Reconstruction of the Higgs Mass in $H \rightarrow \tau\tau$ Events by Dynamical Likelihood techniques

Christian Veelken - LLR/École Polytechnique 91128 Palaiseau - France

1. Motivation
Several scenarios for physics beyond the Standard Model (SM) predict an enhanced production of tau leptons. The sensitivity of analyses searching for “new physics” models is enhanced significantly by analyzing the distribution of the tau-pair mass, $M_{\tau\tau}$, in selected events, compared to performing simple counting experiments. The gain in sensitivity depends to a large extent on the separation between potential signals and the dominant irreducible SM background, $Z/\gamma^{*} \rightarrow \tau\tau$ Drell-Yan production, i.e. on the resolution of the algorithm:

An improvement in mass resolution increases the sensitivity in searches for “new physics”, leading either to earlier discovery or to more stringent exclusion limits.

The compatibility to reconstruct $M_{\tau\tau}$ arises from the fact that with a lifetime of $\sim 87$μm taus leptons decay almost instantaneously: The neutrinos produced in tau decays escape detection, carrying away an unknown amount of energy and momentum.

2. Kinematics of Tau lepton decays
In about two-thirds of the cases taus decay into a system of hadrons (mostly charged and neutral pions) plus a tau neutrino. The kinematics of hadronic tau decays is described by 2 parameters:

- $X$, the fraction of tau lepton energy (in the laboratory frame) carried by the visible decay products
- $\phi$, the azimuthal angle of the tau lepton in the laboratory frame.

In about one-third of the cases taus decay into electron or muon plus 2 neutrinos. The kinematics of leptonic tau decays are described by 3 parameters: $X$, $\phi$ and $m_{\nu\nu}$, the mass of the neutrino system.

3. Likelihood Formalism
The probability density $p$ is taken to be zero.

The likelihood model is used to compute probabilities:

$$P(M_{\tau\tau} | \mu) = \int \delta (M_{\tau\tau} - \mu_{\tau\tau} | \mu) p(\bar{\mu} | \mu) d\bar{\mu}$$

for a series of mass hypotheses $M_{\tau\tau}$. The integral on the right hand side corresponds to taking a weighted average over all hypothetic configurations which are compatible with the measured observables $\bar{\mu}$, a technique known as marginalisation.

The best estimate $\mu_{\tau\tau}$ for the tau pair mass is taken to be the maximum of $P(M_{\tau\tau})$ within the series.

Lower (upper) limits on the reconstructed mass $\mu_{\tau\tau}$ are determined for every event by the 0.16 (0.84) quantiles of the series of mass hypotheses $M_{\tau\tau}$ and associated probability values $P(M_{\tau\tau})$.

4. Phase-Space model for hadronic Tau decays
Decays of taus into hadrons, $\tau \rightarrow \tau_1 \nu_\tau$, are described by a model motivated by two-body phase-space considerations, assuming the system of all hadrons produced in the tau decay to constitute one “particle” (of mass $m_{\tau\tau}$):

$$d\Gamma = \frac{1}{2\pi} \frac{1}{1 - \frac{m_{\tau\tau}^2}{M^2}}$$

The region allowed by tau decay kinematics is $m_{\tau\tau}^2 \leq X \leq 1$. Outside of this region the probability density $p$ is taken to be zero.

The phase-space model represents well the sum of all hadronic decay modes, as comparison with detailed Monte Carlo simulation [1] demonstrates.

5. Matrix Element for leptonic Tau decays
Decays of taus into electrons and muons, $\tau \rightarrow l \nu_l$, are described by the Matrix Element [2]:

$$\frac{d\Gamma}{dXd\phi} \propto \frac{m_{\tau\tau}^4}{4m_{\nu}^2} \left( m_{\tau\tau}^2 + 2m_{\nu}^2 \right)^{\Gamma/2}$$

The physically allowed region is given by $0 \leq X \leq 1$ and $0 \leq m_{\nu} \leq m_{\tau}\sqrt{1-X}$.

Comparison with the detailed Monte Carlo simulation shows that a simple phase-space model is not adequate to describe leptonic tau decays.

6. $E_T$ Likelihood
The compatibility of a given tau decay hypothesis with the measured transverse energy is described by the likelihood:

$$L_{MET} = \frac{1}{2\pi V} \exp \left( -\frac{1}{2} \left( E_{l\nu} - \sum p_{E_{l\nu}} \right)^T V^{-1} \left( E_{l\nu} - \sum p_{E_{l\nu}} \right) \right)$$

assuming that the neutrinos of momentum $p_{\nu\nu}$ produced in the tau decays are the only source of missing transverse energy in the event.

$|V|$ denotes the determinant of $V$.

The components $E_{l\nu} = \sum p_{E_{l\nu}}$ and $E_{l\nu} = -\sum p_{E_{l\nu}}$ are computed by summing the momenta of all particles reconstructed by the particle-flow algorithm [3].

The expected resolution of the $E_T$ reconstruction is represented by the covariance matrix $V$ and is estimated on an event-by-event basis using the $E_T$-significance algorithm [4].

7. Performance
The $M_{\tau\tau}$ resolution achieved by the algorithm typically amounts to 15-20% relative to the true mass of the tau pair.

The figures on the right show the distribution of $M_{\tau\tau}$ reconstructed in Monte Carlo simulated events for a SM Higgs signal of $m_H = 125$ GeV and $Z/\gamma^{*} \rightarrow \tau\tau$ background events, compared to an alternative observable, the mass of the visible decay products of the two taus, in the channel where one tau decays into hadrons and the other into a muon.

The reconstruction of the tau-pair mass is clearly seen to improve the signal-to-background separation.

Overall the sensitivity of the Higgs $\rightarrow \tau\tau$ analysis increases by about 30%, corresponding to adding 70% more data.

The computation of the integrals [*] is performed numerically, using the VEGAS [5] algorithm. The average time needed to compute $M_{\tau\tau}$ amounts to 1 second per event.

References: