Invisible Higgs @ LHC
(from B → K + missing)

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1 Higgs Search at the LHC

The Higgs boson is the last particle in the standard model that hasn’t been observed directly!

The History:
Legacy of LEP -- precision electroweak measurements

LEPEWWG as of July 2006:

Minimal chi-square at Higgs mass = 85 GeV with an uncertainty of +39 GeV and -28 GeV
Precision Tests of the Standard Model

Lepton couplings

Pulls in global fit
Very recently Fermilab announced exclusion of a SM Higgs in the mass range 160 - 170 GeV from an inclusive search at CDF and D0.

FIG. 4: Observed and expected (median, for the background-only hypothesis) 95% C.L. upper limits on the ratios to the SM cross section, as functions of the Higgs boson mass for the combined CDF and DØ analyses. The limits are expressed as a multiple of the SM prediction for test masses (every 5 GeV/c^2) for which both experiments have performed dedicated searches in different channels. The points are joined by straight lines for better readability. The bands indicate the 68% and 95% probability regions where the limits can fluctuate, in the absence of signal. The limits displayed in this figure are obtained with the Bayesian calculation.
The State of the Higgs: May 2009

- Direct search limit from LEP: $m_H > 114.4$ GeV
- Electroweak fit sensitive to $m_t$ (Now $m_t = 173.1 \pm 1.3$ GeV)
- Best-fit value for Higgs mass: $m_H = 84^{+34}_{-26}$ GeV
- 95% confidence-level upper limit: $m_H < 154$ GeV, or 185 GeV including direct limit
- Tevatron exclusion: $m_H < 160$ GeV or $> 170$ GeV
The focus has now shifted to Tevatron and the LHC:
Main production mechanisms of the Higgs at hadron colliders:

- Associated production with $W/Z$: $q\bar{q} \rightarrow V + H$
- Vector boson fusion: $qq \rightarrow V*V* \rightarrow qq + H$
- Gluon–gluon fusion: $gg \rightarrow H$
- Associated production with heavy quarks: $gg, q\bar{q} \rightarrow Q\bar{Q} + H$

Ref: A. Djouadi, hep-ph/0503172
Among them gluon fusion is the dominant mechanism!

At Tevatron:

\[
\sigma(p\bar{p} \rightarrow H + X) \text{ [pb]} \\
\sqrt{s} = 1.96 \text{ TeV} \\
\text{MRST/NLO} \\
m_t = 178 \text{ GeV}
\]

Ref: A. Djouadi, hep-ph/0503172
At LHC:

\[ \sigma(pp \rightarrow H + X) \text{ [pb]} \]

\[ \sqrt{s} = 14 \text{ TeV} \]

MRST/NLO

\[ m_t = 178 \text{ GeV} \]
Decay channels depend on the Higgs mass:

Ref: A. Djouadi, hep-ph/0503172
Figure 4: The region excluded by the combined LEP results in the $h_0 \rightarrow \text{invisible}$ search. The 95% CL upper limit on $\xi^2$, the production rate as a fraction of the Standard Model total rate, is shown, together with the expected range assuming there is no signal.
2 HIDDEN SECTOR SCALAR, 
AND ITS COSMOLOGICAL BOUND

Assuming renormalizability, Lagrangian of hidden sector scalar,

\[ \mathcal{L}_{\text{scalar}} = \frac{1}{2} (\partial S)^2 - \frac{1}{2} m_S^2 S^2 - \frac{\lambda S}{4!} S^4 - \frac{\hat{\lambda}}{2} S^2 H^\dagger H. \]

\( Z_2 \) symmetry ensures \( S \) is stable \( \Rightarrow S = \text{dark matter candidate}, \)

\[ \Omega_S h^2 \simeq \frac{0.1 \text{pb}}{\langle \sigma_S v_{\text{rel}} \rangle}, \quad \iff \quad \langle \sigma_S v_{\text{rel}} \rangle = \frac{\hat{\lambda}^2 m_S^2}{\pi m_h^4} \Phi(m_S). \]

Now considering WMAP data (\( \Omega_c h^2 = 0.1131 \pm 0.0034 \))

\[ \frac{\hat{\lambda}^2 m_S^2}{\pi m_h^4} \gtrsim \frac{0.1 \text{pb}}{\Omega h^2 |_{\text{WMAP5yr}}} \]

\[ \Rightarrow \hat{\lambda} \gtrsim 3.5 \times \left( \frac{1 \text{ GeV}}{m_S} \right) \times \left( \frac{m_h}{150 \text{ GeV}} \right)^2. \]
If \( m_h \simeq 150(115) \) GeV and \( m_S \simeq 1 \) GeV we get \( \hat{\lambda} \gtrsim 3.5(1.2) \), respectively, which is within the strong coupling regime where the perturbative description of the model is not available.

