$h \to \mu\tau$ at Hadron Colliders

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We study the observability for a lepton flavor-changing decay of a Higgs boson $h \to \mu\tau$ 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 ν_μ-ν_τ 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.

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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 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 [1] $p\bar{p} \to Wh, Zh$. The leptonic decays of W, Z provide a good trigger and $h \to b\bar{b}$ may be reconstructible with adequate b-tagging and $b\bar{b}$ mass resolution, allowing a Higgs boson reach of $m_h \sim 120$–130 GeV [2]. For a heavier Higgs boson $m_h \approx 2M_W$, the leading production channel via gluon fusion $gg \to h$ and the relatively clean decay mode $h \to WW^* \to \ell\bar{\nu}\bar{\ell}\nu$ 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 3σ statistical level for $L \approx 25$ fb^{-1} [2]. 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 $b\bar{b}h, b\bar{b}A$ is enhanced by $\tan^2\beta$ and $h, A \to b\bar{b}, \tau\bar{\tau}$ 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

$$\kappa_{ij} \frac{\sqrt{m_i m_j}}{v} h^0 \bar{\psi}_i \psi_j , \qquad (1)$$

where i, j are generation indices and $v \approx 246$ GeV is the Higgs vacuum expectation value. κ_{ij} is a product of the model parameter λ_{ij} and the neutral Higgs mixing $\cos\alpha$ [7]. Although they are free parameters without *a priori* knowledge of a more fundamental theory, λ_{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 [8–11]. 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 ν_μ and ν_τ exists as indicated by the Super-K experiment [12], then it will necessarily lead to the decay $h \to \mu\tau$. The branching fraction depends on the particular model of the Higgs sector, which can be parametrized by κ_{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 [9]. 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 boson were recently discussed [10], and their search at a muon collider [13] was studied [11]. In this work, we propose to look for the signal at the upgraded Tevatron and the LHC. The leading production mechanism for a neutral Higgs boson through gluon fusion is

$$pp(\bar{p}) \to ggX \to hX \to \mu\tau X\,. \tag{2}$$

We find that due to the unique flavor-changing signature and the distinctive kinematics of the signal final state, the Tevatron run II will have significant sensitivity to such a coupling, making this signal a possible Higgs discovery channel for $m_h \approx 100\text{–}140$ GeV if $\kappa_{\mu\tau} \sim \mathcal{O}(1)$. At the LHC, the sensitivity is substantially improved leading to a probe for the coupling to a level of $\kappa_{\mu\tau} \sim 0.15$ and extending the mass coverage to 160 GeV.

h production and decay at hadron colliders.—The dominant decay mode for a SM-like Higgs boson is $h \to b\bar{b}$ for $m_h < 130$ GeV and $h \to WW^*$ for a heavier mass. The partial decay width for $h \to \mu\tau$ is given by

$$\Gamma(h \to \mu\tau) = \frac{\kappa_{\mu\tau}^2}{4\pi} \frac{m_\mu m_\tau}{v^2}\, m_h\,. \tag{3}$$

Here and henceforth $\mu\tau \equiv \mu^-\tau^+ + \mu^+\tau^-$. In comparison to the $\tau^+\tau^-$ mode in the SM, we have $\Gamma(h \to \mu\tau)/\Gamma(h \to \tau\tau) = 2\kappa_{\mu\tau}^2(m_\mu/m_\tau)$. In Fig. 1, we show these decay branching fractions versus the Higgs boson mass. The $\mu\tau$ mode is plotted assuming $\kappa_{\mu\tau} = 1$, for which $\mathrm{BR}(h \to \mu\tau)$ is at the 1% level. For $\kappa_{\mu\tau} \approx 3$, the $\mu\tau$ mode can be as large as the SM $\tau^+\tau^-$ mode. For $m_h > 140$ GeV, this mode dies away quickly due to the opening of the large WW^* mode. This is the primary reason for the limitation to a low Higgs mass ($m_h < 140$) at a muon collider [11,13].

