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Tevatron constraints on models of the Higgs boson with exotic spin and parity using decays to bottom-antibottom quark pairs

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Combined constraints from the CDF and D0 Collaborations on models of the Higgs boson with exotic spin J and parity P are presented and compared with results obtained assuming the standard model value $J^P = 0^+$. Two models with either $J^P = 0^-$ or $J^P = 2^+$ bosons were tested. Both collaborations analyzed approximately 10 fb^{-1} of proton-antiproton collisions with a center-of-mass energy of 1.96 TeV collected at the Fermilab Tevatron. They combined analyses of the $WH \to \ell\nu b\bar{b}$, $ZH \to \nu\bar{\nu}b\bar{b}$, and $ZH \to \ell^+\ell^- b\bar{b}$ channels. Upper limits at the 95% credibility level on the production rates of the exotic Higgs bosons, expressed as fractions of the standard model Higgs boson production rate, are set at 0.36 for the 0^- hypothesis and 0.36 for the 2^+ hypothesis, assuming a particle mass of 125 GeV/c^2. If the production rate times the branching ratio to a bottom-antibottom pair is the same as that predicted for the SM Higgs boson, then the exotic bosons are excluded with significances of 5.0 standard deviations and 4.9 standard deviations for the 0^- and 2^+ hypotheses, respectively.

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The Higgs boson discovered by the ATLAS [1] and CMS [2] Collaborations in 2012 using data produced in proton-proton collisions at the Large Hadron Collider (LHC) at CERN allows many stringent tests of the electroweak symmetry breaking in the standard model (SM) and extensions to the SM to be performed. To date, measurements of the Higgs boson's mass and width, its couplings to other particles, and its spin and parity quantum numbers J and P are consistent with the expectations for the SM Higgs boson [3, 4]. The CDF and D0 Collaborations at the Fermilab Tevatron observed a 3.0 standard deviation (s.d.) excess of events consistent with a Higgs boson signal, largely driven by those channels sensitive to the decay of the Higgs boson to bottom quarks ($H \to b\bar{b}$) [5, 6]. The Tevatron data are also consistent with the predictions for the properties of the SM Higgs boson [5]-[11].

Ref. [12] proposed to use the Tevatron data to test models for the Higgs boson with exotic spin and parity, using events in which the exotic Higgs boson X is produced in association with a W or a Z boson and decays to a bottom-antibottom quark pair, $X \to b\bar{b}$. This proposal used two of the spin and parity models in Ref. [13], one with a pseudoscalar $J^P = 0^-$ state and the other with a graviton-like $J^P = 2^+$ state. For the SM Higgs boson, which has $J^P = 0^+$, the differential production rate near threshold is linear in β, where $\beta = 2p/\sqrt{\hat{s}}$, p is the momentum of the X boson in the VX ($V = W$ or Z) reference frame, and $\sqrt{\hat{s}}$ is the total energy of the VX system in its rest frame. For the pseudoscalar model, the dependence is proportional to β^3. For the graviton-like model, the dependence is proportional to β^5; however, not all $J^P = 2^+$ models share this β^5 factor [12]. These powers of β alter the kinematic distributions of the observable decay products of the vector boson and the Higgs-like boson X, most notably the invariant mass of the VX system, which has a higher average value in the $J^P = 0^-$ hypothesis than in the SM 0^+ case, and higher still in the $J^P = 2^+$ hypothesis. These models predict neither the production rates nor the decay branching fractions of the X particles.

