Constraints on models for the Higgs boson with exotic spin and parity in $VH \to Vbb$ final states

We present constraints on models containing non-standard model values for the spin $J$ and parity $P$ of the Higgs boson, $H$, in up to $9.7 \text{ fb}^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ collected with the D0 detector at the Fermilab Tevatron Collider. These are the first studies of Higgs boson $J^P$ with fermions in the final state. In the $ZH \rightarrow \ell\ell bb$, $WH \rightarrow \ell\ell bb$, and $ZH \rightarrow \nu\nu bb$ final states, we compare the standard model (SM) Higgs boson prediction, $J^P = 0^+$, with two alternative hypotheses, $J^P = 0^-$ and $J^P = 2^+$. We use a likelihood ratio to quantify the degree to which our data are incompatible with non-SM $J^P$ predictions for a range of possible production rates. Assuming that the production rate in the signal models considered is equal to the SM prediction, we reject the hypothesis that our data is the result of a combination of the SM-like Higgs boson and either a $J^P = 0^-$ or a $J^P = 2^+$ signal, we exclude a $J^P = 0^-$ fraction above 0.80 and a $J^P = 2^+$ fraction above 0.67 at the 95% CL. The expected exclusion covers $J^P = 0^-$ ($J^P = 2^+$) fractions above 0.54 (0.47).

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After the discovery of a Higgs boson, $H$, at the CERN Large Hadron Collider (LHC) [1, 2] in bosonic final states, and evidence for its decay to $b$ quarks and to pairs of fermions at the CMS experiment [3], it is important to determine the new particle’s properties using all decay modes available. In particular, the spin and parity of the Higgs boson are important in determining the framework of the mass generation mechanism. The SM predicts that the Higgs boson is a CP-even spin-0 particle ($J^P = 0^+$). If the Higgs boson is indeed a single boson, the observation of its decay to two photons at the LHC precludes spin 1 according to the Landau-Yang theorem [5, 6]. Other $J^P$ possibilities are possible. An admixture of $J^P = 0^+$ and $J^P = 0^-$ can arise in Two Higgs Doublet models (2HDM) [7, 8] of type II such as found in supersymmetric models. A boson with tensor couplings ($J^P = 2^+$) can arise in models with extra dimensions [9]. The ATLAS and CMS Collaborations have examined the possibility that the $H$ boson has $J^P = 0^-$ or $J^P = 2^+$ using its decays to $\gamma\gamma$, $ZZ$, and $WW$ states [10]. The $J^P = 0^-$ hypothesis is excluded at the 97.8% and 99.95% CL by the ATLAS and CMS Collaborations, respectively, in the $H \rightarrow ZZ \rightarrow 4\ell$ decay mode. Likewise, the $J^P = 2^+$ hypothesis is excluded at the $\geq 99.9\%$ CL by the ATLAS Collaboration when combining all bosonic decay modes, and at the $\geq 97.7\%$ CL by the CMS Collaboration in the $H \rightarrow ZZ \rightarrow 4\ell$ decay mode (depending on the production processes and the quark-mediated fraction of the production processes). However, the $J^P$ character of Higgs bosons decaying to pairs of fermions, and in particular to $bb$, has not yet been studied. In this Letter we present tests of non-SM models describing produc-
tion of bosons with a mass of 125 GeV, \( J^P = 0^- \) or \( J^P = 2^+ \), and decaying to \( bb \). We explore two scenarios for each of the hypothesis: (a) the new boson is a \( J^P = 0^- \) (\( J^P = 2^+ \)) particle and (b) the observed resonance is either a combination of these non-SM \( J^P \) states and a \( J^P = 0^+ \) state or distinct states with degenerate mass. In the latter case, we do not consider interference effects between states.

Unlike the LHC \( J^P \) measurements, our ability to distinguish different Higgs boson \( J^P \) assignments is not based primarily on the angular analysis of the Higgs boson decay products. It is instead based on the kinematic correlations between the vector boson \( V(V = W, Z) \) and the Higgs boson in \( VH \) associated production. Searches for associated \( VH \) production are sensitive to the different kinematics of the various \( J^P \) combinations in several observables, especially the invariant mass of the \( VH \) system, due to the dominant \( p \) and \( d \) wave contributions to the \( J^P = 0^- \) and \( J^P = 2^+ \) production processes [13, 14]. The \( p \) and \( d \) wave contributions to the production cross sections near threshold vary as \( \beta^3 \) and \( \beta^5 \), respectively, whereas the \( s \) wave contribution for the SM Higgs boson varies as \( \beta \), where \( \beta \) is the ratio of the Higgs boson momentum and energy.