In Fig. 2 we show the total cross section for $gg \to h$ as well as the final states from the h decay versus m_h at the (a) Tevatron and (b) LHC. The production is SM-like as we take $\kappa_{tt} = 1$. We normalize our signal cross section to include next-to-leading order QCD corrections [14], and use the CTEQ4M distribution functions [15]. The scales on the right-hand side give the number of events expected for 4 fb^{-1} at the Tevatron (the 2 fb^{-1} luminosity at the CDF and D0 detectors are combined) and 10 fb^{-1} at the LHC. We see that for the m_h range of 110–140 GeV and $\kappa_{\mu\tau} = 1$, there may be about 10–40 events produced at the Tevatron and 100–4000 events at the LHC.

$h \to \mu\tau$ signal and SM backgrounds.—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 τ to decay to an electron or (at least one charged) hadrons, excluding the mode to a muon. We do not require explicit τ tagging in the analysis. We simulate the detector coverage at the Tevatron (LHC) by imposing some "basic cuts"

$$p_T^\mu > 20 \text{ GeV}, \qquad p_T^\pm > 10 \text{ GeV}, \qquad |\eta| < 2\ (2.5)\,, \tag{4}$$

where p_T^μ ($p_T^\pm$) is the transverse momentum for the muon (charged track and other observable hadrons from τ decay), and η is their pseudorapidity. We further simulate the detector energy resolutions at the Tevatron [2]

$$\begin{aligned} \Delta E_j/E_j &= 0.8/\sqrt{E_j} \quad \text{for hadrons,} \\ \Delta E_e/E_e &= 0.2/\sqrt{E_e} \quad \text{for electrons,} \end{aligned} \tag{5}$$

and at the LHC [6]

$$\begin{aligned} \Delta E_j/E_j &= 0.65/\sqrt{E_j} \oplus 0.05 \quad \text{for hadrons,} \\ \Delta E_e/E_e &= 0.1/\sqrt{E_e} \oplus 0.005 \quad \text{for electrons.} \end{aligned} \tag{6}$$

The muon is required to be well isolated and we neglect the p_T^μ smearing. We finally veto extra jets in the range

$$p_T^j > 20 \text{ GeV}, \qquad |\eta^j| < 3 \tag{7}$$

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

$$pp(\bar{p}) \to Z(\gamma^*) \to \tau^+\tau^- \to \mu\nu_\mu\nu_\tau\tau\,, \tag{8}$$

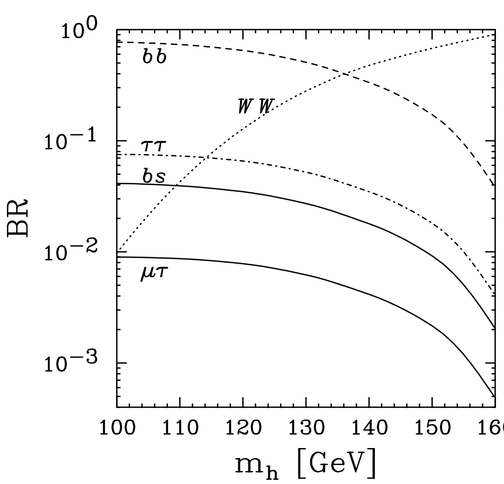

FIG. 1. The Higgs boson decay branching fraction versus m_h. The coupling parameters κ_{ij} are taken to be one.

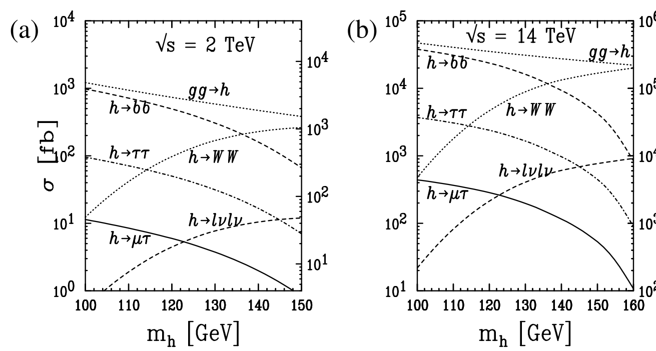

FIG. 2. The Higgs boson production cross section via gluon fusion versus m_h at the (a) Tevatron and (b) LHC. The solid curve is for the $\mu\tau$ mode, assuming $\kappa_{\mu\tau} = 1$. The scales on the right-hand side give the number of events expected for (a) 4 fb^{-1} at the Tevatron and (b) 10 fb^{-1} at the LHC. Various subsequent decay modes $\tau^+\tau^-$, WW^*, and $WW^* \to \ell\bar{\nu}\bar{\ell}\nu$ are depicted for comparison.

