$h \rightarrow \mu^+ \mu^-$ via gluon fusion at the LHC

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Abstract

We study the observability of the $h \rightarrow \mu^+ \mu^-$ decay in the Standard Model and the MSSM at the LHC. The observation of the $h\mu\mu$ coupling is important to determine whether the Higgs particle that generates mass for the weak bosons is also responsible for mass generation of the second generation of fermions. We find that the signal via the gluon fusion channel is comparable to that from the weak-boson fusion. By combining these two channels, observing $h \rightarrow \mu^+ \mu^-$ is feasible at the LHC with a delivered luminosity of 300 fb$^{-1}$ at 3σ statistical significance for 110 GeV $< m_h < 140$ GeV in the Standard Model. This corresponds to a $h\mu\mu$ coupling determination at about 15% accuracy assuming $h\bar{t}t$, $h\bar{b}b$ couplings SM-like. The observation becomes more promising in the MSSM for $\tan\beta > 8$ and $M_A < 130$. 
I. Introduction

The Higgs mechanism is widely believed to be responsible for the electroweak gauge symmetry breaking and possibly for the fermion mass generation. Searching for Higgs bosons have thus become high priority in future collider experiments, and the Large Hadron Collider (LHC) that is under construction at CERN has the promise to discover the Standard Model (SM) Higgs boson or the counterparts in theories with a Supersymmetric extension [1]. After the initial discovery, it would be more important and more challenging to understand the properties of the Higgs bosons, in particular their couplings to the SM particles. Precisely because of the role of the Higgs bosons in the mass generation mechanism, they couple to the SM particles proportional to their masses. Such characteristics of Higgs bosons should be thoroughly tested at collider experiments.

At the LHC, the SM Higgs ($h$) couplings to $WW$, $ZZ$, $t\bar{t}$, $\tau^-\tau^+$, as well as the loop-induced couplings to $gg$, $\gamma\gamma$ can all be directly probed by combining several production and decay channels [1, 2]. At an $e^+e^-$ linear collider, this list can be extended to include $b\bar{b}$, $c\bar{c}$ [3]. The next channel anticipated would be $\mu^+\mu^-$, which would be the first observation for a Higgs boson to decay to second-generation fermions. It is in fact very important to explore this channel. First, it is necessary to confirm the proportionality of $m_\mu$ for the Higgs coupling $h\mu\mu$ as predicted by the SM. Secondly, this channel may be sensitive to new physics such as non-universality between $I_3 = -\frac{1}{2}$ fermions in certain classes of SUSY models or induced by radiative corrections. Last but not least, the concept of a muon collider Higgs factory relies on the $h\mu\mu$ coupling [4]. Due to the rather small branching fraction for $h \rightarrow \mu^+\mu^-$, it will be very challenging to observe this channel in collider experiments. An early study of this channel at the LHC based on the weak-boson fusion, $WW, ZZ \rightarrow h \rightarrow \mu^+\mu^-$, was carried out [3]. There would be about $1 - 2\sigma$ statistical effect obtained at the LHC for an integrated luminosity of 300 fb$^{-1}$. At a future $e^+e^-$ linear collider with $\sqrt{s} \geq 800$ GeV and an integrated luminosity of 1000 fb$^{-1}$, it may be possible to reach a 15% measurement for the $h\mu\mu$ coupling [6].

We note that the leading Higgs production at the LHC is via the gluon fusion, yielding the process

$$gg \rightarrow h \rightarrow \mu^+\mu^-.$$  

Because of the large Higgs production rate at the LHC and the very clean experimental signature of $\mu^+\mu^-$, we are thus motivated to explore this channel and wish to improve the observability of $h \rightarrow \mu^+\mu^-$. It is important to note that the cross section for the process of Eq. (1) is proportional to $\Gamma(h \rightarrow gg) \times BR(h \rightarrow \mu^+\mu^-)$. The partial width $\Gamma(h \rightarrow gg)$ is dominated by the top-quark loop in the SM, and will receive contributions from new particles beyond the SM that are colored and couple to $h$ significantly. The branching fraction $BR(h \rightarrow \mu^+\mu^-)$ may also deviate from the SM prediction, especially if the new physics contribution breaks the universality between the muon and the $b$-quark. We thus expect that the process of Eq. (1) would be sensitive to new physics beyond the SM. As a concrete example, we also include discussions in the minimal supersymmetric Standard Model (MSSM) in our analysis.

