STUDY OF W-->JETS RECONSTRUCTION AND RESOLUTION

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Summary

Using the Montecarlo program ISAJET[1] 1000 events were generated of the type W+jets and neutral Higgs (700 GeV mass) decaying to WW to study the resolution and the background rejection if one of the W's from the Higgs decays into hadron jets. With a rather simplistic calorimeter simulation with hadron energy resolution $\delta E/E=.02+50\%/\sqrt{E}$, we find one can achieve signal-to-background ratios of the order of 1/2 and W mass resolutions of the order of 9 GeV (full width half maximum).

Introduction

For masses well above WW and ZZ threshold Higgs scalars will decay predominantly into W's and Z's, a neutral Higgs going 2/3 of the time into W^+W^- and 1/3 into ZZ. The cleanest signature would be into purely leptonic decays which limits the search to the ZZ channel. To have a reasonable chance of discovery (assuming negligible background), an expected signal of 10 events is the minimum requirement. The branching ratio of Higgs into charged leptons (including both e's and μ's) is close to 10^{-3}. It is unlikely that a detector measuring both e's and μ's will have better than 50% efficiency for reconstructing all 4 leptons, so the minimum detectable cross section for $10^{40}cm^2$ integrated luminosity is 2pb, this limits the accessible Higgs masses to less than 800 GeV[2]. The branching ratio is a factor of 6 larger if only one Z decays to charged leptons and the other to ν's (appearing as very high missing E_t). The background is also expected to be small in this case but, since the Higgs would appear as a Jacobean peak, the number of events to aim for should be a few times higher so the minimum cross section needed may be around 1pb implying a maximum observable mass of 1.2 TeV. If, however, one can measure hadronic decays the WW mode becomes accessible. The branching ratio with one W decaying to $e\nu$ or $\mu\nu$ and the other to quarks is 8%, a factor of 15 higher than to leptons plus ν's. It is clearly a very important channel to measure and holds the promise of discovering Higgs particles at higher masses than the purely leptonic channels. The problem in this case, of course, is that the backgrounds are considerable and the measurement is difficult. However, the background can be directly measured by moving off the W mass region, unlike the case of Z's decaying to ν's, which can only be estimated. The results from this study indicate that it is possible to observe a high mass Higgs decaying to WW with one of the W's decaying hadronically, but the study is not complete in that a truly realistic detector simulation was not attempted.

Event Simulation

In order to study the ability to separate Higgs-->WW with one of the W's decaying to hadron jets from the dominant background of high p_t W's with recoiling jets, 1000 Montecarlo events were generated with ISAJET (version 5.22, ref.1) at 40 TeV center of mass energy for each of the following reactions:

(1) pp--> W^+W^- each W having 300 GeV $<p_t<$ 350 GeV, one W decaying to $e\nu$ and the other to quarks.

(2) pp--> W+jets with the W having 300 GeV $<p_t<$ 350 GeV and decaying to $e\nu$.

The present version of ISAJET does not yet have an exact generation of Higgs mesons but reaction 1) can be used to simulate it; the average WW pair mass is 700 GeV and modifying the decay matrix element of the W's so that they are longitudinally polarized one obtains a fairly good approximation to the production and decay of a heavy neutral Higgs meson. Figure 1 shows the p_t and mass of the WW pairs generated with reaction (1). In both reactions the W decaying leptonically was required to have $|y|<2$.

A similar study to the one presented here was done in Snowmass '84[3], however, at that time ISAJET did not include initial state radiation effects nor could it produce WW pair events. Also, as will be shown below, in this study much use is made of the fact that the W's are longitudinally polarized to get a sample of events with good resolution and good background rejection by means of relatively simple cuts.

