Reconstruction of the Higgs Mass in H → ττ Events by Dynamical Likelihood techniques

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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, $Z/\gamma^* \to \tau\tau$ 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 complication to reconstruct $M_{\tau\tau}$ arises from the fact that with a lifetime of $c\tau = 87\mu m$ tau 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
- ϕ, 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**, ϕ and

- $m_{\nu\nu}$, the mass of the neutrino system.

3. Likelihood Formalism

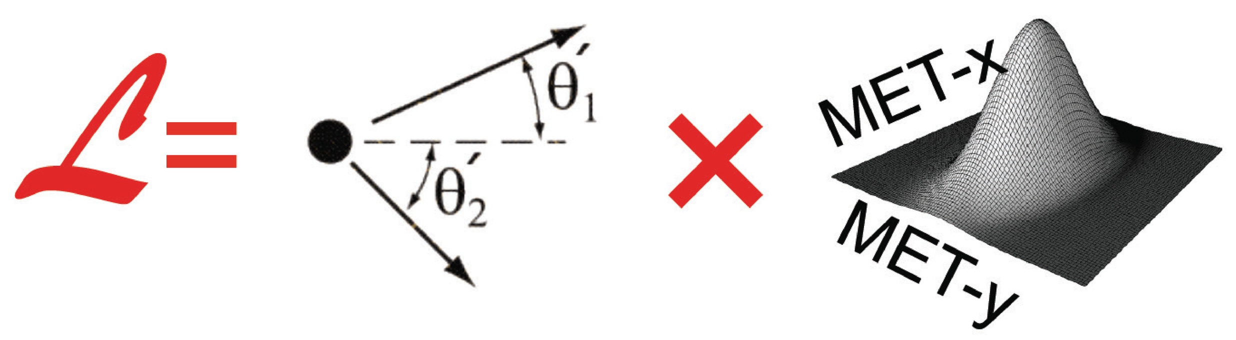
The number of parameters needed to describe tau-pair decays:

- 4 if of both taus decay hadronically
- 5 if one tau decays to hadrons and the other tau into an electron or muon
- 6 if both taus decay leptonically

are constrained by only 2 measurements: the components $\not{E}_x$ and $\not{E}_y$ of the missing transverse momentum reconstructed in the event.

The fact that the reconstruction of tau decay kinematics is underconstrained by measured observables is addressed via a likelihood approach.

$M_{\tau\tau}$ values are reconstructed by combining the measured observables $\not{E}_x$ and $\not{E}_y$ with a probability model, which includes terms for tau decay kinematics and for the missing transverse energy resolution:



The model makes a prediction for the probability density $p(\vec{x}|\vec{y},\vec{a})$ to observe the values $\vec{x} = (\not{E}_x, \not{E}_y)$ measured in an event, given that the unknown parameters specifying the kinematics of the tau pair decay have values $\vec{a} = (X_1, \phi_1, m_{\nu\nu}^1, X_2, \phi_2, m_{\nu\nu}^2)$ and the momenta of the visible decay products are equal to the observed $\vec{y} = (p_1^{vis}, p_2^{vis})$.

In case of hadronic tau decays $m_{\nu\nu}$ is treated as a constant of value zero.

The likelihood model is used to compute probabilities:

$$P(M^i_{\tau\tau}) = \int \delta\left(M^i_{\tau\tau} - M_{\tau\tau}(\vec{y},\vec{a})\right) p(\vec{x}|\vec{y},\vec{a}) d\vec{a} \qquad [*]$$

for a series of mass hypotheses $M^i_{\tau\tau}$.

The integral on the right hand side corresponds to taking a weighted average over all hypothetic configurations which are compatible with the measured observables $\vec{y}$, a technique known as **marginalization**.

The weight is given by the probability density p.

The best estimate $\hat{M}_{\tau\tau}$ for the tau pair mass is taken to be the maximum of $M^i_{\tau\tau}$ within the series.

