We study the observability for a lepton flavor-changing decay of a Higgs boson $h \rightarrow \mu \tau$ at hadron colliders. Flavor-changing couplings of a Higgs boson exist at tree level in models with multiple Higgs doublets. The $h_{\mu \tau}$ coupling is particularly motivated by the favorable interpretation of $\nu_\mu - \nu_\tau$ oscillation. We find that at the Tevatron Run II the unique $\mu \tau$ signature could serve as the Higgs discovery channel, surpassing expectations for Higgs boson searches in the SM and in a large parameter region of the MSSM. The sensitivity will be greatly improved at the LHC, beyond the coverage at a muon collider Higgs factory.

The standard model (SM) of electroweak interactions and many of its extensions generically predict the existence of Higgs bosons. Detecting Higgs bosons and studying their properties in future collider experiments would provide crucial information for the mechanism of electroweak symmetry breaking and hopefully fermion flavor physics as well. These have been the most prominent issues in contemporary particle physics.

The upgraded Fermilab Tevatron will start its mission next year with c.m. energy $\sqrt{s} = 2$ TeV and an annual luminosity $L \approx 2$ fb$^{-1}$ per detector (Run IIa). Ultimately, one would hope to reach an integrated luminosity of $L \approx 15 - 30$ fb$^{-1}$ (Run IIb). In terms of the search for the SM Higgs boson ($h$), the most promising processes beyond the LEP2 reach would be electroweak gauge boson-Higgs associated production $pp \rightarrow Wh, Zh$. The leptonic decays of $W, Z$ provide a good trigger and $h \rightarrow b\bar{b}$ may be reconstructible with adequate $b$-tagging and $b\bar{b}$ mass resolution, allowing a Higgs boson reach of $m_h \approx 120 - 130$ GeV [3]. For a heavier Higgs boson $m_h \approx 2M_W$, the leading production channel via gluon fusion $gg \rightarrow h\bar{h}$ and the relatively clean decay mode $h \rightarrow WW^* \rightarrow \ell\ell\nu\bar{\nu}$ may be useful in digging out a weak Higgs boson signal [3]. It is believed that a SM-like Higgs boson may be observable up to a mass of about 180 GeV at a $3\sigma$ statistical level for $L \approx 25$ fb$^{-1}$ [3]. In the minimal supersymmetric extension of the standard model (MSSM), the mass of the lightest CP-even Higgs boson is bounded by $m_h \lesssim 130$ GeV [4]. When the CP-odd Higgs state ($A$) of the MSSM is heavy $m_A \gtrsim 2M_Z$, the lightest Higgs boson has SM-like properties and the conclusion for a light SM Higgs boson search remains valid in a large parameter region of the MSSM. The only exception is when $m_A \sim \mathcal{O}(M_Z)$ and $\tan\beta$ (ratio of the Higgs vacuum expectation values) is large, where the production of $bbh, b\bar{b}A$ is enhanced by $\tan^2\beta$ and $h, A \rightarrow bb, \tau\bar{\tau}$ may be accessible [5]. At the CERN Large Hadron Collider (LHC) with $\sqrt{s} = 14$ TeV and $L \approx 100 - 300$ fb$^{-1}$, one expects to fully cover the range of theoretical interest $m_h \lesssim 1$ TeV for the SM Higgs boson, or to discover at least one of the MSSM Higgs bosons [6].

The Higgs sector is the least constrained in theories beyond the SM. It is thus prudent to keep an open mind when studying Higgs physics phenomenologically and experimentally. A particularly important question about the Higgs sector is its role in fermion flavor dynamics, i.e., the generation of fermion masses and flavor mixings. There have been attempts to explain flavor mixings by a generalized Higgs sector with multiple Higgs doublets. It is argued [7] that the fermion flavor mixing structure due to the Higgs coupling at tree level can be of the form,

$$\kappa_{ij} \frac{\sqrt{m_i m_j}}{v} h^{0} \bar{\psi}_i \psi_j ,$$

where $i,j$ are generation indices and $v \approx 246$ GeV is the Higgs vacuum expectation value. $\kappa_{ij}$ is a product of the model parameter $\lambda_{ij}$ and the neutral Higgs mixing $\cos \alpha$ [7]. Although they are free parameters without a priori knowledge of a more fundamental theory, $\lambda_{ij}$ is naturally order of unity from a model-building point of view and $\cos \alpha = 1$ corresponds to no Higgs mixing. Such Higgs-fermion couplings would yield flavor-changing neutral currents, and therefore lead to rich phenomenology [8,1]. However, transitions involving the light generations are naturally suppressed and the largest couplings occur between the third and second generations.

