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A new mass reconstruction technique for resonances decaying to $\tau\tau$

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ABSTRACT

Accurate reconstruction of the mass of a resonance decaying to a pair of τ leptons is challenging because of the presence of multiple neutrinos from τ decays. The existing methods rely on either a partially reconstructed mass, which has a broad spectrum that reduces sensitivity, or the collinear approximation, which is applicable only to the relatively small fraction of events. We describe a new technique, which provides an accurate mass reconstruction of the original resonance and does not suffer from the limitations of the collinear approximation. The major improvement comes from replacing assumptions of the collinear approximation by a requirement that mutual orientations of the neutrinos and other decay products are consistent with the mass and decay kinematics of a τ lepton. This is achieved by maximizing a probability defined in the kinematically allowed phase space region. In this paper we describe the technique and illustrate its performance using $Z/\gamma^* \to \tau\tau$ and $H \to \tau\tau$ events simulated with the realistic detector resolution. The method is also tested on a clean sample of data $Z/\gamma^* \to \tau\tau$ events collected by the CDF experiment at the Tevatron. We expect that this new technique will allow for a major improvement in searches for the Higgs boson at both the LHC and the Tevatron.

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1. Introduction

Invariant mass reconstruction is commonly used in experimental searches for new physics, such as for the Higgs or Z' bosons, as well as in measurements of properties of known resonances. This technique is relatively straightforward for e^+e^-, $\mu^+\mu^-$, or di-jet final states. The accuracy of mass reconstruction in these channels is dominated by the detector resolution for lepton or jet momenta. The sensitivity of "mass bump-hunting" analyses depends critically on how narrow the signal invariant mass distribution is compared to the (usually broad) distributions in background processes. Unfortunately, this simple strategy is much less effective in searches for resonances decaying to a pair of τ leptons because the τ lepton energy associated with neutrinos escapes detection, and only visible products (leptons in the case of leptonic τ decays or low multiplicity jets in the case of hadronic τ decays) are observed in the detector.

Each τ lepton decay involves one or two neutrinos, depending on the final state: hadronic ($\tau \to \nu_\tau +$hadrons) or leptonic ($\tau \to \nu_\tau + l\overline{\nu_l}$, where l=e or μ). In pp or $p\overline{p}$ collisions, the full energy of neutrinos cannot be determined. Instead, one can only reconstruct a transverse energy imbalance in the detector (or missing transverse energy, $\not\!\!E_T$), which is a representative of the total transverse momentum of all neutrinos in the event. Therefore, when two or more neutrinos are produced in the same event, their individual transverse momenta and directions cannot be reconstructed. The situation in decays of heavy resonances into two τ leptons is even more complex. In these events, the two τ's are often produced "back-to-back" and the missing momentum associated with their neutrinos partially cancels out. As a result, the invariant mass of a resonance cannot be directly reconstructed from the $\not\!\!E_T$ and visible decay products of τ leptons. Various techniques exist to partially reconstruct the mass of resonances in $\tau\tau$ final states. However, the reconstructed mass distributions for signal processes are rather broad (with long tails and typical core resolutions on the order of $\sim 20\%$), which makes it difficult to separate them from the background and considerably reduces the signal significance. This poses a major challenge for the Higgs boson searches in the $H \to \tau\tau$ channel, one of the most important channels for discovering a low-mass Higgs boson at the LHC [1,2], whether in the context of the Standard Model or beyond (for example, in supersymmetric models). Another challenge in searching for a low-mass Higgs boson in the $\tau\tau$ channel is the large and irreducible background from $Z/\gamma^* \to \tau\tau$ events. This is because the Z/γ^* background is several orders of magnitude larger than any expected Higgs signal, and its broad partially reconstructed mass distribution completely dominates the signal region (for example, see Fig. 1 or Ref. [3]). Therefore, a major improvement in $\tau\tau$ invariant mass, $M_{\tau\tau}$, reconstruction techniques

