Unique Higgs boson signature at colliders

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The HyperCP collaboration has observed three events for the decay $\Sigma^+ \rightarrow p\mu^+\mu^-$. The three events may be interpreted as a new narrow-width CP-odd scalar $a$ with the mass $214.3 \pm 0.5$ MeV. Here $a$ decays dominantly into di-muon ($\mu^+\mu^-$). As the consequence of tiny mass difference between $m_a$ and $2m_{\mu}$ ($2m_{\mu} \approx 211.3$ MeV), di-muon will be boosted to almost the same direction at colliders. Such kind of di-muon events have been overlooked in the past experiments. Provided that the precision data preferred light SM-like Higgs boson $h$ decays dominantly into $aa$ other than into $bb$, in order to be consistent with null Higgs boson search at LEP, the $h \rightarrow aa \rightarrow 4\mu$ ($2\mu^+2\mu^-$) will be the unique Higgs boson signature which has not been noticed before. The SM-like Higgs boson may hide itself from the usual analysis of LEP and Tevatron experiments, which should be reanalyzed in the light of new theoretical and experimental developments. In this paper, we also investigate this unique Higgs boson signature at colliders and conclude that the SM-like Higgs boson could be discovered with rather low integrated luminosity, provided that the $h \rightarrow 4\mu$ reconstruction efficiency is not extremely low. It is not impossible that such kind of unique Higgs boson 4$\mu$ events are now lurking in the existing LEP and/or Tevatron data.

I. INTRODUCTION

Understanding the mechanism of electro-weak symmetry breaking (EWSB) is the primary goal for high energy experiments, namely Tevatron at Fermilab, the Large Electron-Positron (LEP), the Large Hadron Collider (LHC) at CERN, and the proposed International Linear Collider (ILC). In the standard model (SM) of high energy physics, EWSB is realized via a weak-doublet fundamental Higgs field. After EWSB spontaneously, namely Higgs field acquiring a vacuum expectation value (VEV), only one neutral Higgs boson is left in particle spectrum. The Higgs boson mass is theoretical unknown within the SM. Therefore searching it in all mass regions is necessary and great efforts have been put on it since the establishment of the SM. The latest direct search at LEP sets the lower bound of SM Higgs boson of 114.3 GeV at 95% confidence level (CL) [1]. The Higgs boson can also affect electro-weak observables through radiative corrections. Therefore precise measurements of these observables can predict the Higgs boson mass. Based on the global fit of data from LEP, SLD and Tevatron, the Higgs boson mass in SM is predicted to be $m_H = 98^{+52}_{-36}$ GeV and $m_H < 208$ GeV at 95% CL using the top quark mass $m_t = 174.3 \pm 3.4$ GeV [2]. However the notorious three 3-$\sigma$ anomalies may indicate new dynamics beyond the SM. Moreover excluding these anomalies from the global fit data, the preferred even lighter Higgs boson mass has shown certain tension with direct search limit at LEP [3].

The constraint on Higgs boson mass from LEP direct search can be greatly modified in the physics beyond the SM. For example, in the next-to-minimal supersymmetric model (NMSSM) [5] in which a gauge singlet superfield is introduced, the SM-like CP-even Higgs boson $h$ can mainly decay into light $a$ pair where $a$ is a (mostly singlet) CP-odd Higgs boson $a$. Such light $a$ may due to the approximate R-symmetry [7]. The relevant limit on $m_a$ can be deduced from the measurements of more final states $Zh \rightarrow Zaa \rightarrow Zb\bar{b}b\bar{b}$ or $Zh \rightarrow Zaa \rightarrow Z\tau\tau\tau\tau$. The weaker limit of $m_h$ can be obtained [6] primarily due to dominance of $h \rightarrow aa$. Recently the authors of Ref. [8] studied the specific scenario in which $m_h$ can be lighter than 100 GeV while $Br(h \rightarrow aa) > 0.7$ and $m_a < 2m_{\mu}$.

