Likelihood-based Technique for Measuring the Energy of Hadronically Decaying Tau Leptons

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Motivation

- Efficient tau lepton identification and accurate energy measurement play a key role in many searches for new physics and can be indispensable in certain scenarios:
  - mSUGRA with large tanβ, SUSY in stau-coannihilation region, MSSM Higgs searches, NMSSM scenarios with expanded Higgs sector etc.

- Tau branching ratio to hadrons 64%
  - many analyses at CDF use hadronic decay mode
Motivation

Can we do any better?

Challenge for Particle-Flow at CDF:

- Large calorimeter segmentation $(\Delta \eta = 0.1) \times (\Delta \phi = 15^\circ)$
- Small tau size $(5^\circ - 10^\circ)$

A new method proposed here provides many significant improvements:

- Better energy scale and significantly better resolution
- Uncertainty of the energy measurement on a jet-by-jet basis
- Improved separation of hadronic taus from jet backgrounds
- Expandable on the more general case of quark/gluon jets (not yet implemented)
Likelihood ingredients:

1) **measured quantities:** detector responses associated with tau candidate
2) **set of parameters:** decay products content and energies

\[ L = f(\text{detector responses} | \text{particles and energies}) \]

**Likelihood output:** probability that the assumed combination of particles of given momenta could have produced observed response of detector sub-systems

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**CDF detector and tau leptons**

Central Outer Tracker (COT)
Electromagnetic Calorimeter (EM)
Central Electromagnetic Shower (CES)
Hadronic Calorimeter (HAD)

*strip-wire chamber inside EM at the expected maximum of lateral electromagnetic shower profile*

To reconstruct tau energy we use Likelihood based on particle's type-specific signatures in the detector sub-systems
Calorimeter response (Monte Carlo)

charged pions

- take into account correlation between energy depositions in EM and HAD
- EM: 1 tower
- HAD: 3x3 towers

photons / electrons

- assume no difference in responses between photons and electrons
- EM: 1 tower
- HAD: 1 tower

isolated $\pi^\pm$, $25 < E_\pi < 26$ GeV, MC

isolated electrons, $25 < E_e < 26$ GeV, MC

We use MC to determine response functions for each particle type in the energy range from 1 to 100 GeV with a step of 1 GeV. This set of functions we consider as particle's PDF.

$$p.d.f. = f^{\text{Calorimeter}}_\pi (E^{EM}, E^{HAD} | E_\pi)$$

$$p.d.f. = f^{\text{Calorimeter}}_\gamma (E^{EM}, E^{HAD} | E_\gamma)$$
Shower Max response (Monte Carlo)

MIP response to charged pions – can be ignored in the likelihood.

assumes no difference in responses between photons and electrons

isolated electrons, 25 < \( E_e < 26 \) GeV, MC

\[
p.d.f. = f_{\gamma}^{\text{ShowerMax}}(E_{\text{CES}} | E_{\gamma})
\]

Shower Max helps determine particle content
Construction of the likelihood

\[ L = f_{\pi \gamma}^{\text{Calorimeter}} (E^{\text{EM(5)}}, E^{\text{HAD}} \mid E_\gamma, E_\pi) \times f_{\gamma}^{\text{ShowerMax}} (E^{\text{CES}} \mid E_\gamma) \]

- \( E_\pi \) – measured in the Tracker, fixed parameter
- \( E_\gamma \) – likelihood maximization
- visible tau energy \( E_\tau^{\text{rec}} = E_\pi + E_\gamma \)
- use shape of \( L (E_\gamma) \) to estimate uncertainties

response to a combination of particles could be derived from response functions measured for isolated particles!

\[ f_{\pi \gamma}^{\text{Calorimeter}} = \int_0^{E^{\text{EM}}} \int_0^{E^{\text{HAD}}} f_\pi (x, y; E_\pi) \times f_\gamma (E^{\text{EM}} - x, E^{\text{HAD}} - y; E_\gamma) \, dx \, dy \]