Here the combination of the CDF [9] and D0 [10] studies of the J^P assignments of the state X, with mass $m_X = 125$ GeV/c^2, in the $X \to b\bar{b}$ decay reported in Ref. [11] is discussed. The $WH \to \ell\nu b\bar{b}$, $ZH \to \ell^+\ell^- b\bar{b}$, and $WH + ZH \to \not{E}_T b\bar{b}$ channels, where $\ell = e$ or μ and $\not{E}_T$ is the missing transverse energy, are used. Whilst the event selections are similar (CDF), or identical (D0), to those used in their SM counterparts [14]-[19] these analyses however are optimized to distinguish the $J^P = 0^-$ and the $J^P = 2^+$ hypotheses from the SM 0^+ hypothesis. The exotic particles are considered either in addition to, or replacing, the SM Higgs boson; a mixture of all three states is not considered. The CDF multivariate analysis (MVA) discriminants were newly trained to separate the exotic Higgs boson signals from the SM backgrounds. In the $WH \to \ell\nu b\bar{b}$ and $VH \to \not{E}_T b\bar{b}$ channels, events deemed to be background-like by the new discriminants are then classified according to the SM-optimized MVA discriminants in order to improve the performance of tests between the SM and exotic hypotheses. Depending on the channel, D0 uses either the reconstructed dijet mass or the MVA used in the SM Higgs boson search to separate events into high- and low-purity samples. The mass of the VX system is then used to discriminate between the exotic and SM hypotheses. For the $ZH \to \ell\ell b\bar{b}$ analysis the invariant mass of the two leptons and the two highest p_T jets is used. For the $\ell\nu b\bar{b}$ and $\nu\nu b\bar{b}$ final states the transverse mass M_T is used, where $M_T^2 = (E_T^V + E_T^X)^2 - (\vec{p}_T^{\,V} + \vec{p}_T^{\,X})^2$ and the transverse momenta of the Z and W bosons are taken to be $\vec{p}_T^{\,Z} = \vec{\not{E}}_T$ and $\vec{p}_T^{\,W} = \vec{\not{E}}_T + \vec{p}_T^{\,\ell}$, respectively.

Standard model Higgs boson signal events are simulated using the leading-order (LO) cal-

culation from PYTHIA [20], with CTEQ5L (CDF) and CTEQ6L1 (D0) [21] parton distribution functions (PDFs). The $J^P = 0^-$ and $J^P = 2^+$ signal samples are generated using MADGRAPH 5 version 1.4.8.4 [22], with modifications provided by the authors of Ref. [12]. Subsequent particle showering is modeled by PYTHIA. Normalization of the the SM Higgs boson rate predictions to the highest-order calculations and the treatment of the backgrounds is as in the SM Higgs analyses [6] and Refs. therein. For example, the data-driven methods used to normalize the V plus light-flavour and heavy-flavour jet backgrounds are described in Refs. [23, 24].

Following Ref. [6] both Bayesian and modified frequentist calculations of the upper limits on exotic X boson production with and without SM Higgs production, best-fit cross sections allowing for the simultaneous presence of a SM Higgs boson and an exotic X boson, and hypothesis tests for signals assuming various production rate times branching ratio values for the exotic bosons are performed. Both methods use likelihood calculations based on Poisson probabilities that include SM background processes and signal predictions for the SM Higgs and exotic bosons multiplied by their respective scaling factors, $\mu_{\rm SM}$ and $\mu_{\rm exotic}$. A value of one for either $\mu_{\rm SM}$ or $\mu_{\rm exotic}$ corresponds to a cross section times branching ratio as predicted for the SM Higgs boson. Systematic uncertainties on the predicted rates and on the shapes of the distributions and their correlations are treated as described in Ref. [6]. Theoretical uncertainties in cross sections and branching ratios are considered fully correlated between CDF and D0, and between analyses. The uncertainties on the measurements of the integrated luminosities, which are used to normalize the expected signal yields and the MC-based background rates, are 6.0% (CDF) and 6.1% (D0). Of these values, 4% arises from the inelastic $p\bar{p}$ cross section [25], which is fully correlated between CDF and D0. The dominant uncertainties on the backgrounds are constrained by the data in low s/b regions of the discriminant distributions. Different methods were used by CDF and D0 to estimate V+jets and multijet backgrounds and so their uncertainties are considered uncorrelated. Similarly, the uncertainties on the data-driven estimates of the b-tag efficiencies are considered uncorrelated between CDF and D0, as are the uncertainties on the jet energy scales, the trigger efficiencies, and lepton identification efficiencies. Bayesian upper limits and best-fit cross sections assuming uniform priors for non-negative signal cross sections are given; the modified frequentist method was used to perform the hypothesis tests. Systematic uncertainties are parameterized by nuisance parameters with Gaussian priors, truncated so that no predicted yield for any process in any search channel is negative.