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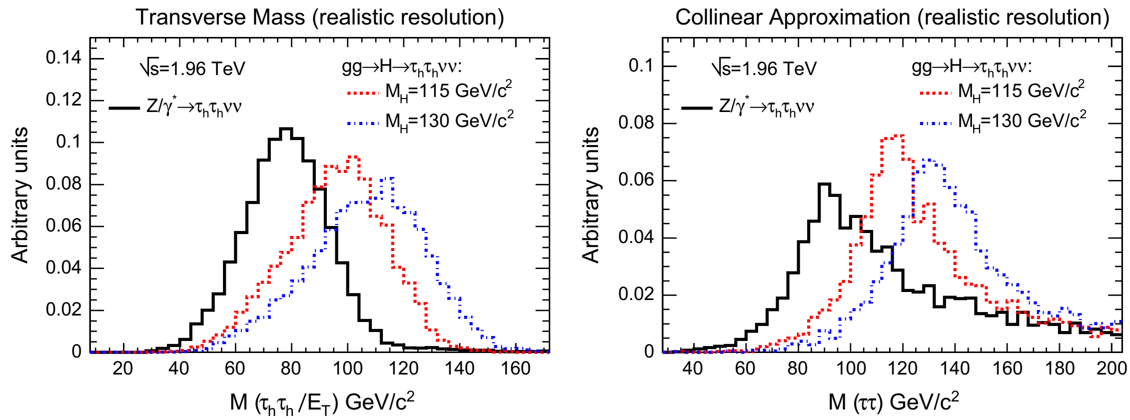

Fig. 1. Example of the transverse mass (left plot) defined as an invariant mass of $\not\!\!E_T$ and visible τ decay products, and the fully reconstructed mass (right plot) using the collinear approximation for three event samples: inclusive $Z/\gamma^* \to \tau\tau$ and $gg \to H \to \tau\tau$ with $M_H = 115$ and $130\ \mathrm{GeV}/c^2$. Results are obtained for the fully hadronic $\tau\tau$ decay mode. Events are simulated with a realistic detector resolution (discussed in Section 3.3). All distributions are normalized to unit area.

is needed in order to significantly enhance the sensitivity of $H \to \tau\tau$ searches at the Tevatron and LHC experiments.

In this paper, we propose a new method, which substantially improves the accuracy of the $\tau\tau$ invariant mass reconstruction. We expect that it will lead to a major improvement in the sensitivity of the Higgs boson searches in the $H \to \tau\tau$ channel at the Tevatron and the LHC. In the next section, we briefly review currently used methods. Section 3 describes the new technique and illustrates its performance using a Monte Carlo simulation with a realistic detector resolution. In Section 4, we report the results of tests on a clean sample of data $Z/\gamma^* \to \tau\tau$ events collected by the CDF experiment at the Tevatron. Finally, we conclude in Section 5.

2. Review of the commonly used techniques for $\tau\tau$ mass reconstruction

The two methods frequently used at hadron colliders either rely on reconstructing a partial invariant mass or use the collinear approximation. In this section, we review these techniques and discuss their advantages and shortcomings.

2.1. The transverse mass method

Neutrinos from the τ decays escape detection and make it impossible to determine the 4-momenta of τ leptons and thus $M_{\tau\tau}$. Therefore, one of the simplest and frequently used methods relies on a partial (or reduced) invariant mass reconstruction. Examples include either the invariant mass of visible decay products of the two τ leptons, the visible mass, or the invariant mass of the visible decay products and $\not\!\!E_T$ in the event, the transverse mass. The latter is defined as follows:

$$M^2(\tau_{\mathrm{vis}_1}, \tau_{\mathrm{vis}_2}, \not\!\!E_T) = P^\mu P_\mu$$

$$P^\mu = P^\mu(\tau_{\mathrm{vis}_1}) + P^\mu(\tau_{\mathrm{vis}_2}) + P^\mu(\not\!\!E_T) \tag{1}$$

