Black Holes at the LHC can Determine the Spin of Higgs bosons

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Abstract

We propose a new method to determine the spin of Higgs bosons at the LHC by using the decay products of black holes. Black holes may be produced if TeV-scale gravity theories are correct, and black holes decay into several particles. This decay results in the emission of high energy particles, including Higgs bosons. The difference of the degree of freedom between spin 0 and spin 1 Higgs bosons leads to a difference of the number of reconstructed Higgs bosons. From this fact, we can determine the spin of Higgs bosons with 5\sigma significance by using the integrated luminosity \( L \sim 2.4 \text{ fb}^{-1} \), which can be accumulated in only one month operation.
The theories of TeV-scale gravity have the possibility that we can operate the experiments which directly access Planckian and transPlanckian region. The most exciting phenomenon in these theories may be the production of black holes at the LHC [1–3], Tevatron [4] and future linear colliders [5]. Once black holes are produced, black holes decay by emitting the Hawking radiation. Since we do not know the fundamental theory of the quantum gravity, we can calculate only the decay of transPlanckian black holes and in the following we neglect the decay processes in the Planckian region.

TransPlanckian black holes have masses \( M_{BH} \), which is beyond the fundamental scale \( O(\text{TeV}) \). The temperature of such black holes \( T_{BH} \) is typically a few hundred GeV [1,2]. Thus the decay products of black holes have energies beyond 100GeV and black holes have the possibility to produce the particles which are not discovered yet, like Higgs bosons. In fact, [3] claimed that the black holes produced at the LHC decay into Higgs bosons, leading to the \( 5\sigma \) discovery on the first day of its operation. (If the fundamental scale is 1TeV.)

In this letter, we show that the spin of Higgs bosons can also be determined by the decay of black holes.

It was difficult to determine the spin of the Higgs bosons at the LHC Most channels suffer from too large backgrounds or too few events, and hence detailed studies of angular distributions are not easy. But in this letter, we propose a completely different method to determine the spin, not relying on the angular distributions.

As a beginning we briefly review the mechanism of black hole production and decay.

The black hole decay occurs in several stages: balding phase, spin-down phase, Schwarzschild phase and Planck phase [1]. Through the balding phase, black holes will settle down to a symmetrical rotating black holes by emitting gauge and gravitational radiation. In the spin-down phase, by emitting the Hawking radiation they lose their spin and enter Schwarzschild phase. Schwarzschild black holes emit quanta and lose their energies. After this phase, their properties are very difficult to analyse because of the quantum gravity effects.
In this letter we concentrate on the non-spinning Schwarzschild black hole. Since the production cross section of spinning black holes is \( \sim 2 - 3 \) times higher than that of Schwarzschild black holes \([7]\), and in the spin-down phase the spin-1 Higgs boson emission is preferred to the Schwarzschild phase because spin-1 Higgs bosons can carry angular momentum by themselves, making the spin of the Higgs boson easy to detect. So our approximation is conservative.

The parton level non-spinning black hole production cross section is given by \([2]\):

\[
\sigma(M_{BH}) \sim \pi R_S^2 = \frac{1}{M_D^2} \left[ \frac{M_{BH}}{M_D} \left( \frac{8\Gamma\left(\frac{n+3}{2}\right)}{n + 2} \right) \right]^{2/(n+1)},
\]

where \( n \) is the number of extra dimensions, \( R_S \) is the Schwarzschild radius of \((n+4)\)-dimensional black holes and \( M_D \) is the fundamental scale of TeV-scale gravity theories, which is often given by:

\[
M_D^{n+2}V_n = M_{pl}^2,
\]

where \( V_n \) is the \( n \)-dimensional volume of compactified extra dimensions.

But in order to validate the supposition that the produced object is truly a black hole, the entropy of the object must be large enough. \([1, 8]\) concluded that the necessary condition is

\[
M_{BH} \gtrsim 5M_D
\]

We have to integrate equation (1) in order to obtain the total cross section. In that process we convolute the parton distribution function of protons with energies \( \sqrt{s}/2 = 7 \TeV \). The final result depends on \( n, M_D \) and \( M_{BH}^{\text{min}} \). From equation (3), \( M_{BH}^{\text{min}} = 5M_D \).

Once black holes are produced, they decay by emitting the Hawking radiation. The decay processes of black holes are governed by the temperature of black holes \( T_{BH} \). The temperature is given by \([9]\):

\[
T_{BH} = \frac{n+1}{4\pi R_S}.
\]

The energy spectrum of decay products is obtained by averaging Planck formula, and it is roughly:

\[
\langle E \rangle \sim 2T_{BH}.
\]
So now we can obtain the number of particles emitted from black holes $N$.

$$N = \frac{M_{BH}}{2T_{BH}} \propto \left( \frac{M_{BH}}{M_D} \right)^{(n+2)/(n+1)}. \quad (6)$$

Black holes do not discriminate the Standard Model (SM) particles, and thus the probability of a certain particle being emitted from them depends on the degree of freedom of the particle. That of the SM is about 120, and that of spin 0 Higgs bosons is 1.

Here we end the brief review, and from now we consider how to determine the spin of Higgs bosons by using black holes produced at the LHC.