To test compatibility of non-SM \( J^P \) models with data we use the D0 studies of \( ZH \rightarrow \ell\ell bb \) [15], \( WH \rightarrow t\bar{t}bb \) [19], and \( ZH \rightarrow \nu\bar{\nu}bb \) [20] with no modifications to the event selections. Lepton flavors considered in the \( WH \rightarrow t\bar{t}bb \) and \( ZH \rightarrow \ell\ell bb \) analyses include electrons and muons. Events with taus that decay to these leptons are considered as well, although their contribution is small. The D0 detector is described in Refs. [21–23].

We use 9.5–9.7 fb\(^{-1} \) of integrated luminosity collected with the D0 detector satisfying relevant data-quality requirements in each of the three analyses. The SM background processes are either estimated from dedicated data (multijet backgrounds), or from Monte Carlo (MC) simulation. The \( V+jets \) and \( t\bar{t} \) processes are generated using \textsc{alpgen} [24], single top processes are generated using \textsc{singletop} [25], and diboson (\( VV \)) processes are generated using \textsc{pythia} [26]. The SM Higgs boson processes are also generated using \textsc{pythia}. The signal samples for the \( J^P = 0^- \) and \( J^P = 2^+ \) hypotheses are generated using \textsc{madgraph} 5 [27]. We have verified that \( J^P = 0^+ \) samples produced with \textsc{madgraph} agree well with the SM \textsc{pythia} prediction.

In the following, we denote a non-SM Higgs boson as \( X \), reserving the label \( H \) for the SM \( J^P = 0^- \) Higgs boson. \textsc{madgraph} can simulate several non-SM models, as well as user-defined models. These new states are introduced via dimension-5 Lagrangian operators [16]. The \( J^P = 0^- \) samples are created using a model from the authors of Ref. [15]. The non-SM Lagrangian can be expressed as [16]

\[
\mathcal{L}_{\text{non-SM}} = \frac{\lambda}{4} F_{\mu
u} \tilde{F}^{\mu\nu},
\]

where \( F_{\mu\nu} \) is the field-strength tensor for the vector boson, \( A \) is the new boson field, \( c_G^4 \) is a coupling term, and \( \Lambda \) is the scale at which new physics effects arise. The \( J^P = 2^+ \) signal samples are created using a Randall-Sundrum (RS) model, an extra-dimension model with a massive \( J^P = 2^+ \) particle that has graviton-like couplings [28–31]. This model’s Lagrangian can be expressed as \( L_{\text{RS}} = \frac{\lambda}{4} G_{\mu
u} T_{\mu\nu} \), where \( G_{\mu\nu} \) represents the \( J^P = 2^+ \) particle, \( c_G^4 \) is a coupling term, \( T_{\mu\nu} \) is the stress-energy tensor of the vector boson, and \( \Lambda \) is the effective Planck mass \( \Lambda \). The mass of the non-SM Higgs-like particle \( X \) is set to 125 GeV, a value close to the mass measured by the LHC Collaborations [1, 2] and also consistent with measurements at the Tevatron [3]. We study the decay of \( X \) to \( bb \) only. For our initial sample normalization we assume that the ratio \( \mu \) of the product of the cross section and the branching fraction, \( \sigma(VX) \times B(X \rightarrow bb) \), to the SM prediction is \( \mu = 1.0 \) [32, 33], and subsequently define exclusion regions as functions of \( \mu \). We use the CTEQ6L1 PDF set for sample generation, and \textsc{pythia} for parton showering and hadronization. The MC samples are processed by the full D0 detector simulation. To reproduce the effect of multiple \( pp \) interactions in the same beam crossing, each simulated event is overlaid with an event from a sample of random beam crossings with the same instantaneous luminosity profile as the data. The events are then reconstructed with the same programs as the data.

All three analyses employ a \( b \)-tagging algorithm based on track impact parameters, secondary vertices, and event topology to select jets that are consistent with originating from a \( b \) quark [34, 35].