where $P^\mu(\not\!\!E_T) = (\sqrt{\not\!\!E_{T_x}^2 + \not\!\!E_{T_y}^2}, \not\!\!E_{T_x}, \not\!\!E_{T_y}, 0)$ is a 4-momentum corresponding to missing transverse energy and $P^\mu(\tau_{\mathrm{vis}_1})$ and $P^\mu(\tau_{\mathrm{vis}_2})$ are the 4-momenta of the visible τ decay products. The advantage of these techniques is that the partial mass can be defined for all signal events, thus preserving the statistical power of the available data. However, ignoring or not fully accounting for the neutrino momenta biases and broadens the reconstructed $M_{\tau\tau}$ distributions, and therefore leads to a significantly reduced sensitivity in searches and measurements. This problem is particularly prominent in the low-mass $H \to \tau\tau$ search, where the signal cannot be separated from the much larger and very broad $Z \to \tau\tau$ background. To illustrate this, we use inclusive $Z/\gamma^* \to \tau\tau$ and $gg \to H \to \tau\tau$ (with $M_H = 115$ and $130\ \mathrm{GeV}/c^2$) events produced in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV. Events are simulated with Pythia [5] Monte Carlo generator supplemented with the TAUOLA package [6] for τ decays. We select events with $\not\!\!E_T > 10$ GeV and where both τ leptons have visible $p_T > 10\ \mathrm{GeV}/c$ and pseudo-rapidity[1] $|\eta| < 1$. We assume 10% resolution for hadronic τ-jets and 5 GeV resolution for x- and y-components of $\vec{\not\!\!E}_T$ (the realistic detector resolution is further discussed in Section 3.3). The left plot in Fig. 1 shows the transverse mass $M(\tau_{\mathrm{vis}_1}, \tau_{\mathrm{vis}_2}, \not\!\!E_T)$ distribution for the simulated events.

2.2. Collinear approximation technique

The collinear approximation is another frequently used technique [1,2]. This method was first proposed in Ref. [4] to reconstruct the invariant mass in $\tau\tau$ decays of a Higgs boson produced in association with an energetic jet. It is based on two important assumptions: that the τ lepton and all its decay products are collinear (i.e., $\phi_\nu = \phi_{\mathrm{vis}}$ and $\theta_\nu = \theta_{\mathrm{vis}}$); and that the $\not\!\!E_T$ in the event is due only to neutrinos. In this case, the total invisible momentum carried away by neutrinos in each τ decay can be estimated by solving two equations:

$$\not\!\!E_{T_x} = p_{\mathrm{mis}_1} \sin\theta_{\mathrm{vis}_1} \cos\phi_{\mathrm{vis}_1} + p_{\mathrm{mis}_2} \sin\theta_{\mathrm{vis}_2} \cos\phi_{\mathrm{vis}_2}$$

$$\not\!\!E_{T_y} = p_{\mathrm{mis}_1} \sin\theta_{\mathrm{vis}_1} \sin\phi_{\mathrm{vis}_1} + p_{\mathrm{mis}_2} \sin\theta_{\mathrm{vis}_2} \sin\phi_{\mathrm{vis}_2} \tag{2}$$

where $\not\!\!E_{T_x}$ and $\not\!\!E_{T_y}$ are the x- and y-components of the $\vec{\not\!\!E}_T$ vector, p_{mis_1} and p_{mis_2} are the combined invisible momenta (there can be two ν's in a τ decay) of each τ decay, and $\theta_{\mathrm{vis}_{1,2}}$ and $\phi_{\mathrm{vis}_{1,2}}$ are the polar and azimuthal angles of the visible products of each τ decay. Then, the invariant mass of the $\tau\tau$-system can be calculated as $M_{\tau\tau} = m_{\mathrm{vis}}/\sqrt{x_1 x_2}$, where m_{vis} is the invariant mass of visible τ decay products, and $x_{1,2} = p_{\mathrm{vis}_{1,2}}/(p_{\mathrm{vis}_{1,2}} + p_{\mathrm{mis}_{1,2}})$ are momentum fractions carried away by visible τ decay products. Despite offering the great advantage of a fully reconstructed $\tau\tau$ mass ($M_{\tau\tau}$) instead of a partial visible mass, the collinear approximation still has significant shortcomings. The technique works well for events where the

[1] The pseudo-rapidity is defined as $\eta = -\ln\tan\theta/2$, where θ is a polar angle respect to the beam line.