For both the $J^P = 0^-$ and $J^P = 2^+$ models, we compute two 95% credibility upper limits on $\mu_{\rm exotic}$, one assuming $\mu_{\rm SM} = 1$ and the other assuming $\mu_{\rm SM} = 0$. The expected limits are the median expectations assuming no exotic boson is present. The results are listed in Table 1. Two-dimensional credibility regions, which are the smallest regions containing 68% and 95% of the posterior probabilities, are shown in Fig. 1. The points in the ($\mu_{\rm SM}$, $\mu_{\rm exotic}$) planes that maximize the posterior probability densities are shown as the best-fit values. These best-fit values are ($\mu_{\rm SM}$=1.0, $\mu_{0^-} = 0$) for the search for the $J^P = 0^-$ state, and ($\mu_{\rm SM}$=1.1, $\mu_{2^+} = 0$) for the search for the $J^P = 2^+$ state. Fig. 2 shows the upper limits on the fraction $f_{JP} = \mu_{\rm exotic}/(\mu_{\rm exotic} + \mu_{\rm SM})$, as a function of the total $\mu = \mu_{\rm exotic} + \mu_{\rm SM}$, assuming a uniform prior probability density in non-negative f_{JP}, extended to include fractions larger than 1.0 in order not to saturate the limits at $f_{JP} = 0.95$ for $\mu < 0.6$, where the test is weak.

In the modified frequentist approach [26, 27] we compute p values for the discrete two-

Channel	Observed (Limit/σ_{SM})	Median Expected (Limit/σ_{SM})
$J^P = 0^-$, $\mu_{\rm SM} = 0$	0.36	0.32
$J^P = 0^-$, $\mu_{\rm SM} = 1$	0.29	0.32
$J^P = 2^+$, $\mu_{\rm SM} = 0$	0.36	0.33
$J^P = 2^+$, $\mu_{\rm SM} = 1$	0.31	0.34

Table 1: Observed and median expected Bayesian upper limits at the 95% credibility level on $\mu_{\rm exotic}$ for the pseudoscalar ($J^P = 0^-$) and graviton-like ($J^P = 2^+$) boson models, assuming either that the SM Higgs boson is also present ($\mu_{\rm SM} = 1$) or absent ($\mu_{\rm SM} = 0$).

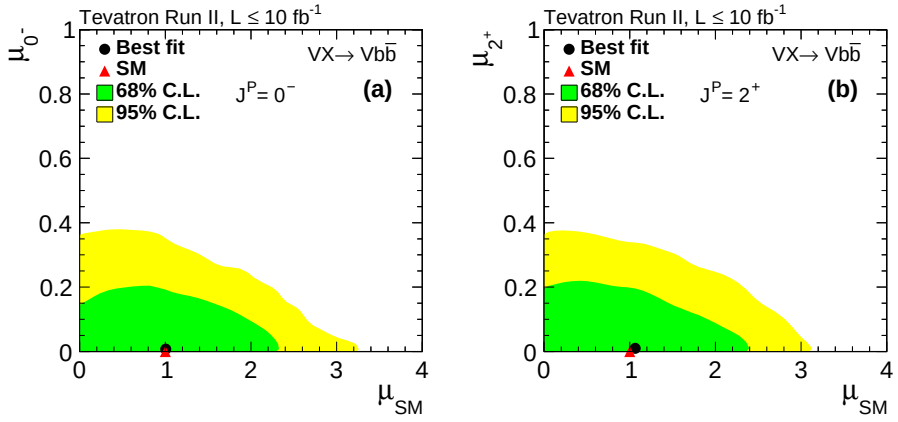

Figure 1: Two-dimensional credibility regions in the ($\mu_{\rm exotic}$, $\mu_{\rm SM}$) plane, for the combined CDF and D0 searches for (a) the pseudoscalar ($J^P = 0^-$) boson, and (b) the graviton-like ($J^P = 2^+$) boson.

hypothesis tests, the SM Higgs boson hypothesis (the "null" hypothesis) ($\mu_{\rm SM}$=1, $\mu_{\rm exotic}$=0) and the exotic ("test") hypothesis ($\mu_{\rm SM}$=0, $\mu_{\rm exotic}$=1), both assuming that SM background processes are present. The log-likelihood ratio, LLR, is defined to be $-2\ln(p({\rm data}|{\rm test})/p({\rm data}|{\rm null})$, where the numerator and denominator are maximized over systematic uncertainty variations [6]. The LLR distributions are shown in Ref. [11]. We define the p values $p_{\rm null} = P({\rm LLR} \leq {\rm LLR_{obs}}|{\rm SM})$ and $p_{\rm test} = P({\rm LLR} \geq {\rm LLR_{obs}}|{\rm exotic})$. The median expected p values $p^{\rm exotic}_{\rm null,med}$ in the test hypothesis and $p^{\rm SM}_{\rm test,med}$ in the SM hypothesis quantify the sensitivities of the two-hypothesis tests for exclusion and discovery, respectively. The p values for both exotic models, as well as ${\rm CL_s} = p_{\rm test}/(1-p_{\rm null})$, are shown in Table 2. Wilks's theorem [28] was used to compute $p_{\rm test}$, $p_{\rm null}$ and $p_{\rm test}$. The similarity of the limits and p values obtained for the $J^P = 0^-$ and the $J^P = 2^+$ searches is expected since the exotic models predict excesses in similar portions of the kinematic space.