The effects of such light CP-odd $a$ could be observed at low energy experiments. Recently HyperCP Collaboration has observed three events for the decay $\Sigma^+ \rightarrow p\mu^+\mu^-$. If the long-distance contributions are properly included, it is possible to account for the branching ratio within the SM [10]. However probability of all three events with the same di-muon ($\mu^+\mu^-$) mass is less than one percent. Thus it is natural to interpret three events from a new narrow-width particle with mass $214.3 \pm 0.5$ MeV [3]. The theoretical investigations [11] indicate that the new particle can’t be CP-even scalar or vector boson if they satisfy also the constraints from $K^\pm \rightarrow \pi^\pm\mu^+\mu^-$, $K_S \rightarrow \pi^0\mu^+\mu^-$ and $B \rightarrow X_s\mu^+\mu^-$. However the light CP-odd Higgs boson $a$ in the NMSSM can be identified as the new light particle [12, 13].

Assuming there exists the light CP-odd scalar with mass around 214 MeV as implied by HyperCP experiment, in this paper we will investigate its phenomenological implications, especially for the SM-like Higgs boson. Ref. [5] has investigated the NMSSM scenario with $O(\text{GeV})$ $a$. For our purpose in section II, we would like to study the NMSSM parameter space with the mass of $a$ around 214 MeV. In section III, we will explore the unique behavior of $a \rightarrow \mu^+\mu^-$ at colliders due to the tiny mass difference between $m_a$ and $2m_{\mu}$. In section IV, we carry out the detail simulation of signals and backgrounds of SM-like Higgs boson $h \rightarrow aa \rightarrow \mu^+\mu^-\mu^+\mu^-$ at colliders. Section V is allocated to the conclusion and
II. NMSSM PARAMETER SPACE WITH $m_a \sim 214$ MEV

We utilize NMHDECAY \cite{14} to scan parameter space in the NMSSM where $A_\lambda \approx A_\kappa \approx 0$ and ignore fine-tuning constraints \cite{0,8}. We choose large $\tan \beta$ and suitable $\mu$ as mentioned in Ref. \cite{12}. In Table I we show three benchmark points allowed by current experiment constraints embedded in NMHDECAY, and all points have the $m_a$ around 214.3 MeV. It is clear that point 3 has large $\text{BR}(h \to aa)$ as we required. Varying $\tan \beta$ and $\mu$ while keeping other parameters the same with point 3, we show the more allowed points in Fig. 1. Both the table and figure show that there exist possible parameter space as we required, i.e. $\text{BR}(h \to aa)$ is large, the SM-like Higgs boson is around $O(100)$ GeV and CP-odd $a$ is very light around 214 MeV.

| Points | $\text{BR}(h \to aa)$ | $m_a$ | $m_h$ | $\lambda$ | $\kappa$ | $\tan \beta$ | $\mu$ |
|--------|-----------------------|-------|-------|----------|---------|-------------|------|
| 1      | $3.25 \times 10^{-5}$ | 217.9 | 115.1 | 0.072    | 0.15    | 52.2        | 131.8|
| 2      | $8.82 \times 10^{-7}$ | 214.4 | 115.3 | 0.026    | 0.05    | 33.6        | -151.1|
| 3      | 0.812                 | 212.5 | 88.4  | 0.067    | 0.024   | 33.7        | 130.0|

Points $|\mu| = 100$ MeV, $M_{SUSY} = 1000$ GeV, $M_{A_1,2,3} = 100, 300, 500$ GeV. The $(\times)$ points indicate $m_h < 114(> 114)$ GeV.

| Points | $M_{SUSY}$ | $M_1$ | $M_2$ | $M_3$ | $A_2$ (GeV) |
|--------|------------|-------|-------|-------|-------------|
| 1      | 300        | 100   | 200   | 300   | 500         |
| 2      | 500        | 100   | 500   | 800   | 700         |
| 3      | 1000       | 100   | 300   | 500   | 1500        |

TABLE I: Benchmark points in the NMSSM with $m_a \sim 214$ MeV.