**FIG. 1:** Cosmological constraints for a stable \( S \) from the relic abundance. Allowed parameter space in \((\hat{\lambda} = \lambda/v_0, m_S)\) plane with \( m_h = 115, 150 \) and 185 GeV, respectively.
We can easily avoid this cosmological constraint if the singlet $S$ decays into light particles, by breaking $Z_2$ symmetry from QG effects, eg.

scalar particle may decays to a pair of photons or gluons through dim=5 operators,

\[ C_1 \frac{SF_{\mu\nu}F_{\mu\nu}}{\Lambda} + C_2 \frac{SG^a_{\mu\nu}G^a_{\mu\nu}}{\Lambda} \]

where $C_1 \sim C_2 \sim O(1)$ are (unknown) parameters. One should notice that both operators respect gauge symmetry but break $Z_2$ symmetry. The life time of the scalar is suppressed by a large cutoff scale ($\Lambda \sim M_{\text{Planck}}$) but certainly much shorter than the age of universe so that we can avoid the strong constraint from the relic density measurements.
Preliminary (work in progress)
3 $B \to K + \nu \bar{\nu}$ AND $B \to K + \text{ missing}$

Here we will focus on $B^+ \to K^+\nu\bar{\nu}$ decay as its experimental upper bound is closest to the SM prediction as shown in Table I. Using the SM expectation value

$$\text{Br}_{\text{SM}}(B^+ \to K^+\nu\bar{\nu}) = 5.1 \pm 0.8 \times 10^{-6},$$

and the current upper bound from BELLE [13] on this final state as

$$\text{Br}(B \to K + \mathcal{E}) < 14 \times 10^{-6},$$

We consider as

$$\text{Br}(B \to KSS) = \text{Br}(B \to K + \mathcal{E}) - \text{Br}_{\text{SM}}(B^+ \to K^+\nu\bar{\nu})$$

And for $B \to KSS$ decay

the effective Hamiltonian for this decay can be expressed as

$$H_{\text{eff}} = \frac{\lambda V_{tb}^* V_{ts}}{m_h^2} C_s \bar{s}(1 + \gamma_5)bSS.$$ 

**cf.**

$$H_{\text{eff}}(b \to q\nu_{\text{SM}} \bar{\nu}_{\text{SM}}) = \frac{G_F\alpha}{2\pi\sqrt{2}}V_{tb}V_{ts}^* C_{10}^\nu \bar{q}\gamma^\mu(1 - \gamma_5)b\bar{\nu}\gamma_\mu(1 - \gamma_5)\nu,$$
Motivation for $B \rightarrow K(K^*) \nu \nu$ ($b \rightarrow s$ with 2 neutrinos)

BSM:
New particles

Other weakly coupled particles: light dark matter

$\text{SM: BF}(B \rightarrow K^* \nu \nu) \sim 1.3 \times 10^{-5}$

c.f. SM: $\text{BF}(B \rightarrow K^- \nu \nu) \sim 4 \times 10^{-6}$

[Belle preliminary (275 $x$ 10$^6$ B Bbar) : $\text{BF}(B \rightarrow K^- \nu \nu) < 3.6 \times 10^{-5}$]
Tag-recoil analyses: $B_1 \rightarrow \text{tag}, B_2 \rightarrow \tau^+ \nu, K^+ \nu\bar{\nu}, \nu\bar{\nu}$

Neutrino analyses require extra kinematic and/or particle selection constraints. Use $BB$ initial state to achieve this.