II. Signal and Background Studies

We study the signal process of Eq. (1) at the LHC with the center-of-mass energy $\sqrt{s} = 14$ TeV. We first note that in the SM, the rate of $h \rightarrow \mu^+\mu^-$ channel becomes vanishingly small.
once the $h \rightarrow WW^*$, $ZZ^*$ channels are open. We thus concentrate on the mass range

\[ 110 \text{ GeV} < m_h < 140 \text{ GeV}. \]  

(2)

This is also the mass window favored by supersymmetric extensions of the SM.

Because of the very clean final state of $\mu^+\mu^-$, we will consider the inclusive channel. We use CTEQ4M structure functions [7]. We calculate the signal cross section by normalizing the rate with respect to the output of the packages HIGLU [8] for the SM and HDECAY [9] for MSSM. The NLO $K$-factor for the Higgs production via gluon fusion is about 2.5 at the LHC energy, larger than that previously reported (around 1.5) [8] due to increased accuracy in gluon parton density functions at low $x$. The Higgs production is treated in the narrow width approximation, which is fully justifiable because the physical Higgs width is much less than the experimental detector resolution. The irreducible SM background comes from the Drell-Yan production

\[ q\bar{q} \rightarrow Z^*, \gamma^* \rightarrow \mu^+\mu^- . \]  

(3)

We have normalized the background cross section with respect to that with QCD corrections [10]. We stress that we will know this DY background quite well from the direct measurement at the LHC experiments.

We simulate the experimental detector coverage by imposing the kinematical cuts on both muons

\[ p_T > 20 \text{ GeV}, \quad \eta < 2.5. \]  

(4)

The detector smears the muon momentum approximately to a Gaussian form of a width $\sigma = 1.6 \text{ GeV}$ [1, 5]. To optimize the statistical significance, we find that the maximum $S/\sqrt{B}$ occurs when this invariant mass window is $\pm 1.4\sigma$ around the peak. We thus take the invariant mass as

\[ m_h - 2.24 \text{ GeV} < m(\mu^+\mu^-) < m_h + 2.24 \text{ GeV}, \]  

(5)

which captures 84% of the signal. An identification efficiency of 90% for each muon is also included in our analysis.

| $m_h$(GeV) | Gluon fusion | W boson fusion |
|------------|--------------|---------------|
|            | signal | background | signal | background |
| 115        | 4.50  | 2085       | 0.092  | 0.82       |
| 120        | 3.89  | 1441       | 0.081  | 0.62       |
| 130        | 2.63  | 821        | 0.062  | 0.40       |
| 140        | 1.51  | 526        | 0.037  | 0.28       |

TABLE I: SM cross sections in fb for both gluon fusion and weak-boson fusion signals, and the corresponding backgrounds after all cuts. The cuts used are in Eqs. (4) and (5). A 90% muon identification efficiency factor is included. The weak-boson fusion results are taken from Ref. [5].

We first give the signal and background cross sections in Table I after the cuts and the efficiency factor as discussed above for the Higgs mass range of interest in Eq. (2). For comparison, results for weak-boson fusion are also listed, as taken from Ref. [5]. Although
the signal rate is larger for gluon fusion than that for weak-boson fusion by more than a factor of 40, the background here is substantially larger as well. However, we emphasize that the Drell-Yan background will be precisely measured at the LHC experiments. The systematic effects due to theoretical uncertainties will be minimal. The signal we are looking for is a $\mu^+\mu^−$ mass peak at an approximately known location on a very well-measured, nearly flat background. In contrast, the weak-boson fusion process yields a signal-to-background ratio of better than 10%. The further challenge is to understand systematic errors better.