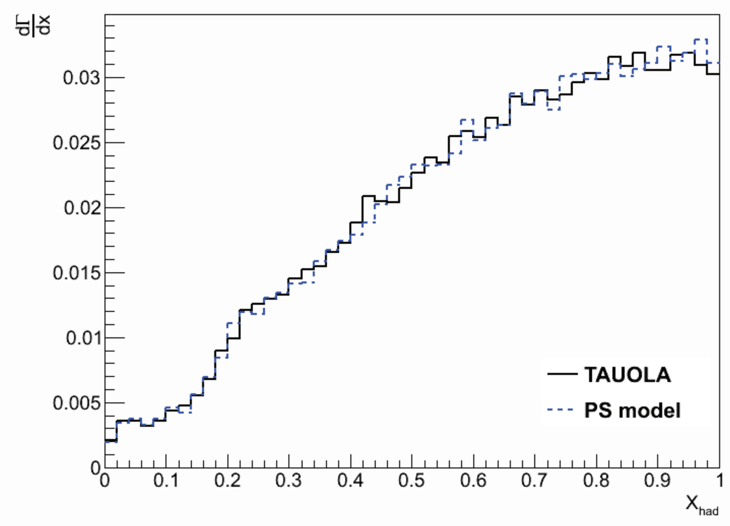
Lower (upper) limits on the reconstructed mass $\hat{M}_{\tau\tau}$ are determined for every event by the 0.16 (0.84) quantiles of the series of mass hypotheses $M^i_{\tau\tau}$ and associated probability values $P(M_{\tau\tau})$.

4. Phase-Space model for hadronic Tau decays

Decays of taus to hadrons, $\tau \to \tau_{had}\nu$, 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_{vis}):

$$\frac{d\Gamma}{dX d\phi} = \frac{1}{2\pi}\left(\frac{1}{1-\frac{m^2_{vis}}{m^2_\tau}}\right).$$

The region allowed by tau decay kinematics is $\frac{m^2_{vis}}{m^2_\tau} \leq X \leq 1$. 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.

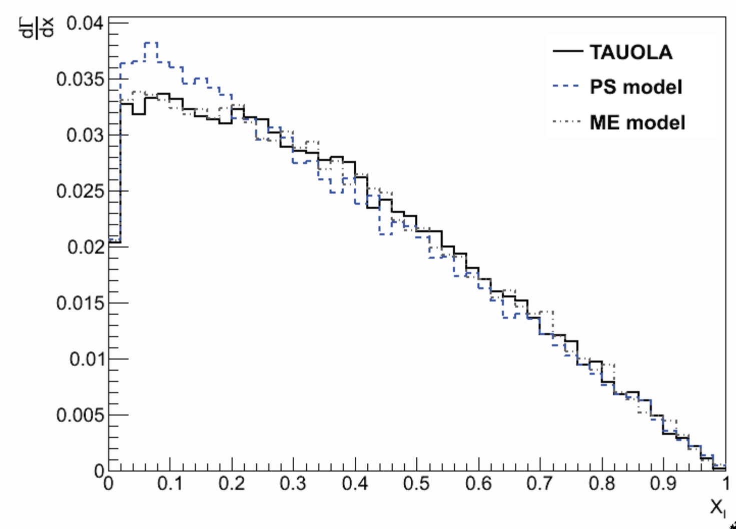
5. Matrix Element for leptonic Tau decays

Decays of taus into electrons and muons, $\tau \to l\nu\nu$ (l = e, μ), are described by the Matrix Element[2]:

$$\frac{d\Gamma}{dX dm_{\nu\nu} d\phi} \propto \frac{m_{\nu\nu}}{4m^2_\tau}\left[(m^2_\tau + 2m^2_{\nu\nu})(m^2_\tau - m^2_{\nu\nu})\right].$$

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

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



6. $\not{E}_T$ Likelihood

The compatibility of a given tau decay hypothesis with the measured transverse energy is described by the likelihood:

$$\mathcal{L}_{MET} = \frac{1}{2\pi\sqrt{|V|}} \cdot \exp\left(-\frac{1}{2}\begin{pmatrix}\not{E}_x - \sum p^\nu_x \\ \not{E}_y - \sum p^\nu_y\end{pmatrix}^T \cdot V^{-1} \cdot \begin{pmatrix}\not{E}_x - \sum p^\nu_x \\ \not{E}_y - \sum p^\nu_y\end{pmatrix}\right),$$

assuming that the neutrinos of momentum p^ν produced in the tau decays are the only source of missing transverse energy in the event.

$|V|$ denotes the determinant of V.