- Explicitly identify the decay of one “tag” $B$
  - Fully reconstructed $B \rightarrow D + X$ hadronic decays ... full knowledge of kinematics
  - $b \rightarrow c$ semileptonic decays ......................... some ambiguity, more tags

- Study the recoil for the decay of interest
  - Typically we require the recoil to have
    - Exact charged-particle content expected for signal
    - Number and total energy $E_{\text{extra}}$ of neutrals observed less than an analysis-dependent threshold
  - Tagging efficiencies can be checked by “double-tagging”

➢ All analyses apply anti-continuum shape cuts
Search for $B \to K^* \nu \nu$ (532 x $10^6$ B Bbar pairs)

Result from a blind analysis.

$Yield = 4.7^{+3.1}_{-2.6}$

(1.7σ stat. significance)

Sideband = 19

MC expectation = 18.7±3.3

Extra Calorimeter Energy (GeV)

$B(B^0 \to K^{*0} \nu \nu) < 3.4 \times 10^{-4}$ (at 90% C.L)
\( B \rightarrow K(\ast) \nu \nu \) are particularly interesting and challenging modes (\( B \rightarrow \tau \nu \) is even a small background)

The experimental signature is \( B \rightarrow K + \text{Nothing} \)

The “nothing” can also be light dark matter (mass of order (1 GeV))

Direct dark-matter searches cannot see \( M<10 \text{ GeV} \) region

C. Bird et al
PRL 93 201803

(T. Adams et al.
PRL 87 041801; A. Dedes et al., PRD 65 015001)
TABLE I: Expected BRs in the SM and experimental bounds (90% C.L.) in units of $10^{-6}$. The SM values for $K, \pi, K^*$ include the long distance contributions through intermediate on-shell $\tau$, which can be dominant for $\pi$ case [11].

<table>
<thead>
<tr>
<th>mode</th>
<th>BRs in the SM [9, 10, 11, 12]</th>
<th>Experimental bounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to K\nu\bar{\nu}$</td>
<td>$5.1 \pm 0.8$</td>
<td>$&lt; 14$ [13]</td>
</tr>
<tr>
<td>$B \to \pi\nu\bar{\nu}$</td>
<td>$9.7 \pm 2.1$</td>
<td>$&lt; 100$ [14]</td>
</tr>
<tr>
<td>$B \to K^*\nu\bar{\nu}$</td>
<td>$8.4 \pm 1.4$</td>
<td>$&lt; 80$ [15]</td>
</tr>
<tr>
<td>$B \to \rho\nu\bar{\nu}$</td>
<td>$0.49^{+0.61}_{-0.38}$</td>
<td>$&lt; 150$ [13]</td>
</tr>
</tbody>
</table>

**Expectation value within the SM** is

$$Br_{SM}(B^+ \to K^+\nu\bar{\nu}) = 5.1 \pm 0.8 \times 10^{-6}$$

**Recent BELLE result** is

$$Br(B \to K + E) < 14 \times 10^{-6}$$
Measuring $|V_{td}/V_{ub}|$ ($= \sin \gamma/\sin \beta$ within the SM) through $B \to M\nu\bar{\nu}$ ($M = \pi, K, \rho, K^*$) decays

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We propose a new method for the precise determination of $|\nu_{td}/\nu_{ub}|$ from the ratios of branching ratios $B(B \to \rho \nu\bar{\nu})/B(B \to \rho_1 \nu)$ and $B(B \to \pi \nu\bar{\nu})/B(B \to \pi_1 \nu)$. These ratios depend only on the ratio of the Cabibbo-Kobayashi-Maskawa (CKM) elements $|\nu_{td}/\nu_{ub}|$ with little theoretical uncertainty, when very small isospin breaking effects are neglected. As is well known, $|\nu_{td}/\nu_{ub}|$ equals $(\sin \gamma/\sin \beta)$ for the CKM version of $C_P$ violation within the standard model. We also give in detail analytical and numerical results on the differential decay width $d \Gamma(B \to K^* \nu\bar{\nu})/dq^2$ and the ratio of the differential rates $d \mathcal{B}(B \to \rho \nu\bar{\nu})/dq^2$ as well as $\mathcal{B}(B \to \rho \nu\bar{\nu})/\mathcal{B}(B \to K^* \nu\bar{\nu})$ and $\mathcal{B}(B \to \pi \nu\bar{\nu})/\mathcal{B}(B \to K \nu\bar{\nu})$.