The \( ZH \rightarrow \ell\ell bb \) analysis [15] selects events with two isolated charged leptons and at least two jets. A kinematic fit corrects the measured jet energies to their best fit values based on the constraints that the dilepton invariant mass should be consistent with the \( Z \) boson mass [36] and that the total transverse momentum of the leptons and jets should be consistent with zero. The event sample is further divided into orthogonal “single-tag” (ST) and “double-tag” (DT) channels according to the number of \( b \)-tagged jets. The SM Higgs boson search uses random forest (RF) [37] discriminants to provide distributions for the final statistical analysis. The first RF is designed to discriminate against \( t\bar{t} \) events and divides events into \( t\bar{t} \)-enriched and \( t\bar{t} \)-depleted ST and DT regions. In this study only events in the \( t\bar{t} \)-depleted ST and DT regions are considered. These regions contain \( \approx 94\% \) of the SM Higgs signal.

The \( WH \rightarrow t\bar{t}bb \) analysis [19] selects events with one charged lepton, significant imbalance in the transverse energy (\( E_T \)), and two or three jets. This search is also sensitive to the \( ZH \rightarrow \ell\ell bb \) process when one of the charged leptons is not identified. Using the outputs of the \( b \)-tagging algorithm for all selected jets, events are divided into four orthogonal \( b \)-tagging categories, “one-tight-tag” (1TT), “two-loose-tag” (2LT), “two-medium-
tag” (2MT), and “two-tight-tag” (2TT). Looser b-tagging
categories correspond to higher efficiencies for true b
quarks and higher fake rates. Outputs from boosted de-
cision trees (BDTs) [37], trained separately for each jet
multiplicity and tagging category, serve as the final dis-
criminants in the SM Higgs boson search.

The $2H \rightarrow \nu\nu b$ analysis [20] selects events with large
$E_T$ and exactly two jets. This search is also sensitive
to the $WH$ process when the charged lepton from the
$W \rightarrow e\nu$ decay is not identified. A dedicated BDT is used
to provide rejection of the large multijet background.

Two orthogonal b-tagging channels, medium (MT), and
tight (TT), use the sum of the b-tagging discriminants
of the two selected jets. BDT classifiers, trained sepa-
ately for the different b-tagging categories, provide the
final discriminants in the SM Higgs boson search.

These three analyses are among the inputs to the D0
SM Higgs boson search [38], yielding an excess above the
SM background expectation that is consistent both in
shape and in magnitude with a SM Higgs boson signal.
The best fit to data for the $H \rightarrow bb$ decay channel for the
product of the signal cross section and branching fraction,
is $\mu = 1.29^{+1.24}_{-1.17}$ for a mass of 125 GeV. When including
data from both Tevatron experiments, the best fit to data
yields $\mu = 1.59^{-0.72}_{+0.69}$ [39].

Discrimination between the $J^P$ values of non-SM and
SM hypotheses is achieved by using mass information of the
$VX$ system. For the $\ell\ell b\bar{b}$ final state we use the invariant
mass of the two leptons and either the two highest
b-tagged jets (DT) or the two highest $p_T$ non-tagged jet (ST)
as the final discriminating variable. For the final states that have neutrinos, the discrimi-

nating variable is the transverse mass of the $VX$ system
which is defined as $M_T^2 = (E_T^V + E_T^X)^2 - (p_T^V + p_T^X)^2$
where the transverse momenta of the $Z$ and $W$ bosons
are $p_T^Z = E_T - m_Z$, and $p_T^W = E_T + m_W$. For the $\ell\ell b\bar{b}$ final state
the two jets can either be one b-tagged jet (1TT) and the
highest $p_T$ non-tagged jet, or the two b-tagged jets from any of the other three b-tagging categories: 2LT, 2MT, or 2TT.

