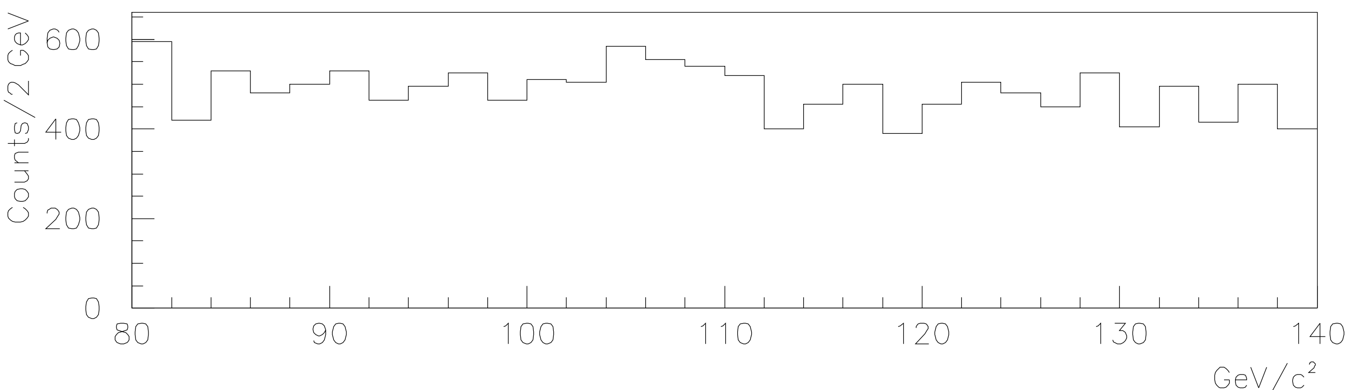
[1] Particle data group, Euro. Phys. Jr. B **15**, 103, 274 (2000).
[2] L3 Collaboration, /hep-ex/0011043, Phys. Lett. B **495**, 18-25(2000).
[3] ALEPH Collaboration, /hep-ex/00111045, Phys. Lett. B **495**, 1-17(2000).
[4] Z. Kunszt, Nucl. Phys. **B247**, 339 (1984); D. Dicus and S. Willenbrock, Phys. Rev. D **39**, 751 (1989).
[5] T. Garavaglia, Waikwok Kwong, Dan-Di Wu, Phys. Rev. D **48**, R1899-R1903 (1993).
[6] M. Spira, A. Djouadi, D. Graudenz, and P. M. Zerwas, Nucl. Phys. **B 453**, 17 (1995).
[7] M. Spira, Fortsch. Phys. **46**, 203 (1998).
[8] D. Denegri, *The CMS Detector and Physics at LHC*, CERN-PPE/95-183.
[9] D. Froidevaux, E. Richter-Was, *Is the* $H \rightarrow b\bar{b}$ *observable at LHC*, Atlas Internal Note, Phys-NO-043 (1994).

FIGURE CAPTION

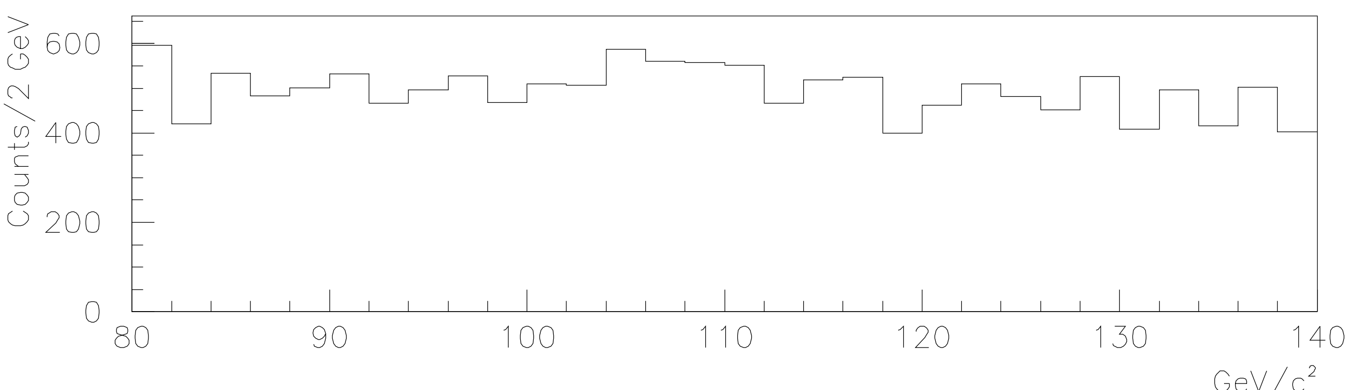
FIG. 1. Two-jet invariant mass distributions. The vertical axes shows counts/2 GeV/c^2 bin. The horizontal axes shows two-jet invariant mass values in GeV/c^2.
(a) $t\bar{t}H$ signal and $t\bar{t}Z$ events.
(b) QCD $t\bar{t}gg$ background.
(c) Signal plus background.



(a) ttZ+ttH



(b) Background JJMass



(c) Signal+Background JJMass