[S0556-2821(98)00513-X]

PACS number(s): 12.15.Hh, 13.25.Hw
2 Theory of $B \rightarrow M \nu \bar{\nu}$ ($M = \pi, K, \rho, K^*$) decays

$$H_{\text{eff}} = \frac{G_F \alpha}{2\pi \sqrt{2}} C_{10}^\nu (V_{tb}V_{ts}^*) \bar{q} \gamma^\mu (1 - \gamma_5) b \bar{\nu} \gamma_\mu (1 - \gamma_5) \nu,$$  \hspace{1cm} (1)

where $G_F$ is the Fermi constant, $\alpha$ is the fine structure constant (at the $Z$ mass scale), and $V_{ij}$ are elements of the CKM matrix. In Eq. (1), the Wilson coefficient $C_{10}^\nu$ has the following form, including $O(\alpha_s)$ corrections:

$$C_{10}^\nu = \frac{X(x_t)}{\sin^2 \theta_W},$$  \hspace{1cm} (2)

where

$$X(x_t) = X_0(x_t) + \frac{\alpha_s}{4\pi} X_1(x_t).$$  \hspace{1cm} (3)

In Eq. (3),

$$X_0(x_t) = \frac{x_t}{8} \left[ \frac{x_t + 2}{x_t - 1} + \frac{3x_t - 6}{(x_t - 1)^2} \ln(x_t) \right],$$

is the Inami-Lim function [10], and

$$X_1(x_t) = \frac{4x_t^3 - 5x_t^2 - 23x_t}{3(x_t - 1)^2} - \frac{x_t^4 + x_t^3 - 11x_t^2 + x_t}{(x_t - 1)^3} \ln(x_t)$$

$$+ \frac{x_t^4 - x_t^3 - 4x_t^2 - 8x_t}{2(x_t - 1)^3} \ln^2(x_t) + \frac{x_t^3 - 4x_t}{(x_t - 1)^2} Li_2(1 - x_t) + 8x_t \frac{\partial X_0(x_t)}{\partial x_t} \ln(x_\mu),$$

where

$$Li_2(1 - x_t) = \int_1^{x_t} dt \frac{\ln(t)}{1 - t},$$

is the Spence function, and

$$x_t = \frac{m_t^2}{m_w^2}, \quad \text{and} \quad x_\mu = \frac{\mu^2}{m_w^2}.$$
The hadronic matrix elements for $B \to P \nu \bar{\nu}$ ($P$ is a pseudoscalar meson, $\pi$ or $K$) decays can be parametrized in terms of the form-factors $f^P_+(q^2)$ and $f^P_-(q^2)$ in the following way:

$$< P(p_2) | \bar{q} \gamma_{\mu} (1 - \gamma_5) b | B(p_1) > = p_{\mu} f^P_+(q^2) + q_{\mu} f^P_-(q^2) ,$$

(4)

where $p = p_1 + p_2$ and $q = p_1 - p_2$. For $B \to V \nu \bar{\nu}$ ($V$ is the vector $\rho$ or $K^{*}$ meson) decays, the hadronic matrix element can be written in terms of five form-factors:

$$< V(p_2, \varepsilon) | \bar{q} \gamma_{\mu} (1 - \gamma_5) b | B(p_1) > = -\varepsilon_{\mu\nu\alpha\beta}\varepsilon^{*\nu} p_2^\alpha q^\beta \frac{2V(q^2)}{m_B + m_V} - i[\varepsilon^*_\mu(m_B + m_V)A_1(q^2) - (\varepsilon^* q)(p_1 + p_2)_\mu \frac{A_2(q^2)}{m_B + m_V} - q_{\mu}(\varepsilon^* q)\frac{2m_V}{q^2}(A_3(q^2) - A_0(q^2)))]$$

(5)

with condition

$$A_3(q^2 = 0) = A_0(q^2 = 0).$$

(6)

Note that after using the equations of motion the form-factor $A_3(q^2)$ can be written as a linear combination of the form-factors $A_1$ and $A_2$ (for more details see the first reference in [12]):

$$A_3(q^2) = \frac{1}{2m_V} [(m_B + m_V)A_1(q^2) - (m_B - m_V)A_2(q^2)].$$

(7)