To improve the discrimination between the non-SM
signals and backgrounds in the $\ell\ell b\bar{b}$ and $\nu\nu b\bar{b}$ final states,
we use the invariant mass of the dijet system, $M_{jj}$, to
select two regions with different signal purities. Events
with dijet masses in the range $100 \leq M_{jj} \leq 150$ GeV
($70 \leq M_{jj} < 150$ GeV) for $\ell\ell b\bar{b}$ ($\nu\nu b\bar{b}$) final states com-
prise the “high-purity” region (HP), while the remaining
events are in the “low-purity region” (LP). As a result of the kinematic fit, the HP region for the $\ell\ell b\bar{b}$ final state
is narrower than that for the $\nu\nu b\bar{b}$ final state, given the
correspondingly narrower dijet mass peak. For the $\ell\ell b\bar{b}$
final state we use the final BDT output ($D$) of the SM
Higgs boson search [19]. Since events with $D \leq 0$ provide
negligible sensitivity to SM or non-SM signals, we do not
consider them further. We separate the remaining events
into two categories with different signal purities. The LP
category consists of events with $0 \leq D \leq 0.5$, and the
HP category of events with $D > 0.5$.

Figure 4 illustrates the discriminating variables for the
three analysis channels in the high-purity categories for the
most sensitive b-tagging selections. Distributions for
additional subchannels can be found in Ref. [40].

We perform the statistical analysis using a modified
frequentist approach [38, 41, 42]. We use a negative log-
likelihood ratio (LLR) as the test statistic for two hy-
potheses: the null hypothesis, $H_0$, and the test hypothe-

sis, $H_1$. This LLR is given by $LLR = -2\ln(L_{H_1}/L_{H_0})$,
where $L_{H_1}$ is the joint likelihood for hypothesis $x$ eval-
uated over the number of bins in the final discriminating
variable distribution in each channel. To decrease the
effect of systematic uncertainties on the sensitivity, we
fit the signals and backgrounds by maximizing the likeli-
hood functions by allowing the systematic effects to vary
within Gaussian constraints. This fit is performed sepa-

rately for both the $H_0$ and $H_1$ hypotheses for the data
and each pseudo-experiment.

We define $CL_s$ as $CL_{H_1}/CL_{H_0}$ where $CL_{H_1}$ is the
hypothsis for the data $x$, $CL_{H_1} = P_{H_1}(LLR \geq LLR^{obs})$, and
$LLR^{obs}$ is the LLR value observed in the data. $P_{H_1}$ is de-
defined as the probability that the LLR falls beyond $LLR^{obs}$
for the distribution of LLR populated by the $H_1$ model.
For example, if $CL_s \leq 0.05$ we exclude the $H_1$ hypoth-
hesis in favor of the $H_0$ hypothesis at $\geq 95\%$ CL.

Systematic uncertainties affecting both shape and rate
are considered. The systematic uncertainties for each in-
dividual analysis are described in Refs. [18, 20]. A sum-
mary of the major contributions follows. The largest
contribution for all analyses is from the uncertainties on the
cross sections of the simulated $V+ $ heavy-flavor jets backgrounds which are $20\%$-$30\%$. All other cross
section uncertainties for simulated backgrounds are less
than $10\%$. Since the multijet background is estimated
from data, its uncertainty depends on the size of the
data sample from which it is estimated, and ranges from
$10\%$ to $30\%$. All simulated samples for the $WH \rightarrow \nu\nu b$
and $ZH \rightarrow \nu\nu b$ analyses have an uncertainty of $6.1\%$
from the integrated luminosity [13], whereas the simu-
lated samples from the $ZH \rightarrow \ell\ell b\bar{b}$ analysis have un-
certainties ranging from $0.7\%$-$7\%$ arising from the fitted
normalization to the data [18]. All analyses take
into account uncertainties on the jet energy scale, res-
olution, and jet identification efficiency for a combined
uncertainty of $\approx 7\%$. The uncertainty on the $b$-tagging
rate varies from $1\%$–$10\%$ depending on the number and
quality of the tagged jets. The correlations between the
three analyses are described in Ref. [38].