TABLE I. Signal $h \to \mu\tau$ and SM background cross sections at the 2 TeV Tevatron for $m_h = 100-140$ 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}.

σ (fb)	m_h (GeV)				
	100	110	120	130	140
Basic cuts					
Signal	6.5	5.0	3.6	2.3	1.3
DY			1.4×10^4		
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	$\frac{5.4}{25}$	$\frac{4.1}{14}$	$\frac{2.9}{9.0}$	$\frac{1.9}{6.4}$	$\frac{1.0}{4.9}$
$S/\sqrt{B}$ (20 fb^{-1})	4.9	4.9	4.5	3.4	2.0

and W^+W^- pair production (WW)

$$p p(\bar{p}) \to W^+W^- \to \mu\nu_\mu\tau\nu_\tau\,. \tag{9}$$

The background processes are calculated with the full SM matrix elements at tree level including spin correlations of gauge boson decays. QCD corrections as K factors for the total production rates are also taken into account [16]. With the basic cuts of Eq. (4), the backgrounds turn out to be very large. The results are given by the entries under "basic cuts" in Tables I and II for the Tevatron and LHC, respectively.

There are several distinctive kinematical features for the signal that we can exploit to discriminate it from the backgrounds. First, the missing neutrinos from τ decay are collimated along the charged track since the τ's are ultrarelativistic. Thus, for the signal, the missing transverse momentum (p_T^{miss}) is along the charged track direction and is essentially back-to-back with respect to the muon $\phi(\mu,\pm) \approx 180°$. This is not the case for the WW background. Second, the muons in the signal are stiff $p_T^\mu \sim m_h/2$ as a result of the two-body Higgs decay, while the secondary tracks and hadrons from τ decay are softer. If we define momentum imbalance

$$\Delta p_T = p_T^\mu - p_T^\pm\,, \tag{10}$$

we expect that it would be positive for the signal if the momentum measurements were perfect. This variable turns out to be very powerful in separating the DY background. We now define the "refined cuts" as

$$\phi(\mu,\pm) > 160°, \qquad \Delta p_T > 0, \qquad p_T^\mu > m_h/5\,. \tag{11}$$

The most important aspect for the signal observation is reconstruction of the Higgs boson mass. This is quite feasible for the signal under consideration. This can be done with the following steps: (1) define the missing transverse momentum p_T^{miss} as the imbalance from the observable particles [which is Δp_T in Eq. (10) for the signal case]; (2) reconstruct the τ transverse momentum $\vec{p}_T^{\,\tau} = \vec{p}_T^{\,\pm} + \vec{p}_T^{\,\text{miss}}$, and the longitudinal component $p_z^\tau = p_z^\pm(1 + p_T^{\text{miss}}/p_T^\pm)$; (3) form the $\mu\tau$ invariant mass $m_{\mu\tau}^2 = (p^\mu + p^\tau)^2$. This mass variable should be sharply peaked at m_h for the signal, broadly peaked around M_Z for the DY background, and rather smooth over a large range for the WW background. Indeed, with the proper energy smearing, we find the reconstructed Higgs mass peak within a 5 GeV range. The results are summarized in Tables I and II for the Tevatron and LHC, respectively. The entries under "refined cuts" give the cross sections including the cuts of Eq. (11). The signal-to-background ratio S/B within a 5 GeV window for $m_{\mu\tau}$ is shown next. The last rows illustrate the statistical significance $S/\sqrt{B}$ for the Tevatron with 20 fb^{-1} (CDF and D0 combined) and for the LHC with 10 fb^{-1}.

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

TABLE II. Signal $h \to \mu\tau$ and SM background cross sections at the 14 TeV LHC for $m_h = 100-160$ 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}.