In Eq. (5), $\varepsilon_\mu$, $p_2$ and $m_\nu$ are the polarization 4–vector, 4–momentum and mass of the vector particle, respectively. Using Eqs. (1), (4) and (5), and after performing summation over vector meson polarization and taking into account the number of light neutrinos $N_\nu = 3,
we have:
\[
\frac{d\Gamma}{dq^2}(B^\pm \rightarrow P^\pm \nu \bar{\nu}) = \frac{G_F^2 \alpha^2}{2^8 \pi^5} |V_{tq} V_{tb}^*|^2 \lambda^{3/2}(1, r_p, s) m_B^3 |C_{10}|^2 |f_p^+(q^2)|^2
\]

and
\[
\frac{d\Gamma}{dq^2}(B^\pm \rightarrow V^\pm \nu \bar{\nu}) = \frac{G_F^2 \alpha^2}{2^{10} \pi^5} |V_{tq} V_{tb}^*|^2 \lambda^{1/2}(1, r_v, s) m_B^3 |C_{10}|^2 \\
\times \left[ 8\lambda s \frac{V^2}{(1 + \sqrt{r_v})^2} + \frac{1}{r_v} \left[ \lambda^2 \frac{A_2^2}{(1 + \sqrt{r_v})^2} \right] \\
+ (1 + \sqrt{r_v})^2(\lambda + 12r_v s) A_1^2 - 2\lambda(1 - r_v - s) Re(A_1 A_2) \right]
\]

In Eqs. (8) and (9), \(\lambda(1, r_M, s)\) is the usual triangle function
\[
\lambda(1, r_M, s) = 1 + r_M^2 + s^2 - 2r_M - 2s - 2r_M s \quad \text{with} \quad r_M = \frac{m_M^2}{m_B^2}, \quad s = \frac{q^2}{m_B^2}.
\]

Similarly, calculations for the \(B^\pm \rightarrow M^0 e^\pm \nu\) decay lead to the following results:
\[
\frac{d\Gamma}{dq^2}(B^\pm \rightarrow P^0 e^\pm \nu) = \frac{G_F^2}{192 \pi^3} |V_{qb}|^2 \lambda^{3/2}(1, r_p, s) m_B^3 |f_p^+(q^2)|^2,
\]

and
\[
\frac{d\Gamma}{dq^2}(B^\pm \rightarrow V^0 e^\pm \nu) = \frac{G_F^2 |V_{qb}|^2 \lambda^{1/2} m_B^3}{768 \pi^3} \left[ 8\lambda s \frac{V^2}{(1 + \sqrt{r_v})^2} + \frac{1}{r_v} \left[ \lambda^2 \frac{A_2^2}{(1 + \sqrt{r_v})^2} \right] \\
+ (1 + \sqrt{r_v})^2(\lambda + 12r_v s) A_1^2 - 2\lambda(1 - r_v - s) Re(A_1 A_2) \right].
\]

2010-10-18
Now we relate the branching ratio $\mathcal{B}(B^\pm \to \rho^\pm \nu \bar{\nu})$ with $\mathcal{B}(B^\pm \to \rho^0 e^\pm \nu)$. From Eqs. (9) and (11), we have

$$\frac{\mathcal{B}(B^\pm \to \rho^\pm \nu \bar{\nu})}{\mathcal{B}(B^\pm \to \rho^0 e^\pm \nu)} = 6 \frac{\alpha^2}{4\pi^2} |C_{10}^\nu|^2 \left| \frac{V_{td}}{V_{ub}} \right|^2.$$  

(12)

Here the numerical factor 6 comes from the number of light neutrinos, and isospin symmetry relation between the form-factors of $B^\pm \to \rho^\pm$ and $B^\pm \to \rho^0$. In Eq. (12), we also put $|V_{tb}| = 1$. From Eq. (12), we get

$$\left| \frac{V_{td}}{V_{ub}} \right|^2 = \frac{1}{6C} \left( \frac{\mathcal{B}_{\text{exp}}(B^\pm \to \rho^\pm \nu \bar{\nu})}{\mathcal{B}_{\text{exp}}(B^\pm \to \rho^0 e^\pm \nu)} \right) = \left( \frac{\sin \gamma}{\sin \beta} \right)^2,$$