First we must pay attention to the current bounds on $n$ and $M_D$. According to the review [10], the cases of $n = 2, 3$ are already rejected as the candidates of the TeV-scale gravity. Then the left possibility is $4 \leq n \leq 7$, but since superstring theory or M-theory predict 10- or 11-dimensional spacetime, we choose $n = 6$ and $n = 7$ as candidates. In these cases, the constraints on $M_D$ are very weak [11], and we can roughly set $M_D = 1$ TeV.

Now we have determined $n$, $M_D$ and $M_{\min}^{BH}$. So we can calculate the total cross section of black holes at the LHC. It becomes [2]:

$$\sigma \sim 10^6 \text{ fb}. \quad (7)$$

Here we assume the integrated luminosity $L = 100\text{ fb}^{-1}$. So $\sim 10^8$ black holes are produced.

As stated above, the degree of freedom of the SM is about 120 and that of Higgs bosons is 1. So as $N$ increases, the probability that black holes decay into Higgs bosons drastically decreases. From the figure 1(d) of [2] and our setup, we observe $N \geq 4$. (In the case $M_{BH} = 5\text{ TeV}$.) Since as we increase the mass of produced black hole, the production cross section decreases exponentially, we concentrate on the case of $N = 4$, namely a black hole decay into four particles, including one Higgs boson. We trigger the event by the observation of one reconstructed Higgs boson and that of very high energy ($E_T \gtrsim$ a few TeV) three particles or jets. Three particles except one Higgs boson must satisfy the following conditions:
• The possible particle candidates are gluon, quarks except top, electron, muon and photon. Top, tau, Z and $W^{\pm}$ decay before they are detected, and neutrinos and gravitons (including their Kaluza-Klein excitations) escape from the detection.

• The total electric charge of three particles $Q$ must satisfy $|Q| < 4/3$.

The degree of freedom which satisfies these requirements becomes roughly 110000 d.o.f. Thus $P$, which denotes the probability that the decay of black holes are triggered becomes:

$$P \sim 5.1 \times 10^{-4}.$$  \hspace{1cm} (8)

So from the $10^8$ black holes, 51000 possible candidates are left.

We assume that the masses of Higgs bosons are $m_h = 120$ GeV. By using a program HDECAY \cite{12}, the branching ratios of such Higgs bosons are calculated to be:

$$BR(h \rightarrow b \bar{b}) \sim 0.66,$$  \hspace{1cm} (9a)

$$BR(h \rightarrow W W^*) \sim 0.14,$$  \hspace{1cm} (9b)

$$BR(h \rightarrow g g) \sim 0.076,$$  \hspace{1cm} (9c)

$$BR(h \rightarrow \tau \bar{\tau}) \sim 0.074.$$  \hspace{1cm} (9d)

The trigger conditions stated above are so stringent that the processes (9a-9d) are almost background free.

We assume that in analyzing this process, Higgs boson is already discovered. then we do not have to b-quaarks to be b-tagged, and gluons can also be used for the reconstruction. $WW$ and $\tau\tau$ can be reconstructed when they decay hadronically or semileptonically. So the reconstruction efficiency becomes 0.92. So if we operate the LHC with the integrated luminosity 100 fb$^{-1}$ and under the above trigger assumption, we can observe $51000 \times 0.92 = 47000$ Higgs bosons.

Now, let us assume that Higgs bosons have spin 1. Such situations can be realized in strongly electroweak symmetry breaking models. If the spin of Higgs bosons is 1, the degree of freedom becomes three, leading to the enhancement factor...
3 of produced Higgs bosons in the decay of black holes. So in that case we expect \textbf{140000} spin 1 Higgs bosons will be produced.

Strongly electroweak symmetry breaking models have extra vector bosons which break electroweak symmetry and become the alternative of the Higgs bosons in the SM. Since we are considering 120GeV Higgs bosons, the decay of spin 1 Higgs bosons into $WW$ is highly suppressed, and they mainly decay into fermions. We use electrons, muons and quarks except top for the reconstruction. Then we obtain \textbf{92000} reconstructed spin 1 Higgs bosons.

Now let us finalize our discussion. if the spin of Higgs bosons is truly 0, we can confirm the hypothesis with:

$$\frac{|47000 - 92000|}{\sqrt{42000}} \sim 210\sigma.$$  \hspace{1cm} (10)

For the 5\sigma discovery, only $L = 2.4$ fb$^{-1}$ is needed. Low luminosity run of the LHC is designed to be $10^{33}$ cm$^{-2}$ s$^{-1}$, namely $10^{-6}$ fb$^{-1}$s$^{-1}$. Thus only the one month operation is enough to announce the 5\sigma discovery of the spin 0 nature of Higgs bosons.

So black holes produced at the LHC or other colliders have the potential not only to discover new physics \cite{1, 2, 3}, but also to measure the properties of the SM particles more precisely \cite{5, 14}. One example of the precision measurement is just the determination of the spin of Higgs bosons.

To summarize, in this letter we propose a new method to determine the spin of Higgs bosons at the LHC by the decay of black holes. The method relies on the fact that the probability a black hole decays into a particular particle depends on the degree of freedom of the particle. Spin 1 Higgs bosons have the freedom which is three times larger than that of spin 0 Higgs bosons. This fact results in the difference of the number of reconstructed Higgs bosons. We can reject the hypothesis that Higgs bosons have spin 1 with 5\sigma significance by using the integrated luminosity $L = 2.4$ fb$^{-1}$, which can be accumulated in one month operation.

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