Because of limited amounts of computer time the effects of a calorimeter were not simulated by generating actual showers, but simply by adding the hadronic and electromagnetic energies in cells of $\Delta y\Delta\phi=.05x.05$ (the smallest practical cells possible) and then smearing the energy in each cell by a resolution. Unless explicitly stated the $\delta E/E$ rms resolution is assumed to be $.02+.15/\sqrt{E}$ for the electromagnetic calorimeter and $.02+.50/\sqrt{E}$ for the hadronic calorimeter. These resolutions are based on the Uranium/Liquid-Argon D0 test calorimeters[4] (the constant term has not really been measured and is an educated guess). For each cell one constructs then a 4-vector $\vec{E}_c$ with the direction given by the interaction point and the center of the cell. The calorimeter extends down to $|y|=5.5$, although cells of .05x.05 are not really needed for $|y|>3.0$ as for most events the energy deposited from W's to quarks is below $|y|=3.0$ and the effect of coarser cells on missing E_T is small.

The separation of reactions (1) and (2) depends most critically on the mass resolution of W-->jets. Even before the effects of a realistic detector are included there are limitations on the achievable mass resolution: a) if the decay involves heavy quarks the neutrinos from semileptonic decays will produce energy losses; b) when adding the energy it is impossible to separate the hadrons from W's from other hadrons. The effects from b) become more noticeable when the quarks from W's have significant gluon emission as more cells need

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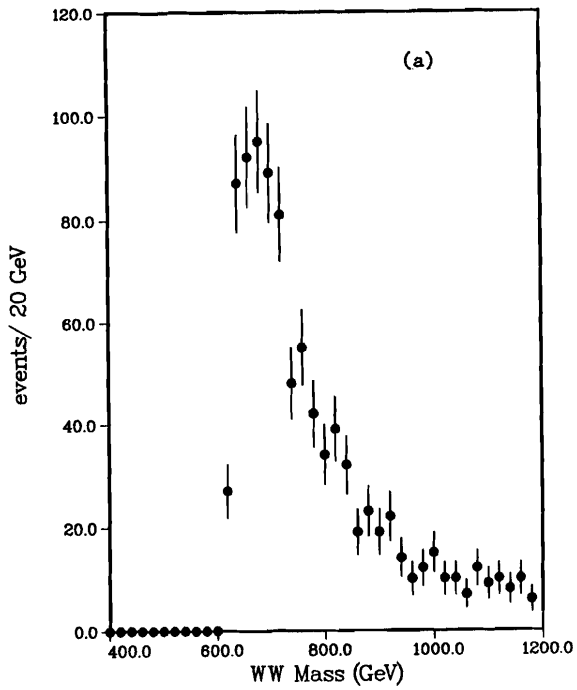

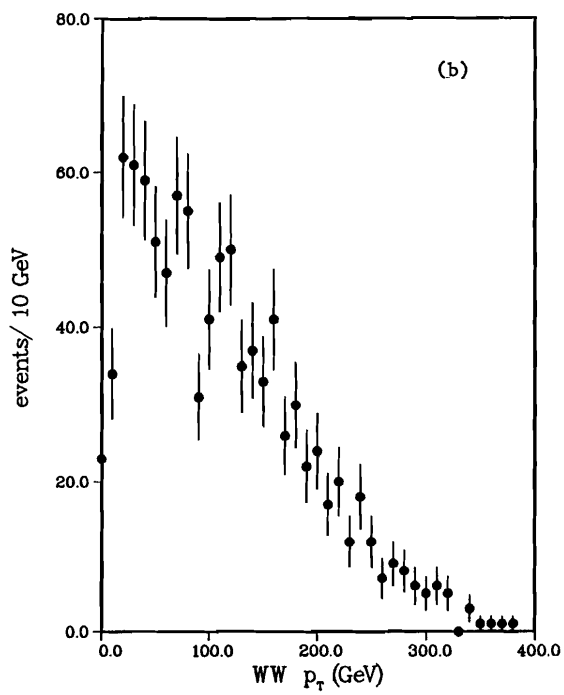

Fig. 1. a) Generated WW mass for reaction (1); (b) generated WW transverse energy for reaction (1).

