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Tau lepton reconstruction at collider experiments using impact parameters

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ABSTRACT

We present a method for the reconstruction of events containing hadronically decaying τ leptons at collider experiments. This method relies on accurate knowledge of the τ production vertex and precise measurement of its decay products. The method makes no assumptions about the τ kinematics, and is insensitive to momentum loss along the beam direction. We demonstrate the method using $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$ events fully simulated in the ILD detector.

1. Introduction

Studies of final states including τ leptons are of interest at current and future collider experiments; as an example, the dominant leptonic decay of the Higgs boson is to a τ pair. A new generation of high energy particle colliders [1–4] is presently under study. A key scientific aim of these facilities is to measure the Higgs boson's properties with great precision, important aspects of which involve measurements of the τ final state. An example is the use of measurements of the τ spin state to probe the CP nature of the Higgs boson. The detectors being designed for use at these accelerators will be equipped with vertex detectors providing unprecedented impact parameter resolution (see *e.g.* [5]), giving rise to intriguing possibilities in the reconstruction of relatively long-lived states such as the τ lepton.

We report on a method which uses a high-precision vertex detector together with other tracking and calorimetric detectors to fully reconstruct the kinematics of events containing hadronically decaying τs (*i.e.* decays in which only one ν is produced) in an unbiased way. We outline previously used techniques for the kinematic reconstruction of single-ν τ decays in Section 2. In Section 3 we define a new procedure which, in certain topologies, can fully reconstruct the τ kinematics with significantly less stringent assumptions than previous approaches. This new method is then applied to $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$ events in Section 4, and we conclude in Section 5.

2. Previous approaches to τ pair reconstruction

In the case of events containing a pair of τ leptons each decaying to a single neutrino, the following method, which assumes knowledge of the rest-frame and invariant mass of the τ pair, but no knowledge about the τ production vertex, is often used at lepton colliders (*e.g.* [6,7]). The τ-pair rest-frame can be assumed to be the centre-of-mass of the colliding beams (in the case of the $e^+e^- \rightarrow \tau^+\tau^-$ process), or the frame recoiling against particles produced in conjunction with the τ pair, as in the case $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$. The τ decay products are then boosted into the assumed τ pair rest frame, in which the energy of the τs is defined by the assumed invariant mass of the τ pair. The τ mass then constrains the τ momentum to be at a fixed angle to the momentum of its hadronic decay products, defining a cone around the hadronic momentum. The two cones in an event, one per τ, have either 0, 1, or 2 intersections, corresponding to the possible solutions for the τ momenta.

At hadron colliders, the unknown net momentum along the beam direction results in less available information to constrain the event kinematics. The invariant mass of τ pairs can be partially estimated using the invariant masses of visible decay products and the missing transverse energy, or by applying the approximation that the ν from τ decay is collinear with the visible τ decay products [8]. Another approach is to combine the measured momenta of visible τ decay products with constraints on the τ mass and global event transverse momentum balance, resulting in an under-constrained system. The likelihood of the various τ decay topologies allowed by the constraints can then be used to choose a best solution, or alternatively to associate a weight to each solution *e.g.* [9–11].

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If the τ production vertex is precisely known, the use of the impact parameters of the charged τ daughters (prongs) brings additional information. The knowledge of the production vertex can come from the reconstruction of particles recoiling against the τs, or from *a priori* knowledge of the interaction point, if the size of the interaction region is sufficiently smaller than the impact parameters of the τ decay products. The use of the impact parameter vectors of charged τ daughters, without full reconstruction of τ decay kinematics, in the analysis of Higgs boson CP properties has been described in *e.g.* [12,13], while their use in fully reconstructing di-τ systems of known invariant mass and momentum has been demonstrated in [14,15].

3. Method

In this section we present methods that can, under certain conditions, fully reconstruct a τ without assuming that it belongs to a τ pair of particular invariant mass or centre-of-mass frame. In Section 3.2 we consider the reconstruction of hadronic single prong final states, in which a single charged hadron is produced with zero or more neutral hadrons and a single neutrino. Such decays account for 49.5% of τ decays. Multiprong hadronic τ decays, in which three or more charged hadrons, zero or more neutral hadrons, and a single neutrino are produced, account for 15.3% of τ decays, are discussed in Section 3.3. Leptonic decays of the τ (35.2%) provide significantly less measurable information about its decay kinematics due to the production of two neutrinos, and are not further considered in this paper.

The method relies on precise knowledge of the τ production vertex and the charged prong trajectories, and on the reconstruction of any neutral hadrons produced in the decay. Constraints on the invariant mass and lifetime of each τ, and on the overall transverse momentum in the event, are then used to determine the τ momenta.

3.1. Tau production vertex

The uncertainty on the τ production position should be small in comparison to the decay length of the τ and the typical impact parameters of its decay products. In final states in which the τs are produced together with more than one prompt charged particle, the production vertex can be directly reconstructed on an event-by-event basis using the tracks of these particles (*e.g.* the μs in the process $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$). The proposed linear electron–positron colliders [1,2] have rather small interaction regions, which may be used as an additional constraint on the interaction point, although this is not done for the results presented in this paper.