(13)

where

$$C = \frac{\alpha^2}{4\pi^2} |C_{10}^\nu|^2.$$

(14)

$$\frac{\mathcal{B}(B^0 \to \rho^0 \nu \bar{\nu})}{\mathcal{B}(B^0 \to \rho^0 e^\pm \nu)} = \frac{3}{2} \left( \frac{\sin \gamma}{\sin \beta} \right)^2 C,$$

(15)

$$\frac{\mathcal{B}(B^\pm \to \pi^\pm \nu \bar{\nu})}{\mathcal{B}(B^\pm \to \pi^0 e^\pm \nu)} = 6 \left( \frac{\sin \gamma}{\sin \beta} \right)^2 C,$$

(16)

and

$$\frac{\mathcal{B}(B^\pm \to K^{\ast \pm} \nu \bar{\nu})}{\mathcal{B}(B^\pm \to \rho^0 e^\pm \nu)} \approx 6 \left| \frac{V_{ts}}{V_{ub}} \right|^2 C.$$

(17)
4 Invisible Higgs (at LHC,...)

We assume a singlet scalar particle, $m_S \leq 2$ GeV, in addition to ALL SM, only interact with Higgs

$$\frac{\lambda}{2v_0} H^\dagger H S^2 \equiv \hat{\lambda} \frac{1}{2} H^\dagger H S^2$$

Then, the effective Hamiltonian for $b \to s SS$ becomes

$$H_{\text{eff}}(b \to s SS) = \frac{\hat{\lambda} V^*_{tb} V_{ts}}{m_H^2} C_s \bar{s}(1 + \gamma_5) b SS$$

Intuitively, $b \to s SS$ decay can be divided into two processes: first $b$ quark decays to $s$ quark plus a off-shell Higgs boson $h$, and subsequently $h$ decays to two light singlets. From the interaction Lagrangian term $\lambda H^+ H S^2 / 2v_0$, with $H^+ = (\phi^-, (v_0 + h - i\phi^0) / \sqrt{2})$, it is easy to show that the Higgs boson decay $h \to SS$ can proceed through a trilinear term $\lambda h SS / 2$. But as we will see later, another term $\lambda \phi^+ \phi^- S^2 / 2v_0$ is also crucial to guarantee the gauge independence of the decay amplitude.
FIG. 2: $b$-quark decays to $s$-quark plus two light singlets. The internal quark lines represent up, charm or top quarks, while the internal dashed lines denote Higgs boson ($h$) or unphysical charged goldstone bosons ($\phi$).
After summing all 9 Feynman diagrams, we obtain

\[ C_s(m_W) = \frac{g^2}{(4\pi)^2} \frac{3m_b x_t}{8v_0} \]

And after QCD running effects,

\[ C_s(\mu_b) = \left( \frac{\alpha_s(\mu_b)}{\alpha_s(m_W)} \right)^{12/23} C_s(m_W) \]

And for form factors, we use

\[ \langle K^- | \bar{s}(1 + \gamma_5) b | B^- \rangle = \frac{p^\mu}{m_b} \langle K^- | \bar{s} \gamma_\mu b | B^- \rangle = \frac{p^\mu}{m_b} \left( f_+(q^2)(p + l)_\mu + (f_0(q^2) - f_+(q^2)) \frac{m_B^2 - m_K^2}{q^2} q_\mu \right) , \]

with

\[ f_+(q^2) = \frac{0.162}{1 - q^2/5.41^2} + \frac{0.173}{(1 - q^2/5.41^2)^2} \]

\[ f_0(q^2) = \frac{0.33}{1 - q^2/37.46} \]
Then, the branching ratio can then be obtained

\[
Br(B \to KSS) = \frac{\lambda^2 |V_{tb}^* V_{ts}|^2}{512 \pi^3 m_B^3 \Gamma_B m_h^4} C_s^2(m_b) \int_{4m_s^2}^{(m_B-m_K)^2} dq^2 
\]

\[
\sqrt{q^2 - 4m_s^2} \sqrt{\frac{(m_B^2 - q^2 - m_K^2)^2}{q^2} - 4m_K^2}.
\]