Table II summarizes our SM results combining both ATLAS and CMS detectors. We first give the delivered luminosity needed to reach a $3\sigma$ observation of the signal, which corresponds to the cross section determination to about 33% accuracy, as estimated by $\sqrt{S+B}/S$. If we assume that the couplings of $ht\bar{t}$ and $hb\bar{b}$ are known to be SM-like, then the above accuracy of $h \to \mu^+\mu^−$ branching fraction determination translates to the $h\mu\mu$ coupling determination to about 17%. We see that combining both signal channels and with two detectors, the typical luminosity needed is about 250 fb$^{-1}$ to reach this level of accuracy. With 300 fb$^{-1}$ delivered to each detector, one can reach a 3.5$\sigma$ observation statistically as shown in the last three columns in Table II. This corresponds to $h \to \mu^+\mu^−$ branching fraction determination to about 29% accuracy, or the $h\mu\mu$ coupling determination to 14%, assuming $ht\bar{t}$, $hb\bar{b}$ couplings SM-like. With extended running or luminosity upgrades, a 5$\sigma$ observation may be a reasonable expectation. Overall, we see that our results for gluon fusion is quite comparable to the earlier study from weak-boson fusion, and that combining these two channels can significantly improve the observability of $h \to \mu^+\mu^−$ at the LHC experiments.

| $m_h$(GeV) | Luminosity required for $3\sigma$ observation (fb$^{-1}$) | Significance for 300 fb$^{-1}$ |
|------------|-----------------------------------------------------------|--------------------------------|
|            | $W, g$ Combined | $g$ fusion | $W$ fusion | $W, g$ Combined | $g$ fusion | $W$ fusion |
| 115        | 238            | 464       | 489       | 3.37         | 2.41       | 2.35       |
| 120        | 227            | 430       | 482       | 3.45         | 2.51       | 2.37       |
| 130        | 267            | 535       | 532       | 3.18         | 2.25       | 2.25       |
| 140        | 531            | 1047      | 1076      | 2.26         | 1.61       | 1.58       |

TABLE II: The SM results for $h \to \mu^+\mu^−$ signal from gluon fusion and weak-boson fusion and the DY background, combining the ATLAS and CMS detectors. The cuts used are in Eqs. (4) and (5). A 90% muon identification efficiency factor is included. The weak-boson fusion results are taken from [5].

Many theories beyond the SM can lead to significant enhancement for the channel $gg \to h \to \mu^+\mu^−$ and thus the signal observation may be easier. As a model-independent generic argument, we study the cross section enhancement factor ($\kappa$) over the gluon fusion channel in the SM. The curves in Fig. 1 show the enhancement factor $\kappa$ needed to reach a $3\sigma$ (solid) and $5\sigma$ (dashed) signal via the gluon fusion channel alone versus the Higgs mass $m_h$, with both detectors and for a delivered luminosity of 300 fb$^{-1}$. We note that for a low Higgs mass $m_h < 110$ GeV, the signal observation is difficult primarily because of the overwhelmingly large DY background from the tail of the $Z$-pole. On the other hand, for $m_h > 140$ GeV, the signal observation becomes increasingly difficult due to the fact that the $h \to \mu^+\mu^−$ channel dies away after the opening of $h \rightarrow W^*W, Z^*Z$ channels. For the mass range of our current interest $110$ GeV $< m_h < 140$ GeV, an enhancement factor of $\kappa \sim 1.2 – 2$ is needed for a $3\sigma$ signal observation and $\kappa \sim 2.1 – 3.3$ for a $5\sigma$ signal observation, for a delivered luminosity
of 300 fb$^{-1}$. To present this in another way, given the $\kappa$ factor, the luminosity required to observe this channel at an $S$ significance level is simply given by:

$$\mathcal{L} = S^2 \frac{\sigma_B}{\kappa^2 \sigma_S^2}$$

where $\sigma_B$ and $\sigma_S$ are the background and SM signal cross sections, respectively, presented in Table I. As a concrete example, we will study the enhancement factor in MSSM next.

