A two-Higgs-doublet interpretation of a small Tevatron $Wjj$ excess

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We show that a $Wjj$ excess in Tevatron data could be explained in the context of the standard non-supersymmetric two-Higgs-doublet model (2HDM) for appropriately chosen parameters. Correlated signals in the $\gamma\gamma$ and $W^+W^-b\bar{b}$ final states are predicted and are on the verge of being detectable. The proposed model is most attractive if the cross section for the $Wjj$ excess is $\lesssim 1 - 2$ pb.

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The discrepancy between the CDF [1] and D0 [2] results implies considerable uncertainty as to whether there is an excess of $Wjj$ events in the $M_{jj} \sim 140$ GeV region. Nonetheless, it is interesting to explore the different theoretical approaches that could produce such an excess. Many possibilities have appeared in the literature, including several Higgs sector approaches. A probably incomplete summary is the following: approaches based on $SU(2)$ doublet scalars with or without extra singlets [3,4]; Z-prime models [5,6]; new colored state models [7,8]; supersymmetry models [9,10]; technicolor models [11]; string theory models [12]; and within the context of the Standard model [13,14]. This Letter demonstrates that the excess could be explained by the simplest non-supersymmetric two-Higgs-doublet (2HDM) model with completely standard Yukawa coupling structure. The model predicts correlated signals in the $\gamma\gamma$ and $W^+W^-b\bar{b}$ final states that are on the verge of detection.

We begin with a general overview of the approach. We employ a two-Higgs-doublet model of Type-II (a convenient summary appears in the HHG [20]). In the context of the 2HDM, the masses of the light and heavy CP-even Higgs bosons, $h$ and $H$, of the CP-odd Higgs boson, $A$, and of the charged Higgs boson $H^\pm$, as well as the value of tan $\beta = v_u/v_d$ ($v_{u,d}$ = $(H^0_{u,d})$ where $H^0_{u,d}$ couple to up-type, down-type quarks, respectively) and the CP-even Higgs sector mixing angle $\alpha$ can all be taken as independent parameters, whose values will determine the $\lambda_i$ of the general 2HDM Higgs potential.

To obtain a $Wjj$ signal with Tevatron cross section of order $\gtrsim 1$ pb, the first ingredient is to note that the cross section for $gg \to A$ is highly enhanced at a given $m_A$ relative to the cross section for a SM Higgs boson at $m_{h,SM} = m_A$ when $\tan \beta < 1$. The $Wjj$ signal derives from the (dominant) $A \to H^\pm W^\mp$ decay channel with $H^\pm \to cs$. Note that this particular mode does not contain b quarks, as consistent with the CDF observations. Using the predicted value of $BR(H^\pm \to cs) \sim 0.2$ for $m_{H^\pm} \sim 140$ GeV when $\tan \beta$ is small, one finds that a cross section for $gg \to A \to H^\pm W^\mp \to csW^\mp$ as large as the CDF value of $\sim 4$ pb can only be achieved for $m_A \in [250,300]$ GeV if $\tan \beta \lesssim 1/10$, a domain for which the top-quark Yukawa coupling is non-perturbative, $\alpha_t \equiv \lambda^2_t/(4\pi) > 1$. However, a smaller $Wjj$ cross section of order $1 - 2$ pb is possible for $\alpha_t \sim 1$. We now present more details.

In the 2HDM there are only two possible models for the fermion couplings that naturally avoid flavor changing neutral currents (FCNC), Model I and Model II. In Model II, our focus here, the tree-level couplings of the Higgs bosons are:

$$
\begin{array}{cccc}
   & h & H & A \\
\hline
   t\bar{t} & \cos \alpha & \sin \alpha & -i\gamma_5 \cot \beta \\
   b\bar{b} & -\sin \alpha & \cos \alpha & -i\gamma_5 \tan \beta \\
   WW, ZZ & \sin(\beta - \alpha) & \cos(\beta - \alpha) & 0
\end{array}
$$

We will fix $\alpha$ relative to $\beta$ by requiring that the $h$ be SM-like, i.e. $\sin(\beta - \alpha) = 1$. We also choose $m_h = 115$ GeV for easy consistency with precision electroweak data. If the $\lambda_i$ of the Higgs potential are kept highly perturbative, the decoupling limit, in which $m_H, m_{H^\pm} \rightarrow m_A$ and $\sin^2(\beta - \alpha) \rightarrow 1$, sets in fairly quickly as $m_A$ increases [21]. To describe a $Wjj$ excess requires that $m_{H^\pm} < m_A$ (but $m_H \sim m_A$ is useful to enhance the signal), implying that the decoupling limit does not apply at the masses of interest. This requires that several of the $\lambda_i$ are substantial but still below the $\lambda^2_t/(4\pi) \sim 1$ beginning of the non-perturbative domain.

Looking at Eq. (1), it is apparent that the cross section for $gg \to A$ can be large when $\cot \beta > 1$. It is also useful to recall that the fermionic loop function for the $A$ is substantially larger than that for the $H$ (the CP-even Higgs that could contribute to the $Wjj$ excess if the $h$ is SM-like); e.g. asymptotically $F^{A}_{1/2}(\tau) \rightarrow 2$ in comparison to $F^{H}_{1/2}(\tau) \rightarrow -4/3$ when $\tau = 4m_t^2/m_A^2 \rightarrow \infty$, implying a cross section gain by a factor of 9/4 for $A$ vs. the $H$ in the heavy fermion mass limit. We have computed the $gg \to A$ (and $gg \to H$) cross section using HIGLU [22] and a private program and obtained essentially the same results. Results for $\sigma(gg \to A)$ are plotted in Fig. 1. These results include NLO and NNLO corrections as in HIGLU. Some useful benchmark numbers for

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1 However, $H^\pm \to t^*b$ has a large branching fraction, as discussed later, but since $t^* \rightarrow Wb$, this channel will not lead to a $jj$ resonance signal.
β tan(BR) shows that β in Fig. 2 where we see that a value of \( \sim \) boson X in Fig. 2 is a representative tan β < 1 values.