to be included to find the W. There is, however, a subset of events with much better resolution than average, i.e. those from light quarks with no (or low momentum) neutrinos and negligible gluon emission. First a set of such events were selected to study their characteristics and find cuts with high efficiency for obtaining an enriched sample. Their most distinctive feature is that they have two close by, but nevertheless well separated, jets of almost equal energy. Cuts, which will be described later, were chosen that make use of that feature. Those cuts were then applied to all hadronic decays of W's. It turns out that the cuts that select W's with good resolution are also very effective in reducing the background contributed by reaction (2).

W Reconstruction

To find the W decaying to jets we use a slightly modified version of the UA1 jet finding algorithm, i.e. we look for the cell with the highest transverse energy deposition (excluding the e from the W decaying leptonically) and then construct a 4-vector $\vec{p}_W$ by the vector sum of all nearby cells within some radius $R = \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$; Δy and $\Delta\phi$ are defined respect to maximum E_t cell. As a first pass we take R<0.6, then calculate the mass of $\vec{p}_W$. If the mass is less than 70 Gev a second pass is made taking R<1.0. Only cells with E_T >400 MeV are included in the sum. This cut reduces the contribution from non-associated hadrons without substantially affecting the W mass calculation. The calculated mass is shown in Fig. 2a for reaction (1) events and Fig. 2b for reaction (2) events. Next we construct a matrix

$$\Sigma_{yy} = \sum_i (E^W_{T_i} \Delta y_i)^2 \qquad \Sigma_{y\phi} = \sum_i E^{W^2}_{T_i} \Delta y_i \Delta\phi_i$$

$$\Sigma_{\phi\phi} = \sum_i (E^W_{T_i} \Delta\phi)^2$$

where $E^W{}_{T_i}$ is the transverse energy of each cell respect to $\vec{p}_W$, Δy_i and $\Delta\phi_i$ the differences of the center of each cell with respect to $\vec{p}_W$ and the sums run over all cells within R<0.6. We then find the major axis ρ for the above matrix. The 4-vectors for two jets are constructed in the following way:

$$\vec{p}_{jet1} = \sum_{\rho<0} \vec{E}_{c_i} \; ; \; \vec{p}_{jet2} = \sum_{\rho>0} \vec{E}_{c_i}$$

with R<0.6 (defined respect to $\vec{p}_W$). We then redefine $\vec{p}_W$ and M_W as:

$$\vec{p}_W = \vec{p}_{jet1} + \vec{p}_{jet2} \; ; \; M_W^2 = \vec{p}_W^{\,2}$$

the new M_W distribution is shown in Fig.2c. A well defined peak for the W events can be seen with a long low mass tail coming from events with part of the energy missing. This low mass tail acts as a background which must be added to the background coming for reaction (2) shown in Fig. 2d. The expected cross section times branching ratio for a 700 GeV Higgs decaying to WW with one W decaying to $e\nu$ and the other to hadrons is 0.1 pb, while the cross section times branching ratio for reaction (2) is 3 pb[3]. If we assume that the efficiency for finding W to $e\nu$ is 50% and include W to $\mu\nu$ events with the same efficiency then 1000 events generated correspond exactly to a nominal year run of 10^{40}