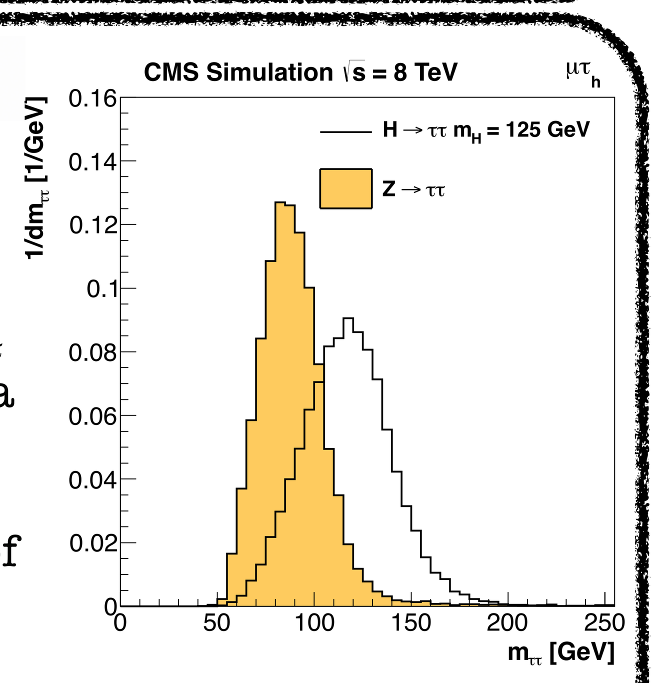
The components $\not{E}_x = -\sum p^{rec}_x$ and $\not{E}_y = -\sum p^{rec}_y$ are computed by summing the momenta of all particles reconstructed by the particle-flow algorithm [3].

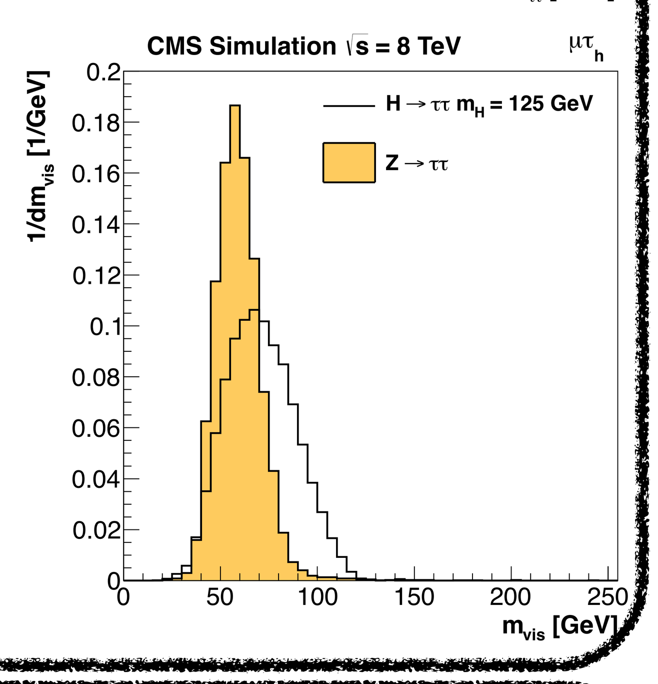
The expected resolution of the $\not{E}_T$ reconstruction is represented by the covariance matrix V and is estimated on an event-by-event basis using the $\not{E}_T$ -significance algorithm [4].

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 $Z/\gamma^* \to \tau\tau$ 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 → ττ 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:

[1] S. Jadach, Z. Was, R. Decker et. al.: "The Tau Decay Library Tauola: Version 2.4", Comput. Phys. Commun. 76 (1993) 361.
[2] K. Hagiwara, B.K Bullok and A.D. Martin: "Tau polarization and its correlations as a probe of new physics", Nucl. Phys. B 395 (1993) 499.
[3] CMS Collaboration: "Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus, and Missing E_T", CMS PAS PFT-09-001 (2009).
[4] CMS Collaboration: "Missing transverse energy performance of the CMS detector", JINST 6 (2011) 9001.
[5] G.P. Lepage, "A New Algorithm for Adaptive Multidimensional Integration", J. Comput. Phys. 27 (1978) 192.