![Figure 1](image1.png)

FIG. 1: $\text{BR}(h \to aa)$ as a function of $m_a$ in the NMSSM with $\tan \beta = 30 \sim 60$, $|\mu| = 100 \sim 300$ GeV, $A_t = 1500$ GeV, $M_{SUSY} = 1000$ GeV and $M_{A_1,2,3} = 100, 300, 500$ GeV. The $(\times)$ points indicate $m_h < 114(> 114)$ GeV.

III. KINEMATIC FEATURE OF $a \to \mu^+ \mu^-$

If we identify $m_a = 214.3 \pm 0.5$ MeV, at colliders the behavior of di-muon as the decay product of $a$ is different from usual cases in the SM and other physics beyond the SM. In the rest frame of $a$, di-muon are almost at rest because the mass difference between $m_a$ and $2m_\mu$ ($2m_\mu \approx 211.3$ MeV) is tiny, compared to the typical energy scale of $a$ at colliders. In the lab frame, the di-muon will be boosted to almost the same direction. As a consequence, the separation $\Delta R$ of di-muon (see Fig. 2) is much smaller than usual case. Here $\Delta R$ is the separation between the two particles in the detector, $\Delta R \equiv \sqrt{\Delta \eta^2 + \Delta \phi^2}$; $\phi$ is the azimuthal angle and $\eta$ denotes pseudo-rapidity.

It should be emphasized that such kind of unusual di-muon events have always been overlooked in the past experiments. For example, for the case of the di-muon reconstruction at ATLAS, in order to suppress the fake muon from pile up and backgrounds etc., one usually sets cut for $\Delta R$ of the di-muon as 0.01 \cite{13}. As such the di-muon reconstruction procedure will totally abandon the di-muon signal from the decay of $a$. Unfortunately the LEP \cite{16} and Tevatron experiments may also have the similar chance to abandon such kind of di-muon. However it is possible \cite{15,16} that advanced muon detector, especially ATLAS and CMS, can identify $\Delta R \sim 0$ di-muon with reasonable efficiency. In fact it is justified to expect that di-muon for $\Delta R \sim 0$ will have some overlapping hits at first and become separate tracks in the end, under the strong magnetic field in the detector. Obviously the efficiency of identifying such kind of di-muon depends on the details of the whole detector, which is unknown yet and deserves further detector simulations \cite{20}.

Provided that the light SM-like Higgs boson $h$ decays dominantly into $aa$ other than into $\bar{b}b$ as discussed in section II, similar to the case of Ref. \cite{8}, and $a$ decays dominantly into $\mu^+\mu^-$ in order to account for HyperCP three events as shown in Ref. \cite{12}, the LEP experiments of direct search for the SM-like Higgs boson can only impose very weak, even null, constraint on the Higgs boson mass. The reason is that we have overlooked the signal events due to the fault of di-muon reconstruction. At LEP, Tevatron and LHC, one will not discover the SM-like Higgs boson unless the di-muon reconstruction algorithm and/or the trigger-system are appropriately realized. Therefore the LEP and Tevatron data should be re-analyzed. According to the global fit of the precision data \cite{4}, the signal of $4\mu (2\mu^+2\mu^-)$ from the decay of the SM-like Higgs boson may lurk in the existing LEP and/or Tevatron data.

IV. SM-LIKE HIGGS BOSON AT COLLIDERS

In this section we will investigate the observability of $4\mu (2\mu^+2\mu^-)$ as the unique signature of the SM-like Higgs
boson at colliders, especially at Tevatron, LHC and LEP. Throughout the paper, CP-odd Higgs boson $a$ is assumed to be 0.215 GeV and the SM-like Higgs boson is the O(100 GeV) or less as implied from precision data [4]. The efficiency of identifying 4$\mu$ from the $h$ decay is taken to be 1. And the real signal events can be obtained by multiplying with the realistic efficiency once available.