In this Letter, the $H_0$ hypothesis always contains SM
background processes and the SM Higgs boson normal-
ized to $\mu \times \sigma^{SM}_{0}$. To test the non-SM cross section we
assign the $H_1$ hypothesis as the sum of the $J^P = 0^-$
or $J^P = 2^+$ signal plus SM background processes, with
no contribution from the SM Higgs boson. We calculate
the $CL_s$ values using signal cross sections expressed as $\mu \times \sigma_{0}^{SM}$ and evaluate the expected values for each of these quantities by replacing LLR$^{exp}$ with LLR$^{SM}$, the median expectation for the $J^P = 0^+$ hypothesis only. Figure 2 illustrates the LLR distributions for the $H_0$ and $J^P = 2^+$ hypothesis, and the observed LLR value assuming $\mu = 1.0$, a production rate compatible with both Tevatron and LHC Higgs boson measurements. The similar plot for $J^P = 0^-$ is shown in Ref. [40]. We interpret $1 - CL_s$ as the confidence level at which we exclude the non-SM hypothesis for the models considered in favor of the SM prediction for $J^P = 0^+$ for the given value of $\mu$. For $\mu = 1.0$ we exclude the $J^P = 0^-$ ($J^P = 2^+$) hypothesis at the 97.6% (99.0%) CL. The expected exclusions are at the 99.86% and 99.94% CL. Results, including those for $\mu = 1.23$, are given in Table I.

Tables detailing the $CL_{H_s}$ values for each individual analysis channel and the combination can be found in Ref. [40]. We also obtain $1 - CL_s$ over a range of SM and non-SM signal strengths. Figure 3 shows the expected and observed 95% CL exclusions as a function of the $J^P = 0^-$ ($J^P = 2^+$) and $J^P = 0^+$ signal strengths, which may differ between the SM and non-SM signals. In the tests shown in Fig. 3, the signal in the $H_1$ hypothesis is the $J^P = 0^-$ ($J^P = 2^+$) signal normalized to $\mu_0 \times (\mu_2) \times \sigma_{0}^{SM}$, and the signal in the $H_0$ hypothesis is the $J^P = 0^+$ signal normalized to $\mu_{0^+} \times \sigma_{0^+}^{SM}$.

We also consider the possibility of a combination of $J^P$ signals in our data (e.g., $J^P = 0^+$ and $J^P = 0^-$). These tests provide constraints on a number of theoretical models such as those containing pseudoscalar bosons in addition to a SM-like Higgs boson. For these studies we fix the sum of the two cross sections to a specific value of $\mu \times \sigma_{0^+}^{SM}$ and vary the fractions $f_{0^-} = \sigma_{0^-}/(\sigma_{0^+} + \sigma_{0^-})$ or $f_{2^+} = \sigma_{2^+}/(\sigma_{0^+} + \sigma_{2^+})$ of non-SM signal and calculate the same $CL_s$ values as above as a function of $f_{0^-}$ or $f_{2^+}$. To study $f_{0^-}$, we now modify $H_1$ to be the sum of the background, the $J^P = 0^-$ signal normalized to $\mu \times \sigma_{0}^{SM} \times f_{0^-}$, and the $J^P = 0^+$ signal normalized to $\mu \times \sigma_{0^+}^{SM} \times (1 - f_{0^-})$. $H_0$ remains as previously defined. We follow an identical prescription for $J^P = 2^+$. Figure 4 presents the value $1 - CL_s$ as a function of the $J^P = 0^-$ signal fraction $f_{0^-}$ for the case of $\mu = 1.0$, and the corresponding figure for the $J^P = 2^+$ hypothesis is available in Ref. [40]. For $\mu = 1.0$ we exclude a $J^P = 0^-$ ($J^P = 2^+$) signal fraction $f_{0^-} > 0.80$ ($f_{2^+} > 0.67$) at the 95% CL.
The expected exclusions are \( f_{0^-} > 0.54 \) (\( f_{2^+} > 0.47 \)). Limits on admixture fractions for other choices of \( \mu \) are shown in [40].

In summary, we have performed tests of models with non-SM spin and parity assignments in Higgs boson production with a W or Z boson and decaying into \( bb \) pairs. We use the published analyses of the \( WH \to \ell
\ell bb \), \( ZH \to \ell
\ell bb \), and \( ZH \to \nu\nu bb \) final states with no modifications to the event selections. Sensitivity to non-SM \( J^P \) assignments in the two models considered here is enhanced via the separation of samples into high- and low-purity categories wherein the total mass or total transverse mass of the \( VX \) system provides powerful discrimination. Assuming a production rate compatible with both Tevatron and LHC Higgs boson measurements, our data strongly reject non-SM \( J^P \) predictions, and agree with the SM \( J^P = 0^+ \) prediction. Under the assumption of two nearly degenerate bosons with different \( J^P \) values, we set upper limits on the fraction of non-SM signal in our data. This is the first exclusion of non-SM \( J^P \) parameter space in a fermionic decay channel of the Higgs boson.