In this Letter we explore the lepton flavor-changing coupling $\kappa_{\mu \tau}$ of a Higgs boson. This is particularly motivated by the favorable interpretation for $\nu_\mu - \nu_\tau$ flavor oscillation from recent atmospheric neutrino experiments [12]. If a large mixing between $\nu_\mu$ and $\nu_\tau$ exists as indicated by the Super-K experiment [12], then it will necessarily lead to the decay $h \rightarrow \mu \tau$. The branching fraction depends on the particular model of the Higgs sector, which can be parameterized by $\kappa_{ij}$. The current constraints on this coupling from low energy experiments are rather weak, giving $\lambda_{\mu \tau} < 10$ derived from the muon anomalous magnetic moment [8]. Other low energy probes are not expected to be sensitive enough to reach the natural size $\lambda_{\mu \tau} \sim \mathcal{O}(1)$. The potentially interesting lepton flavor-changing decay modes for a Higgs...
A probe for the coupling to a level of LHC, the sensitivity is substantially improved leading to extending the mass coverage to 160 GeV.

Well as the final states from the $h$ channel for $\tau^+\tau^-$ and the distinctive kinematics of the signal final state, the comparison to the $\mu\tau$ mode, assuming $\kappa_{\mu\tau} = 1$. The production is SM-like as $\tau^+\tau^-$ modes. This is the primary reason for the limitation to a low Higgs mass ($m_h < 140$ GeV) if $\kappa_{\mu\tau} > 1$. There may be about 10--40 events produced at the Tevatron and 100--4000 events at the LHC.

The signal final state $\mu\tau$ is quite unique: two flavor-changing charged leptons back-to-back in the transverse plane without much hadronic activity. To estimate the observability of the signal in hadron collider environments, we consider the $\tau$ to decay to an electron or (at least one charged) hadrons, excluding the mode to a muon. We do not require explicit $\tau$ tagging in the analysis. We simulate the detector coverage at the Tevatron (LHC) by imposing some "basic cuts"

$$p_T^\mu > 20 \text{ GeV, } p_T^\ell > 10 \text{ GeV, } |\eta| < 2 \text{ (2.5)},$$

where $p_T^\mu$ ($p_T^\ell$) is the transverse momentum for the muon (charged track and other observable hadrons from $\tau$ decay), and $\eta$ is their pseudo-rapidity. We further simulate the detector energy resolutions at the Tevatron

$$\begin{align*}
\Delta E_j/E_j &= 0.8/\sqrt{E_j} \quad \text{for hadrons,} \\
\Delta E_e/E_e &= 0.2/\sqrt{E_e} \quad \text{for electrons,}
\end{align*}$$

and at the LHC

$$\begin{align*}
\Delta E_j/E_j &= 0.65/\sqrt{E_j} + 0.05 \quad \text{for hadrons,} \\
\Delta E_e/E_e &= 0.1/\sqrt{E_e} + 0.005 \quad \text{for electrons.}
\end{align*}$$

The muon is required to be well isolated and we neglect the $p_T^\mu$ smearing. We finally veto extra jets in the range...
\[ p_T^\tau > 20 \text{ GeV}, \ |\eta^\tau| < 3 \] (7)
to maximally preserve the signal kinematics.