A. Choice of the parameters

In our analysis, for simplicity, we assume that the couplings among the SM-like $h$ and gauge bosons as well as fermions the same way as those in SM. Actually this is the reason why we name the CP-even Higgs boson 'SM-like'. Moreover, as discussed in previous, the new decay mode $h \rightarrow aa$ needs to be inserted. We assume the h-a-a coupling as $\frac{g_{a} m_{a} \kappa}{2 \cos \theta_{W}}$ where $g$, $\theta_{W}$ are weak coupling and weak angle as usual and $\kappa$ is dimensionless free parameter which depends on the specific model. In minimal supersymmetric standard model (MSSM), $\kappa = \cos(2\beta) \sin(\alpha + \beta)$ where $\tan \beta$ is the ratio of two vacuum expectation values of Higgs field and $\alpha$ is the mixing angle of neutral Higgs. In the limit $\sin \alpha \rightarrow - \cos \beta$ and $\cos \alpha \rightarrow \sin \beta$, the light CP-even Higgs boson resembles the SM Higgs boson $h$ and $\kappa \rightarrow -1$ for large $\tan \beta$. Throughout the paper we fix $\kappa = -1$ in our numerical analysis. In NMSSM the h-a-a coupling will be altered. However for the light Higgs boson, the different choice of parameter $\kappa$ in NMSSM affects only the total width of SM-like Higgs boson while the branching ratio of $h \rightarrow aa$ keeps almost the same due to the tiny partial decay width to SM particles. For relatively heavy Higgs boson which can decay into $V V^{(*)}$ ($V=W$ or $Z$) with sizeable branching ratio, the variation of h-a-a coupling can affect not only the Higgs boson decay width but also branching ratio of $h \rightarrow aa$. In this paper we focus on the Higgs boson mass of O(100 GeV) or less and $Br(h \rightarrow aa) \sim 1$. Therefore the choice of h-a-a coupling is appropriate for our purpose.

The couplings among $a$ and fermions are taken the same as Ref. [12] in order to account for HyperCP three events, which can be describe as

$$L_{\text{aff}} = -\frac{i}{v} (l_{u} m_{u} \bar{u} \gamma_{5} u + l_{d} m_{d} \bar{d} \gamma_{5} d) a + \frac{i g_{s} m_{t}}{v} \bar{t} \gamma_{5} t a$$

with $l_{d} = -g_{t} \sim O(1), l_{u} = \frac{1}{\tan \beta}$ in NMSSM and $v$ the usual VEV of Higgs field. For large $\tan \beta$ case as preferred by Ref. [12], the up-type quarks have negligible contributions. In our numerical evaluations, we take $\tan \beta = 30$ and $l_{d} = -g_{t} = 1$, and the branching ratio of decay $a \rightarrow \mu^{+} \mu^{-}$ is calculated to be $\sim 1$. Note that $a \rightarrow \pi^{0} \gamma$ is forbidden due to C-parity non-conservation and $a \rightarrow \pi^{0} \gamma$ is assumed negligible [13]. Thus we forbid the decay $a \rightarrow gg$ in our simulations. In fact branching ratio of loop-induced process $a \rightarrow \gamma \gamma$ is much less than of $a \rightarrow \mu^{+} \mu^{-}$.

B. Detail simulations

At hadron colliders, namely Tevatron and LHC, the main signal process for light Higgs boson is $gg \rightarrow h \rightarrow aa \rightarrow \mu^{+} \mu^{-} \mu^{+} \mu^{-}$. In our analysis only quark loop contributions to $gg \rightarrow h$ are included. The signal final states are 4$\mu$ and the main background comes from $ZZ$ production with $Z$ decaying subsequently into di-muon. In practice, we utilize Pythia v6.324 [18] to simulate signal and background after corresponding modifications of couplings and masses.