\[
\begin{array}{cccc}
J^P & 1 - CL_\alpha (s.d.) & f_{J^P} \\
\hline
0^- & 0.9986 (3.00) & 0.976 (1.98) & >0.54 >0.80 \\
2^+ & 0.9994 (3.22) & 0.990 (2.34) & >0.47 >0.67 \\
\hline
\mu = 1.23 & & & \\
0^- & 0.9998 (3.60) & 0.995 (2.56) & >0.45 >0.67 \\
2^+ & 0.9999 (3.86) & 0.998 (2.91) & >0.40 >0.56 \\
\end{array}
\]

TABLE I: Expected and observed \( 1 - CL_\alpha \) values (converted to s.d. in parentheses) and signal fractions for \( \mu = 1.0 \) and \( \mu = 1.23 \) excluded at the 95% CL.

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In this document we provide supplemental information on the constraints on models with non-SM spin and parity for the Higgs boson in the $VH \rightarrow Vb\bar{b}$ final states in up to 9.7 fb$^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected with the D0 detector at the Fermilab Tevatron Collider. We denote a non-SM Higgs boson as $X$.

**Figure 5** Dijet mass distributions for the $\nu\nu b\bar{b}$ and $\ell\ell b\bar{b}$ analyses and the BDT output distribution for the $\ell\nu b\bar{b}$ analysis.

**Figures 6-9** Additional VX invariant and transverse mass distributions for individual analyses.

**Figures 10 and 11** LLR distributions for the individual analyses and their combination.

**Tables II and III** Tables of $CL_{H_{\sigma}}$ and $1 - CL_{s}$ values for the individual analyses and their combination for $\mu = 1.0$ and $\mu = 1.23$.