σ (fb)	m_h (GeV)						
	100	110	120	130	140	150	160
Basic cuts							
Signal	230	200	160	120	69	32	6.6
DY				8.9×10^4			
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	$\frac{190}{160}$	$\frac{160}{91}$	$\frac{130}{63}$	$\frac{91}{47}$	$\frac{54}{37}$	$\frac{25}{30}$	$\frac{5.1}{25}$
$S/\sqrt{B}$ (10 fb^{-1})	47	54	52	42	28	15	3.2

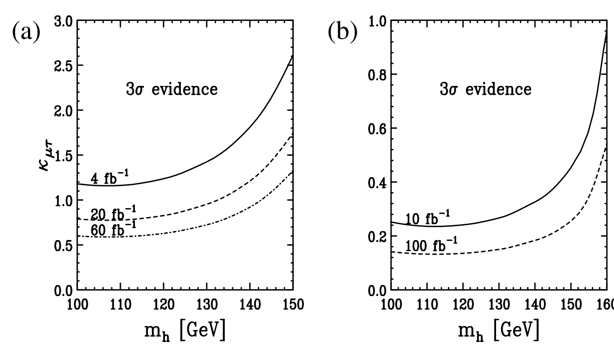

FIG. 3. The value of $\kappa_{\mu\tau}$ at which the signal yields a 3σ statistical evidence versus m_h at the (a) Tevatron and (b) LHC for several luminosities.

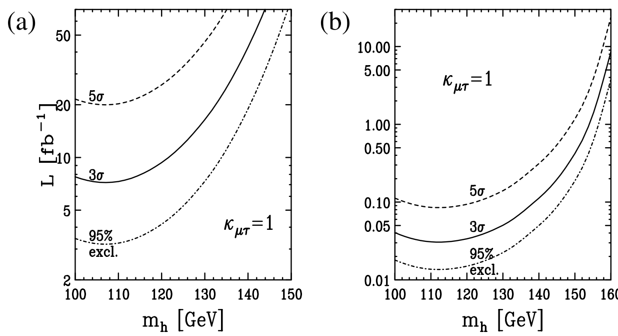

FIG. 4. Integrated luminosity needed to reach a 2σ (95% exclusion), 3σ, and 5σ signal versus m_h at the (a) Tevatron and (b) LHC for $\kappa_{\mu\tau} = 1$.

this coupling the signal would yield a 3σ 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 $m_h \lesssim 140$ GeV. With a higher luminosity of 30 fb^{-1} per detector, one can reach a coupling of 0.6–0.9. At the LHC, the sensitivity is significantly improved and a signal for $\kappa_{\mu\tau} \sim 0.15$ would even be observable with 100 fb^{-1}. Assuming $\kappa_{\mu\tau} \approx 1$, the reach could go beyond $m_h \approx 160$ GeV, in contrast to the accessible limit $m_h \lesssim 140$ GeV at a muon collider [11]. Similarly, one can ask how much luminosity is needed to reach a certain level of observation. Note that the statistical significance scales like $S/\sqrt{B} \sim \kappa_{\mu\tau}^2 \sqrt{L}$. The results are summarized in Fig. 4, where a 2σ (95% confidence level exclusion), 3σ and 5σ signals are illustrated versus m_h at the (a) Tevatron and (b) LHC for $\kappa_{\mu\tau} = 1$. Because of the large number of signal events near the m_h peak at the LHC (see Table II), the statistical accuracy of determining a coupling $\kappa_{\mu\tau} \sim \mathcal{O}(1)$ can be at a few percent level with only $L = 10$ fb^{-1}. Note that strictly speaking, all the bounds quoted here apply to the product $\kappa_{tt}\kappa_{\mu\tau}$. We have implicitly assumed $\kappa_{tt} = 1$ throughout.

In summary, we have studied the observability for a lepton flavor-changing decay of a Higgs boson $h \to \mu\tau$ at the upgraded Tevatron and the LHC. At the Tevatron, the unique signature may serve as the Higgs discovery channel, yielding a 3σ signal for $m_h \sim 110$ GeV and $\kappa_{\mu\tau} \sim 1.2$ 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 $\kappa_{\mu\tau} \sim 0.15$ or determining $\kappa_{\mu\tau} \sim \mathcal{O}(1)$ 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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