3.2. Single prong τ decays

3.2.1. Tau decay plane

In the case of single prong hadronic τ decays, the trajectory of the charged prong (helical in the usual case of a uniform magnetic field) can be used to define a plane (hereafter called the “track plane”) which contains two vectors: $\mathbf{d}$, the vector between the reconstructed interaction point (IP, assumed to be the τ production vertex) and the point on the trajectory closest to the IP (point of closest approach PCA); and $\mathbf{p}$, the tangent to the trajectory at the PCA. In the case of linear trajectories of the τ and of the prong between the PCA and the τ decay vertex, the τ momentum, and therefore also the sum of the momenta of the other decay products of the τ (neutrinos and neutral hadrons), are constrained to lie within this plane.

The difference between the reconstructed track plane and the true τ decay plane (defined by the τ and prong momenta) depends on the decay length of the τ, the accuracy with which the IP position is known, the precision of the charged prong trajectory, and the extent to which the linear approximation of the τ and prong trajectories near the IP is valid.[1]

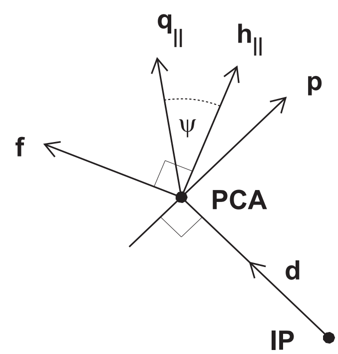

Fig. 1. Parameterisation of the neutrino momentum in the track plane ($\mathbf{q}_{\parallel}$) in terms of the vectors $\mathbf{h}_{\parallel}$ and $\mathbf{f}$, and angle ψ. The track plane is defined by the vectors $\mathbf{p}$ and $\mathbf{d}$.

3.2.2. Parameterisation of neutrino momentum

In this section we describe the parameterisation of the unmeasured neutrino momentum, $\mathbf{q}$, based on the measured prong trajectory and neutral hadron momentum.

Neutral particles are measured as clusters in the calorimeters, or as identified conversions of photons into e^+e^- pairs within the tracker volume. The momentum to be associated to calorimeter clusters can be estimated by assigning the energy of the calorimeter cluster, a mass hypothesis (*e.g.* zero in the case of photon-like clusters, the K_L mass for hadronic clusters), and the direction of a straight line connecting the IP and the energy-weighted mean position of the calorimeter cluster.[2]

The three-momentum $\mathbf{k}$ of the neutral hadronic system can be decomposed into components perpendicular to and within the track plane: $\mathbf{k}_\perp$ and $\mathbf{k}_\parallel$ respectively. Since the τ momentum lies within the track plane, the hadronic momentum perpendicular to the track plane must be balanced by the neutrino, so the perpendicular component of the neutrino momentum $\mathbf{q}_\perp = -\mathbf{k}_\perp$.

The component of the neutrino momentum within the track plane can completely generally be parameterised as

$$\mathbf{q}_\parallel = Q \cdot (\cos\psi \cdot \hat{\mathbf{h}}_\parallel + \sin\psi \cdot \hat{\mathbf{f}}), \quad (1)$$

[3] where Q is the unknown magnitude of the in-plane component of the neutrino momentum, $\mathbf{h}_\parallel$ is the component of the total hadronic momentum ($\mathbf{h} = \mathbf{p} + \mathbf{k}$) in the track plane, and the unit vector $\hat{\mathbf{f}} \equiv \mathbf{f}/|\mathbf{f}|$, where $\mathbf{f} = \mathbf{h}_\parallel \times (\mathbf{d} \times \mathbf{h}_\parallel)$, is within the plane and perpendicular to $\mathbf{h}_\parallel$ (Fig. 1).

Four-vectors p, k, and q corresponding to the three-momenta $\mathbf{p}$, $\mathbf{k}$, and $\mathbf{q}$ can be defined by means of appropriate invariant mass assumptions. The invariant mass of the sum of four-vectors p, k, and q must be equal to the τ lepton mass m_τ. This constraint allows us to write an equation involving Q and $\hat{\mathbf{q}}_\parallel$ (which in turn

[1] The error in this linear approximation scales as the ratio of the decay length of the τ to the radius of curvature of the prong: for a prong with $p_T = 10$ GeV/c produced by a 50 GeV τ of average lifetime, in a field of 3.5 T, this ratio is $< 10^{-3}$. An iterative approach, in which a first iteration uses the helix parameters at the PCA to the IP, while later iterations use the helix parameters at the calculated τ decay position, should reduce any sensitivity to the prong's curvature.

[2] Alternative definitions are possible: for example the line connecting a first estimate of the τ decay position to the identified start of the calorimetric shower.

[3] We define $\hat{\mathbf{x}}$ to be a unit vector parallel to $\mathbf{x}$.