**Figure 12** $1 - CL_{s}$ as a function of the $J^{P} = 2^{+}$ signal fraction, $f_{2^{+}}$, for all analyses combined.

**Figure 13** The expected and observed 95% CL exclusion as functions of the $J^{P} = 0^{-}$ ($J^{P} = 2^{+}$) signal fraction, $f_{0^{-}}$ ($f_{2^{+}}$), and the total signal strength.
FIG. 5: Invariant mass of the dijet system for (a) the $ZH \rightarrow \ell \ell b\bar{b}$ analysis, and (b) the $ZH \rightarrow \nu \nu b\bar{b}$ analysis, and the BDT output for (c) the $WH \rightarrow \ell \nu b\bar{b}$ analysis. The $J^P = 2^+$ and $J^P = 0^-$ samples are normalized to the product of the SM cross section and branching fraction multiplied by an additional factor. Heavy- and light-flavor quark jets are denoted by lf and hf, respectively. Overflow events are included in the highest bin. For all signals, a mass of 125 GeV for the $H$ or $X$ boson is assumed.
FIG. 6: Invariant mass of the $\ell\ell b\bar{b}$ system in the $ZH \to \ell\ell b\bar{b}$ analysis for events in the (a) single-tag high-purity (ST HP), (b) double-tag high-purity (DT HP), (c) single-tag low-purity (ST LP), and (d) double-tag low-purity (DT LP) channels. The $J^P = 2^+$ and $J^P = 0^-$ samples are normalized to the product of the SM cross section and branching fraction multiplied by an additional factor. Heavy- and light-flavor quark jets are denoted by lf and hf, respectively. Overflow events are included in the last bin. For all signals, a mass of 125 GeV for the $H$ or $X$ boson is assumed.
FIG. 7: Transverse mass of the $\ell \nu b\bar{b}$ system in the $WH \to \ell \nu b\bar{b}$ analysis in the high-purity (HP) region for (a) 1 tight-tag (1TT), (b) 2 loose-tags (2LT), (c) 2 medium-tags (2MT), and (d) 2 tight-tags (2TT) channels. The $J^{P}=2^{+}$ and $J^{P}=0^{-}$ samples are normalized to the product of the SM cross section and branching fraction multiplied by an additional factor. Heavy- and light-flavor quark jets are denoted by lf and hf, respectively. Overflow events are included in the last bin. For all signals, a mass of 125 GeV for the $H$ or $X$ boson is assumed.
FIG. 8: Transverse mass of the $\ell v b\bar{b}$ system in the $WH \rightarrow \ell v b\bar{b}$ analysis in the low purity (LP) region for (a) 1-tight-tag (1 TT), (b) 2-loose-tags (2LT), (c) 2-medium-tags (2MT), and (d) 2-tight-tags (2TT) channels. The $J^P = 2^+$ and $J^P = 0^-$ samples are normalized to the product of the SM cross section and branching fraction multiplied by an additional factor. Heavy- and light-flavor quark jets are denoted by lf and hf, respectively. Overflow events are included in the last bin. For all signals, a mass of 125 GeV for the $H$ or $X$ boson is assumed.
FIG. 9: Transverse mass of the $\nu\nu b\bar{b}$ system in the $ZH \rightarrow \nu\nu b\bar{b}$ analysis for events in the (a) medium-tag high-purity (MT HP), (b) tight-tag high-purity (TT HP), (c) medium-tag low-purity (MT LP), and (d) tight-tag low-purity (TT LP) channels. The $J^P = 2^+$ and $J^P = 0^-$ samples are normalized to the product of the SM cross section and branching fraction multiplied by an additional factor. Heavy- and light-flavor quark jets are denoted by lf and hf, respectively. Overflow events are included in the last bin. For all signals, a mass of 125 GeV for the $H$ or $X$ boson is assumed.
FIG. 10: LLR distributions comparing the $J^P = 0^+$ and the $J^P = 0^-$ hypotheses for the (a) $ZH \rightarrow \ell\ell b\bar{b}$ analysis, (b) $WH \rightarrow \ell\nu b\bar{b}$ analysis, (c) $ZH \rightarrow \nu\nu b\bar{b}$ analysis, and (d) their combination. The $J^P = 0^+$ and $J^P = 0^-$ samples are normalized to the product of the SM cross section and branching fraction multiplied by $\mu = 1.0$. The vertical solid line represents the observed LLR value, while the dark and light shaded areas represent 1 s.d. and 2 s.d. on the expectation from the null hypothesis $H_0$, respectively. Here $H_0$ is the SM $J^P = 0^+$ signal plus backgrounds. For all signals, a mass of 125 GeV for the $H$ or $X$ boson is assumed.
FIG. 11: LLR distributions comparing the $J^P = 0^+$ and the $J^P = 2^+$ hypotheses for the (a) $ZH \to \ell\ell b\bar{b}$ analysis, (b) $WH \to \ell\nu b\bar{b}$ analysis, (c) $ZH \to \nu\nu b\bar{b}$ analysis, and (d) their combination. The $J^P = 0^+$ and $J^P = 2^+$ samples are normalized to the product of the SM cross section and branching fraction multiplied by $\mu = 1.0$. The vertical solid line represents the observed LLR value, while the dark and light shaded areas represent 1 s.d. and 2 s.d. on the expectation from the null hypothesis $H_0$, respectively. Here $H_0$ is the SM $J^P = 0^+$ signal plus backgrounds. For all signals, a mass of 125 GeV for the $H$ or $X$ boson is assumed.
<table>
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<th>$WH \rightarrow \ell\nu b\bar{b}$</th>
<th>$ZH \rightarrow \nu\nu b\bar{b}$</th>
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<td>0.016</td>
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<td>0.351</td>
<td>0.007</td>
<td>0.022</td>
</tr>
<tr>
<td>$CL_0^+$ Expected</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
</tr>
<tr>
<td>$CL_0^+$ Observed</td>
<td>0.646</td>
<td>0.965</td>
<td>0.367</td>
<td>0.918</td>
</tr>
<tr>
<td>$1 - CL_s$ Expected</td>
<td>0.850 (1.04 s.d.)</td>
<td>0.941 (1.56 s.d.)</td>
<td>0.969 (1.87 s.d.)</td>
<td>0.9986 (3.00 s.d.)</td>
</tr>
<tr>
<td>$1 - CL_s$ Observed</td>
<td>0.805 (0.86 s.d.)</td>
<td>0.637 (0.35 s.d.)</td>
<td>0.981 (2.07 s.d.)</td>
<td>0.976 (1.98 s.d.)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$CL_2^+$ Expected</th>
<th>$CL_2^+$ Observed</th>
<th>$CL_0^+$ Expected</th>
<th>$CL_0^+$ Observed</th>
<th>$1 - CL_s$ Expected</th>
<th>$1 - CL_s$ Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J^P = 0^-$ vs. $J^P = 0^+$</td>
<td>0.064</td>
<td>0.009</td>
<td>0.023</td>
<td>0.0003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$J^P = 2^+$ vs. $J^P = 0^+$</td>
<td>0.134</td>
<td>0.114</td>
<td>0.002</td>
<td>0.009</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE II: Expected and observed $CL_{H\gamma}$ and $1 - CL_s$ values for $J^P = 0^-$ and $J^P = 2^+$ associated production, assuming signal cross sections equal to the 125 GeV SM Higgs production cross section multiplied by $\mu = 1.0$. The null hypothesis is taken to be the sum of the SM Higgs boson signal and background production.
<table>
<thead>
<tr>
<th>Analysis</th>
<th>$ZH \rightarrow \ell\ell b\bar{b}$</th>
<th>$WH \rightarrow \ell\nu b\bar{b}$</th>
<th>$ZH \rightarrow \nu\nu b\bar{b}$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CL_{0^-}$ Expected</td>
<td>0.046</td>
<td>0.012</td>
<td>0.005</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>$CL_{0^-}$ Observed</td>
<td>0.072</td>
<td>0.245</td>
<td>0.0006</td>
<td>0.005</td>
</tr>
<tr>
<td>$CL_{0^+}$ Expected</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
</tr>
<tr>
<td>$CL_{0^+}$ Observed</td>
<td>0.615</td>
<td>0.971</td>
<td>0.215</td>
<td>0.922</td>
</tr>
<tr>
<td>$1 - CL_s$ Expected</td>
<td>0.908 (1.33 s.d.)</td>
<td>0.975 (1.96 s.d.)</td>
<td>0.989 (2.31 s.d.)</td>
<td>0.9998 (3.60 s.d.)</td>
</tr>
<tr>
<td>$1 - CL_s$ Observed</td>
<td>0.883 (1.19 s.d.)</td>
<td>0.747 (0.67 s.d.)</td>
<td>0.997 (2.78 s.d.)</td>
<td>0.995 (2.56 s.d.)</td>
</tr>
</tbody>
</table>