We can handle more complicated events too. Just need more CPU time for numerical calculation of the integrals involved.
An example on how the likelihood works

Tracker: $p_T = 13.8$ GeV/c
EM: $E_{\text{dep}} = 8.4$ GeV
HAD: $E_{\text{dep}} = 6.1$ GeV
Shower Max: cluster = 8.0 GeV
True photon energy = 5.1 GeV
Reconstruction of visible tau energy

Tau selection for these plots:
- MC Dataset $Z \rightarrow \tau\tau$
- tau selection is done on generator level: any tau decaying hadronically
- only one $\pi^0$ in the final state
- seed track $Pt > 6$ GeV
- $|\eta|<1$
Reconstruction of visible tau energy

Event selection: - MC Dataset $Z \rightarrow \tau \tau$, one tau decays in hadronic mode another decays to electron - at least one photon in the tau jet is required

Selection of hadronically decaying taus:
- highest track $p_T > 6$ GeV/c ;
- $|\eta| < 1$ ; $d_0 < 0.2$ cm ;
- $M_{\text{trk}} \leq 1.8$ GeV/c$^2$ ;
- $N_{\text{trk}}^{\tau,\Delta\theta} = 0$ ; $I_{\pi^0}^{\tau,\Delta\theta} \leq 0.6$ GeV/c ;
- $N_{\text{trk}}^{\tau,\text{cone}} = 1$ or $3$ ;
- $N_{\pi^0}^{\tau,\text{cone}} > 0$

Likelihood based algorithm improves both the energy resolution and the mean value
Reconstruction of $\rho(770)$ invariant mass. MC.

40% of all hadronic taus decay via $\rho(770)$: $\tau^\pm_h \rightarrow \nu_\tau + \rho^\pm \rightarrow \nu_\tau + \pi^0 + \pi^\pm$

Invariant mass of the $\rho(770)$ is very sensitive to relatively small perturbations in 4-momentum assigned to $\pi^0$ and $\pi^\pm$. Good test for likelihood-based method.

$Z \rightarrow \tau_h \tau_\mu$ and $Z \rightarrow \tau_h \tau_e$ modes allow to control background

Only 1 prong taus with at least one $\pi^0$ identified by both algorithms are considered.

Due to differences in Shower Max clustering two algorithms could disagree on the number of $\pi^0$ candidates. To get closer to “apes to aples” comparison we avoid events with no $\pi^0$ reconstructed by one of the algorithms.
Tau selection in data ($Z \rightarrow \tau_\text{h} \tau_\text{e}$ and $Z \rightarrow \tau_\text{h} \tau_\text{\mu}$)

$p_T$ distributions of leptons (e/\mu) and hadronic taus agree well with MC.

Events with 1 prong hadronic taus

Background estimated from “same sign” events in data. Limited by statistics.

Purity of 1 prong taus that are used to extract $\rho(770)$ is better than 95%.
Reconstruction of $\rho(770)$ invariant mass. Data.

$$\tau^+ -\nu_\tau + \rho^+ \rightarrow \nu_\tau + \pi^0 + \pi^\pm$$

1 prong taus with at least one $\pi^0$ identified by both algorithms most likely to contain $\rho(770)$.
Summary

- The likelihood based method allows a substantially improved energy measurement (scale and resolution)
- Power of the method is demonstrated in data with the tau jet invariant mass measurement (which is notoriously hard to improve)
- Ability to measure uncertainty on a jet-by-jet basis allows both reduction of backgrounds (those will be more often poorly measured due to neutral hadrons and more soft particles) and selection of "golden" events in analysis
- Exploring use of overall likelihood value in suppressing backgrounds
- Expansion on the case of regular jets is being considered and can provide a substantial improvement in higgs searches (e.g. in WH → ℓνbb)
- The likelihood based algorithm is now being deployed in a new H → ℏℏ analysis