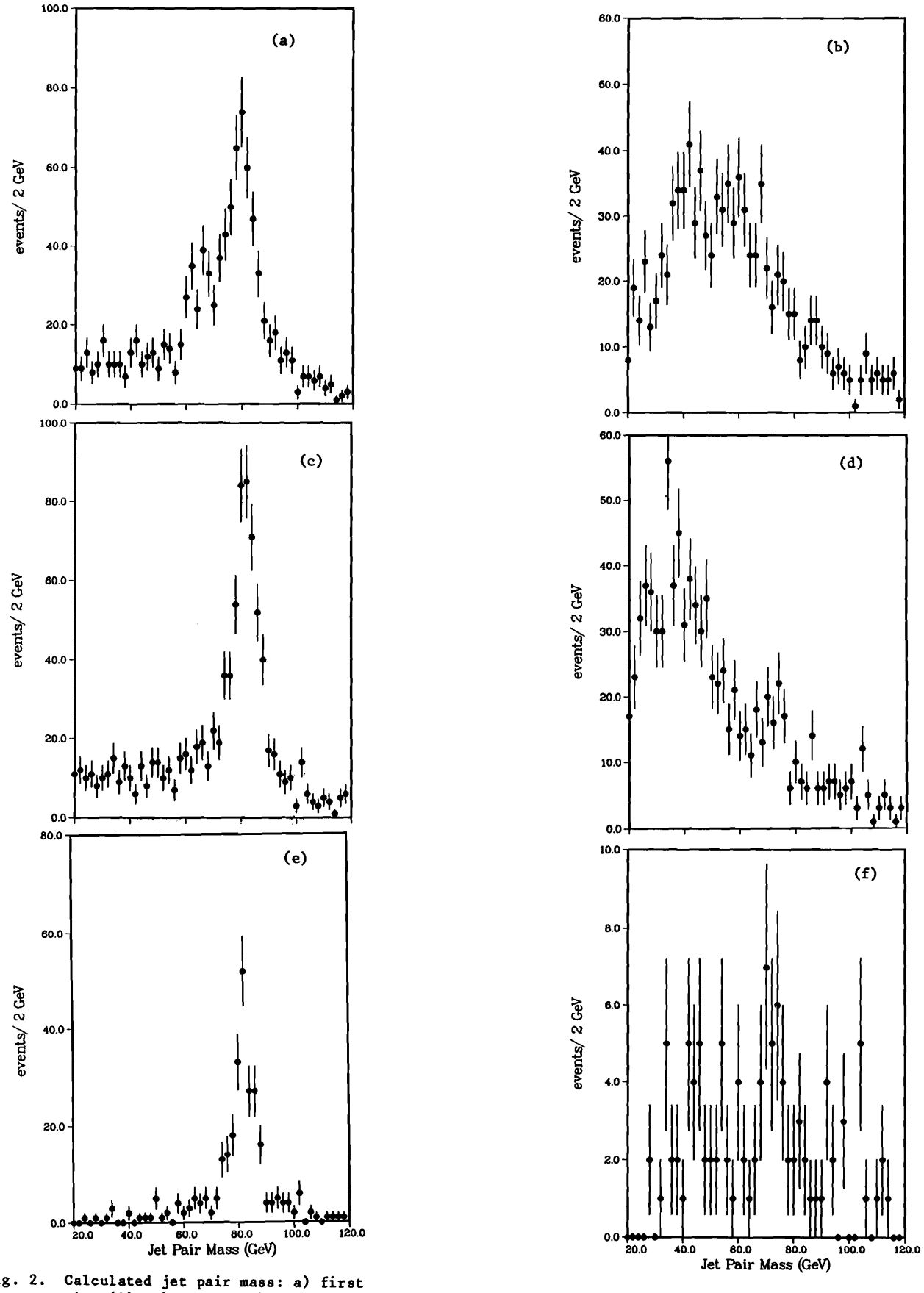

Fig. 2. Calculated jet pair mass: a) first pass reaction (1); b) same as a) reaction (2); c) after finding major axis reaction (1); d) same as c) reaction (2); e) after cuts reaction (1) (see text); f) same as d) reaction (2).

cm^2. Thus the number of events shown in Fig. 2c follows closely the number of expected events in the signal. On the other hand the number of events in the background plots must be multiplied by a factor of 30. Taking events with 74 GeV<M<90 GeV the signal-to-background before any additional cuts is 360/2800 which already gives a signal of $\approx 6\sigma$.