![Diagram](image)

FIG. 1: The enhancement factor $\kappa$ over the SM rate required to observe the $gg \rightarrow h \rightarrow \mu^+\mu^-$ signal at the $3\sigma$ (solid) and $5\sigma$ (dashed) level with 300 fb$^{-1}$ delivered luminosity, including both the ATLAS and CMS detectors.

### III. Minimal Supersymmetric Standard Model

In MSSM there are two Higgs doublets, resulting in 5 physical Higgs states. The relevant parameters are $\tan \beta$, the ratio of the two vacuum expectation values, and $M_A$, the mass of the CP-odd Higgs state. The $\mu^+\mu^-$ mode via gluon fusion may be significantly enhanced in MSSM. First of all, there are SUSY particles such as stops and sbottoms to contribute in the loop. However, there are also subtle cancellations among the diagrams [11]. Secondly, for large $\tan \beta$, the $b$ quark and sbottom contributions can be significant. Thirdly, there may be direct contribution from $A, H \rightarrow \mu^+\mu^-$. [1, 12]. We consider the maximal stop quark mixing scenario [13], defined by the stop mixing parameter $X_t \equiv A_t - \mu \cot \beta = \sqrt{6} M_{SUSY}$, where $A_t$ is the soft SUSY breaking top Yukawa coupling, $\mu$ is the dimensionful Higgs mixing parameter, and $M_{SUSY}$ is the mass of the squarks (where all squarks are assumed to be degenerate in mass). The maximal stop mixing scenario gives us larger $m_h$ to be consistent with the current LEP2 Higgs mass bound [14]. This also happens to lead to a large production cross section of $gg \rightarrow h$ in the low $M_A$ and large $\tan \beta$ limit. For our simulations in the MSSM we have chosen the parameters $M_{SUSY} = 1$ TeV, $\mu = 300$ GeV, and $A_U = A_L = A_D = 1.5$ TeV. The $h\mu\mu$ coupling is insensitive to these parameters.
FIG. 2: The enhancement of \( h \) production of the MSSM relative to the SM in the maximal stop mixing scenario as a function of (a) \( M_A \) (left) and (b) \( \tan \beta \) (right). The curves are labeled by their value for \( \tan \beta \) in (a) and \( M_A \) (GeV) in (b).

In Fig. 2, we present the enhancement factor \( \kappa \) for \( gg \rightarrow h \rightarrow \mu^+\mu^- \) in MSSM. We see that for low \( M_A \) and large \( \tan \beta \) the enhancement can be substantial, as large as a factor of 20–30 at the edge of the \( M_A \) exclusion of 91 GeV [14]. This does not include the possible contribution from \( H, A \) decay yet. As anticipated, in the heavy limit \( M_A > 2M_Z \), we recover the Standard Model result (\( \kappa = 1 \)). Based on comparison to the SM case as discussed for Fig. 1, we conclude that the \( h \rightarrow \mu^+\mu^- \) channel in MSSM can be observed at the 3\( \sigma \) level or better for \( M_A < 130 \) GeV and for \( \tan \beta > 8 \) with 300 fb\(^{-1} \) luminosity delivered.

IV. Conclusions
We have studied the Higgs decay to \( \mu^+\mu^- \) via gluon fusion process at the LHC in the SM and MSSM. We found that this channel is quite comparable and complementary to the channel from the weak-boson fusion. By including both the gluon fusion channel and the weak-boson fusion channel, and by including the ATLAS and CMS detector, the LHC with 300 fb\(^{-1} \) can observe the \( h \rightarrow \mu^+\mu^- \) to a statistical significance of 3\( \sigma \) over a Higgs mass range of 110 GeV < \( m_h < 140 \) GeV. This corresponds to the \( h\mu\mu \) coupling determination about 14% – 17% accuracy if assuming \( htt, hbb \) couplings SM-like. If nature has chosen large \( \tan \beta \) as is preferred in a large class of SUSY models and as favored by present experimental limits, and in addition \( M_A < 130 \) GeV, we might easily observe this channel at the LHC and determine the branching fraction to an accurate level.

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