To conclude, CDF and D0's combined test for the presence of a pseudoscalar Higgs boson with $J^P = 0^-$ and a graviton-like boson with $J^P = 2^+$ in the $WX \to \ell\nu b\bar{b}$, the $ZX \to \ell^+\ell^- b\bar{b}$, and the $VX \to \not{E}_T b\bar{b}$ search channels using models described in Ref. [12], reported in Ref. [11], has been discussed. No evidence is seen for either exotic particle, assuming a mass of 125 GeV/c^2, either in place of the SM Higgs boson or produced in a mixture with a $J^P = 0^+$ Higgs boson. In

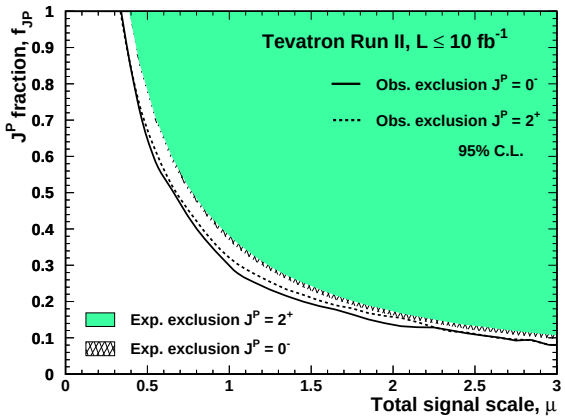

Figure 2: Observed and expected upper limits at the 95% C.L. on the fraction of exotic boson production for the $J^P = 0^-$ and $J^P = 2^+$ hypotheses.

Analysis	$J^P = 0^-$	$J^P = 2^+$
$\mathrm{LLR}_{\mathrm{obs}}$	27.1	25.7
$\mathrm{LLR}^{\mathrm{SM}}_{\mathrm{med}}$	23.7	21.8
$\mathrm{LLR}^{\mathrm{exotic}}_{\mathrm{med}}$	-29.9	-29.6
p_{null}	0.63 (-0.34)	0.66 (-0.41)
$p^{\mathrm{exotic}}_{\mathrm{null,med}}$	1.8×10^{-8} (5.5)	1.9×10^{-8} (5.5)
p_{test}	9.4×10^{-8} (5.2)	1.9×10^{-7} (5.1)
$p^{\mathrm{SM}}_{\mathrm{test,med}}$	4.7×10^{-7} (4.9)	1.2×10^{-6} (4.7)
$\mathrm{CL_s}$	2.6×10^{-7} (5.0)	5.6×10^{-7} (4.9)
$\mathrm{CL}^{\mathrm{SM}}_{\mathrm{s,med}}$	9.4×10^{-7} (4.8)	2.3×10^{-6} (4.6)

Table 2: Observed (obs) and median expected (med) LLR values and p values for the combined CDF and D0 searches for the pseudoscalar ($J^P = 0^-$) boson and the graviton-like ($J^P = 2^+$) boson. The p values are listed, and the corresponding significances in units of standard deviations, using a one-sided Gaussian tail calculation, are given in parentheses.

both searches, the best-fit cross section times the decay branching ratio into a bottom-antibottom quark pair of a $J^P = 0^+$ signal component is consistent with the prediction of the SM Higgs boson. The Bayesian posterior probability densities for the $J^P = 0^-$ and $J^P = 2^+$ searches are shown in Ref. [11]. Upper limits at 95% credibility on the production rate of an exotic Higgs boson in the absence of a SM $J^P = 0^+$ signal are set at 0.36 times the SM Higgs production rate for both the $J^P = 0^-$ and the $J^P = 2^+$ hypotheses. If the production rate of the hypothetical exotic particle times its branching ratio to a bottom-antibottom quark pair is the same as that predicted for the SM Higgs boson, then the exotic models are excluded with significances of 5.0 s.d. and 4.9 s.d. for the $J^P = 0^-$ and $J^P = 2^+$ hypotheses, respectively.

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