Taking as illustration

\[
m_h = 130 \text{ GeV}, \quad m_S = 1 \text{ GeV}, \quad \Lambda_{QCD}^{n_f=5} = 0.225 \text{ GeV}
\]

and with the values [27]

\[
m_b(m_b) = 4.2 \text{ GeV}, \quad m_t = 171.3 \text{ GeV}, \quad A = 0.814, \quad \lambda_{CKM} = 0.2257
\]

and \(V_{ts} = -A \lambda_{CKM}^2\), we can obtain the branching ratio

\[
Br(B \to KSS) = (1.19 \pm 0.29) \times \left(\frac{\lambda}{1 \text{ GeV}}\right)^2 \left(\frac{130 \text{ GeV}}{m_h}\right)^4 \times 10^{-10},
\]

where only the form factor uncertainty has been included in the error estimation.
$$\text{Br}(B \to KSS) = 1.19 \times 10^{-10} \left( \frac{\lambda}{1 \text{ GeV}} \right)^2 \left( \frac{130 \text{ GeV}}{m_h} \right)^4$$

$$\leq \text{Br}_{\text{exp}}(B \to KE) - \text{Br}_{\text{SM}}(B \to K\nu\bar{\nu}) \simeq 8 \times 10^{-6}$$

with

$$\Gamma(h \to SS) = \frac{\lambda^2}{32\pi m_h} \left( 1 - \frac{4m_S^2}{m_h^2} \right)^{\frac{1}{2}}$$

FIG. 3: Higgs boson decay BR with Invisible decay mode predicted from current upper bound of $B \to K\nu\bar{\nu}$ in solid lines. Dashed lines are SM Higgs decay BR.
FIG. 4: Higgs BR with invisible decay mode predicted from the upper bound value for $m_S = 1$ GeV and $\text{Br}(B \rightarrow KSS) = 1 \times 10^{-6}$ or $1 \times 10^{-7}$ respectively.

If $m_h < 150$ GeV, $h \rightarrow SS$ completely dominates the Higgs decay and Higgs is only invisible. Even though the traditional invisible Higgs search can be applied to search for such modes, it is impossible to identify the resonance through invisible modes at the LHC.

When $m_h > 150$ GeV, the partial width of $h \rightarrow SS$ is comparable to the partial widths of conventional channels, such as $h \rightarrow W^+W^-$ or $h \rightarrow ZZ$. The multi-lepton searches for Higgs resonance are still valid but the decay BRs significantly decrease. If the measured event numbers of $h \rightarrow W^+W^-$ or $h \rightarrow ZZ$ are below the expected numbers. There are several possibilities:
5 CONCLUSIONS

Assuming renormalizability, we minimally extend the SM with

\[ \mathcal{L}_{\text{scalar}} = \frac{1}{2} (\partial S)^2 - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_S}{4!} S^4 - \frac{\hat{\lambda}}{2} S^2 H^\dagger H. \]

Then, the effective Hamiltonian for \( b \rightarrow s\ SS \) becomes

\[ H_{\text{eff}}(b \rightarrow sSS) = \frac{\lambda V_{tb}^* V_{ts}}{m_H^2} C_s s (1 + \gamma_5) bSS \]

\[ H_{\text{eff}}(b \rightarrow q\nu_{SM}\bar{\nu}_{SM}) = \frac{G_F \alpha}{2\pi \sqrt{2}} V_{tb} V_{tq}^* C_{10}^\nu \bar{q} \gamma^\mu (1 - \gamma^5) b\bar{\nu} \gamma^\mu (1 - \gamma^5) \nu, \]

We have studied the contribution of virtual Higgs in \( B \rightarrow K\bar{E} \) by assuming Higgs coupling to a light SM singlet scalar \( S \), \( B \rightarrow KSSS \). For \( M_S = 1 \text{ GeV} \),

\[ \text{Br}(B \rightarrow KSS) = (1.19 \pm 0.29) \times \left( \frac{\lambda}{1 \text{ GeV}} \right)^2 \left( \frac{130 \text{ GeV}}{m_h} \right)^4 \times 10^{-10}. \]
Given the current experimental bound and subtracting the known SM contribution,

$$\text{Br}_{\text{exp}}(B \to KE) - \text{Br}_{\text{SM}}(B \to K\nu\bar{\nu}) \simeq 8 \times 10^{-6},$$

we obtain an upper bound on the coupling between the Higgs and singlet scalar $S$. We take the upper bound value of this coupling and compute the $h \to SS$ decay partial width.