Although the lepton flavor-changing signal is quite spectacular, it is not background-free. The leading SM backgrounds include the Drell-Yan (DY) process

\[ pp(\bar{p}) \rightarrow Z(\gamma^*) \rightarrow \tau^+ \tau^- \rightarrow \mu\mu \nu_\tau \tau, \] (8)
and \( W^+W^- \) pair production (WW)

\[ pp(\bar{p}) \rightarrow W^+W^- \rightarrow \mu\mu \tau\tau. \] (9)

The background processes are calculated with the full SM matrix elements at tree level including spin correlations of gauge boson decays. QCD corrections as matrix elements at tree level including spin correlations

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Table 1. Signal \( h \rightarrow \mu\tau \) and SM background cross sections at the 2 TeV Tevatron for \( m_h = 100 - 140 \text{ GeV} \) and \( \kappa_{\mu\tau} = 1 \) after different stages of kinematical cuts. The signal statistical significance \( S/\sqrt{B} \) is presented for 20 fb\(^{-1}\).

| \( \sigma \) [fb] | \( m_h \) [GeV] |
|----------------|----------------|
| basic cuts     |                |
| signal         | 6.5 5.0 3.6 2.3 1.3 |
| DY             | 1.4 \times 10^4 |
| WW             | 380            |
| refined cuts   |                |
| signal         | 5.5 4.2 3.0 1.9 1.0 |
| DY [pb]        | 7.6 6.6 5.6 4.7 3.8 |
| WW             | 60 59 58 57 55  |
| \( S/B \)      | \frac{2}{2} \frac{2}{2} \frac{2}{2} \frac{2}{2} \frac{2}{2} \frac{2}{2} |
| \( S/\sqrt{B} \) (20 fb\(^{-1}\)) | 4.9 4.9 4.5 3.4 2.0 |

Table 2. Signal \( h \rightarrow \mu\tau \) and SM background cross sections at the 14 TeV LHC for \( m_h = 100 - 160 \text{ GeV} \) and \( \kappa_{\mu\tau} = 1 \) after different stages of kinematical cuts. The signal statistical significance \( S/\sqrt{B} \) is presented for 10 fb\(^{-1}\).

| \( \sigma \) [fb] | \( m_h \) [GeV] |
|----------------|----------------|
| basic cuts     |                |
| signal         | 230 200 160 120 69 32 6.6 |
| DY             | 8.9 \times 10^6 |
| WW             | 4000           |
| refined cuts   |                |
| signal         | 200 170 130 94 56 26 5.3 |
| DY [pb]        | 48 42 36 30 24 19 14 |
| WW             | 700 700 690 680 670 650 630 |
| \( S/B \)      | \frac{5}{5} \frac{5}{5} \frac{5}{5} \frac{5}{5} \frac{5}{5} \frac{5}{5} |
| \( S/\sqrt{B} \) (10 fb\(^{-1}\)) | 47 54 52 42 28 15 3.2 |

Discussion and conclusion

So far, for our signal discussion, we have chosen the coupling parameter as \( \kappa_{\mu\tau} = 1 \) for illustration. From a model-building point of view, it is natural for \( \kappa_{\mu\tau} \) to be of order unity, while the upper bound from low energy constraint is about 10. Generically, the cross section scales like \( \kappa_{\mu\tau}^2 \). We explored to what value of this coupling the signal would yield a 3\( \sigma \) evidence statistically near the Higgs mass peak. Figure 3 shows \( \kappa_{\mu\tau} \) versus \( m_h \) at the (a) Tevatron and (b) LHC for several luminosities. We see that at Run IIa where a luminosity of 4 fb\(^{-1}\) is expected combining CDF and D0 data, \( \kappa_{\mu\tau} \sim 1.2 - 1.8 \) can be reached for \( m_h \lesssim 140 \text{ GeV} \).
Figure 3. The value of $\kappa_{\mu t}$ at which the signal yields a 3$\sigma$ statistical evidence, versus $m_h$ at the (a) Tevatron and (b) LHC for several luminosities.

In summary, we have studied the observability for a lepton flavor-changing decay of a Higgs boson $h \rightarrow \mu\tau$ at the upgraded Tevatron and the LHC. At the Tevatron, the unique signature may serve as the Higgs discovery channel, yielding a 3$\sigma$ signal for $m_h \sim 110$ GeV and $\kappa_{\mu t} \sim 1.2$ with 4 fb$^{-1}$ (CDF and D0 combined), surpassing expectations for Higgs boson searches in the SM and in a large parameter region of the MSSM. The sensitivity will be greatly improved at the LHC, probing as small a coupling as $\kappa_{\mu t} \sim 0.15$ or determining $\kappa_{\mu t} \sim O(1)$ better than a few percent accuracy, and extending the reach to $m_h \sim 160$ GeV, beyond the coverage at a muon collider.

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