Background Rejection and Resolution

To reduce the background further one can now make use of the fact that the W's from Higgs are longitudinally polarized and that the W's with good resolution consist of 2 jets with similar E_T. Longitudinal polarization implies that for a two-body decay the decay products have a $\sin^2\theta$ decay distribution in the W rest frame respect to the W direction (in overall center-of-mass), this holds, of course, for both W-->eν as well as for W-->2-jets. Assuming all missing E_T is due to the ν from the W one can solve for the longitudinal momentum of the ν with a 2-fold ambiguity by imposing the W mass. For reaction (1), the solution which gives the lowest WW pair mass is the right one over 80% of the time, so that criteria was used to resolve the ambiguity. Fig 3a shows the calculated WW pair mass which can be compared to the one generated (Fig 1a); clearly the above method reproduces the generated WW pair mass reasonably well. For comparison we show in Fig 3b the W'W' pair mass obtained from the background reaction (2), note that the WW mass is not a useful quantity for separating signal from background. The 4-vectors for the e,ν,jet1 and jet2 are then boosted to their respective W rest frame and we define in that frame:

θ_e = angle between e and W direction in center-of-mass
θ_i = angle between jet1 and W direction in center-of-mass
$r = E_i^{min}/E_i^{max}$.

To favor longitudinal polarization we first require $|\sin\theta_e|>0.8$ and $|\sin\theta_i|>0.8$, this reduces the number of events for reaction (1) between 74 GeV and 90 GeV to 250 and for reaction (2) to 1000 events; the background is still substantially larger than the signal. The next requirement, r>0.8, is most effective in selecting events with good resolution. This is equivalent to demanding that the 2 jets have similar masses. For reaction (1) it removes the W-->$t\bar{b}$ events and those with substantial gluon emission while for reaction (2) it removes asymmetric pairs and multi-jet events. The resulting spectra are shown in Figs. 2e and 2f. The signal to background (S/B) is now 200/600 (corresponding to a 7 σ signal). This ratio can be further improved by making a tighter cut, r>0.9, to obtain S/B=150/300. By making tighter cuts on the variables defined above S/B can be improved further at the expense, however, of a much reduced signal.

The mass resolution, full width half maximum (FWHM), for the W-->jets events with the tightest cuts is 9 GeV. It is worth pointing out that if we simply sum the particles within R>0.6 of the W direction given by ISAJET, imposing a cutoff equivalent to 400 MeV transverse energy in a cell and no resolution smearing, we obtain FWHM=7 GeV. So improving the calorimeter resolution or finer segmentation is unlikely to have a significant impact on the W mass resolution. On the other hand if the hadron calorimeter resolution is degraded to 100%/√E one obtains after all the above cuts