In our simulations, we adopt the following “LHC basic cuts” from [19]:

$$p_T(\mu^{\pm}) > 10 \text{ GeV}, \ |\eta(\mu^{\pm})| < 2.5. \quad (2)$$

At Tevatron we adopt the following “Tevatron basic cuts” from [12]:

$$p_T(\mu^{\pm}) > 12 \text{ GeV}, \ |\eta(\mu^{\pm})| < 2.0. \quad (3)$$

In order to demonstrate the unique kinematics of di-muon, in Fig. 2 we show the separation $\Delta R$ between $\mu^{+} \mu^{-}$ from $a$ decay at Tevatron with $\sqrt{s} = 2 \text{ TeV}$. It should be noted that the result at LHC is similar to that at Tevatron. From the figure we can see clearly that $\Delta R$ is much less than the usual ATLAS cut (say 0.01 [15]), in order to suppress the fake muons. Such kind of di-muon has not been noticed, at least not emphasized, in the past and/or on-going analysis. In order to keep the unique 4$\mu$ signal, special attention to the extremely small $\Delta R$ of di-muon should be paid.

Choosing any one $\mu^{\pm}$ from the two, we can have two $\mu^{+} \mu^{-}$ combinations. In Fig. 3 the invariant mass $M_{\mu^{+}\mu^{-}}$ of signal and background for two combinations at Tevatron are shown. The results at LHC are similar. For
signal, the enhancement around $m_a$ will be smeared due to the limited detector energy resolution and the very tiny decay width, which is $O(10^{-7})$ MeV. The other peak is around $m_h/2$ because of the characteristic of the nearly collinear $\mu^+\mu^-$ from the same $a$ decay, i.e. $M_{\mu^+\mu^-} \approx \frac{1}{2}m_{aa} \approx \frac{1}{2}m_h$. Clearly $M_{\mu^+\mu^-}$ arising from the background for which di-muon comes from $Z$ has peak around $Z$-mass, and $M_{\mu^+\mu^-}$ for another combination is continuous distributed. Such properties can be utilized to suppress background. Namely we can exclude di-muon invariant mass around $m_Z$. However this cut will bring potential risk if $m_h$ is around $2m_Z$.

In Fig. 3 and Fig. 5, we present the 4$\mu$ invariant mass distribution for signal and background at LHC and Tevatron respectively. Here $m_h$ is taken to be 60, 90 and 120 GeV. It is clear that SM-like Higgs boson mass can be precisely reconstructed and 4$\mu$ background is rather low. This conclusion won’t change provided that the efficiency of 4$\mu$ reconstruction is not extremely low. At Tevatron with $1 fb^{-1}$ integrated luminosity, for $m_h = 120$ GeV, we will have 250 signal events. Even the real efficiency for 4$\mu$ reconstruction is 10%, we still have 25 events. At LHC for the same luminosity, Higgs boson mass and reconstruction efficiency, we can have $\sim 1500$ signal events. Provided the rather low 4$\mu$ background from SM, it is very promising to discovery the Higgs boson at LHC and Tevatron via the unique 4$\mu$ mode with rather low luminosity.
same direction at colliders. Such kind of di-muon events have been overlooked in the past experiments. Provided that the SM-like Higgs boson $h$ decays dominantly into $aa$ other than into $b\bar{b}$, in order to be consistent with null Higgs boson search at LEP, the $h \to 4\mu$ will be the unique Higgs boson signature which has not been investigated before. The SM-like Higgs boson may hide itself from the usual analysis of LEP and Tevatron experiments, which should be reanalyzed in the light of new theoretical and experimental developments. In this paper, we investigate this unique Higgs boson signature at colliders in, but actually not limited to, NMSSM and conclude that the SM-like Higgs boson could be discovered with rather low integrated luminosity, provided that the $h \to 4\mu$ reconstruction efficiency is not extremely low. It is not impossible that such kind of unique Higgs boson $4\mu$ events are now lurking in the existing LEP and/or Tevatron data. Moreover we are aware that the simulation presented here is very rough and the full detector simulation is the natural further investigation.

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