| $CL_{2^+}$ Expected | 0.037 | 0.003 | 0.009 | <0.0001 |
| $CL_{2^+}$ Observed | 0.078 | 0.056 | 0.003 | 0.002 |
| $CL_{0^+}$ Expected | 0.500 | 0.500 | 0.500 | 0.500 |
| $CL_{0^+}$ Observed | 0.679 | 0.937 | 0.363 | 0.911 |
| $1 - CL_s$ Expected | 0.925 (1.44 s.d.) | 0.995 (2.56 s.d.) | 0.983 (2.11 s.d.) | 0.9999 (3.86 s.d.) |
| $1 - CL_s$ Observed | 0.885 (1.20 s.d.) | 0.941 (1.56 s.d.) | 0.991 (2.35 s.d.) | 0.998 (2.91 s.d.) |

TABLE III: Expected and observed $CL_H$, and $1 - CL_s$ values for $J^P = 0^-$ and $J^P = 2^+$ VX associated production, assuming signal cross sections equal to the 125 GeV SM Higgs production cross section multiplied by $\mu = 1.23$. The null hypothesis is taken to be the sum of the SM Higgs boson signal and background production.
FIG. 12: (color online) $1 - CL_s$ as a function of the $J^P = 2^+$ signal fraction $f_{2^+}$ for $\mu = 1.0$ for all analyses combined. The horizontal solid line corresponds to the 95% CL exclusion. The dark and light shaded regions represent the expected 1 and 2 s.d. fluctuations of the $J^P = 0^+$ hypothesis.
FIG. 13: (color online) The expected 95% CL exclusion (shaded area) and observed 95% CL exclusion (solid line) as functions of the $J^P = 0^-$ signal fraction $f_0^-$ and the total signal strength in units of the SM Higgs cross section multiplied by the branching ratio. As functions of the $J^P = 2^+$ signal fraction $f_{2^+}$ and the total signal strength, the expected and observed exclusions are shown as the hatched area and dashed line, respectively.