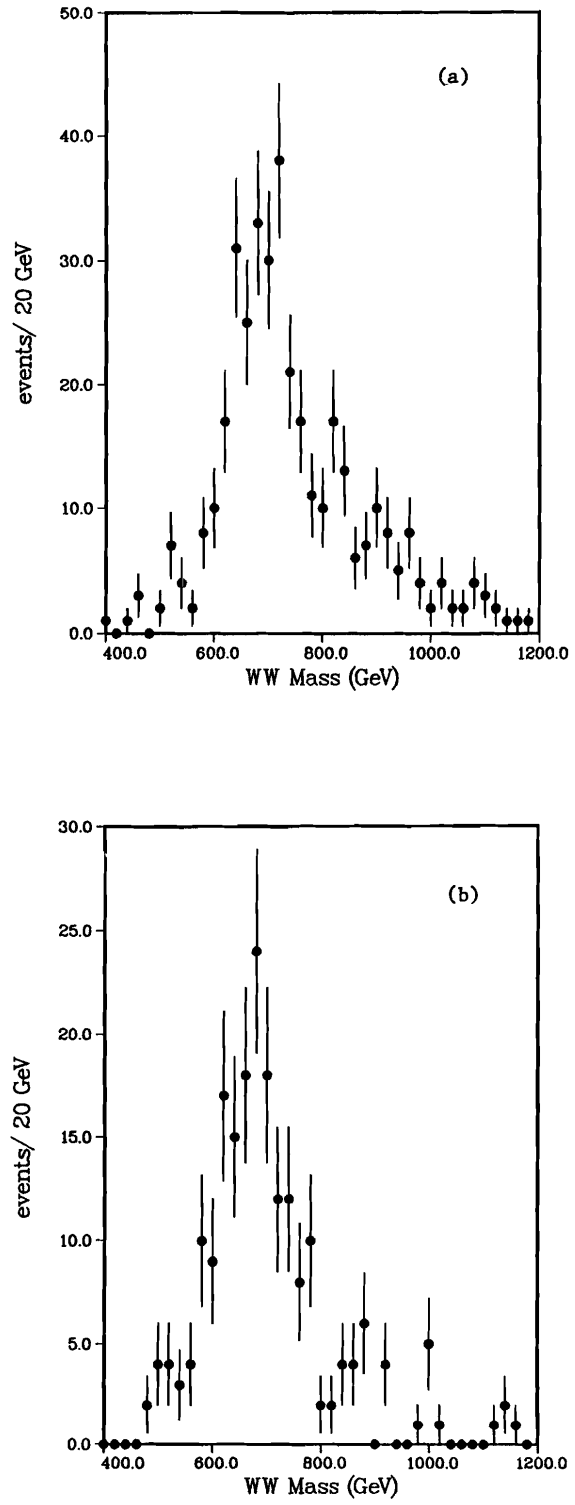

Fig. 3. a) Calculated WW mass for reaction (1); b) calculated W'W' mass for reaction (2).

FWHM=14 GeV. Thus, for hadron calorimeter resolution below 50%/√E, one will be approaching the theoretical limit on the W mass resolution due to background hadrons while, for significantly worse resolution, the calorimeter energy resolution will become the dominant effect. All of the above conclusions assume that longitudinal and transverse shower fluctuations will not have a noticeable effect. To carry these studies further a full detector simulation with realistic shower developments and algorithms for reconstructing them are needed. Although various detector simulation programs exist at this point, estimating their reliability and developing analysis programs using their outputs are non-negligible tasks. Another aspect that has been neglected in this study are the effects of pile-up which are likely to produce some deterioration in the resolution. The importance of pile-up of course depends critically on details of calorimeter construction and electronics.

Conclusion

In conclusion, it seems quite feasible to observe a W decaying to jets coming from a heavy Higgs (mass above 700 GeV) provided one has a calorimeter with energy resolution $\delta E/E$ near 50%/√E and segmentation $\Delta y \Delta \phi$ = .05x.05, and that the integrated total luminosity is of the order of 10^{40} cm^2. The observation of such a signal would be a telltale signature of the existence of a heavy mass Higgs as the direct production of high E_T WW pairs is substantially smaller.

In order to reduce the considerable background coming from W+ jets, a set of cuts are needed which make use of the fact that the W's from Higgs decays are longitudinally polarized. After the cuts are applied we obtain for signal/background 150/300 events (assuming 50% acceptance for finding eν and μν W decays). Given that cross sections are uncertain to within factors of 2 it is clear that the ability to observe such a signal could be seriously jeopardized if the integrated luminosity is much below 10^{40} cm^2. Resolutions of the order of 9 GeV (FWHM) for W-->jets seem achievable for the subset selected by the cuts. The best resolution one could hope for is FWHM=7 GeV (this is determined by the underlying physics background) and if the hadron calorimeter resolution is no better than 100%/√E then FWHM increases to 14 GeV. These estimates of the resolution assume that effects of pile-up and hadronic shower fluctuations are not the dominant contributors. I would like to thank F.E. Paige and J. Gunion for many fruitful discussions.

References

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