FIG. 2: BR(\( H^+ \rightarrow c\bar{s} \)) (solid blue) and BR(\( H^+ \rightarrow t\bar{b} \)) (red dots) as a function of tan β for \( m_{H^\pm} = 140 \) GeV and Model II couplings. Inclusion of off-shell decay configurations is essential for the \( t\bar{b} \) final state.

\[ m_A = 250 \text{ GeV are} \]

\[
\begin{align*}
\tan \beta & \quad 1/3 & \quad 1/5 & \quad 1/10 \\
\sigma(gg \rightarrow A)_{\text{Tevatron}} & \quad 1.4 \text{ pb} & \quad 3.9 \text{ pb} & \quad 15.7 \text{ pb} \\
\sigma(gg \rightarrow A)_{\text{LHC}} & \quad 59.1 \text{ pb} & \quad 164.3 \text{ pb} & \quad 652.9 \text{ pb}
\end{align*}
\]

We define the effective Wjj cross section for a Higgs boson X:

\[
\sigma_{Wjj}^X \equiv BR(X \rightarrow H^\pm W^\mp)BR(H^+ \rightarrow c\bar{s})\sigma(gg \rightarrow X),
\]

where \( X = A \) and \( X = H \) are the relevant Higgs bosons. As a benchmark to keep in mind, we will suppose that \( \sigma_{Wjj}^A \sim 1 \) pb is appropriate for describing the Tevatron Wjj excess. BR(\( H^+ \rightarrow c\bar{s} \)) (computed privately and using HDECAY [23]) is displayed in Fig. 2 where we see that a value of \( \sim 0.22 \) applies for \( \tan \beta \in [1/10, 1/3] \). For \( m_A = 250 \) GeV, Fig. 2 shows that BR(\( A \rightarrow H^\pm W^\mp \)) \( \sim 0.95, 0.874, 0.64 \) for \( \tan \beta = 1/3, 1/5, 1/10 \) (the solid green, magenta, blue lines), respectively. For \( m_A = 250 \) GeV we then obtain BR(\( A \rightarrow H^\pm W^\mp \))BR(\( H^+ \rightarrow c\bar{s} \)) \( \sim 0.21, 0.19, 0.14 \) for \( \tan \beta = 1/3, 1/5, 1/10 \). Using the \( \sigma(gg \rightarrow A) \) cross sections of Eq. (2), for \( m_A = 250 \) GeV we find \( \sigma_{Wjj}^A(Tevatron) \sim 0.3 \text{ pb}, 0.75 \text{ pb}, 2.2 \text{ pb} \) for \( \tan \beta = 1/3, 1/5, 1/10 \), respectively. The corresponding values of \( \alpha_t \) are 0.63, 1.75, 7. Only the latter is uncomfortably (but not drastically) non-perturbative, implying a preference for \( \sigma_{Wjj}^A \sim 1 \) pb. It is quite important to note that the main reason that \( \sigma_{Wjj}^A \) is not larger is the small value of BR(\( H^+ \rightarrow c\bar{s} \)) that is a consequence of the dominance of off-shell \( H^+ \rightarrow t^+\bar{b} \) decays for \( m_{H^\pm} = 140 \) GeV. (This dominance decreases rapidly if \( m_{H^\pm} \) is decreased; for \( m_{H^\pm} \) significantly lower than 140 GeV higher \( \sigma_{Wjj}^A \) would thus be achieved.) For \( m_A \gtrsim 300 \) GeV, \( \sigma_{Wjj}^A \) is about 50% smaller than the \( m_A = 250 \) GeV values quoted above, see Fig. 3.

As apparent from Eq. (2), \( \sigma(gg \rightarrow A) \) is much larger at the LHC. Focusing on \( m_A = 250 \) GeV and including the earlier quoted BR(\( A \rightarrow H^\pm W^\mp \))BR(\( H^+ \rightarrow c\bar{s} \)) values of 0.21, 0.19, 0.14 we obtain \( \sigma_{Wjj}^A(LHC) = 12.4 \text{ pb}, 31.2 \text{ pb}, 91.4 \text{ pb} \) for \( \tan \beta = 1/3, 1/5, 1/10 \), respectively. The number of Wjj events will be enormous for the soon-to-be-achieved \( L = 1 \text{ fb}^{-1} \). We anxiously await the appropriate LHC analyzes.

It is, of course, interesting to assess the extent to which \( gg \rightarrow H \rightarrow H^\pm W^\mp \) with \( H^+ \rightarrow c\bar{s}, H^- \rightarrow \bar{c}s \) could con-
A for event rates one can combine the actual branching ratio observed at the LHC if present and might also be obtained from $\sigma_{Wjj}/\sigma_{Wjj} \sim 2.6, 3.0, 5.0$ for $m_A = m_H = 250, 300, 350$ GeV. Meanwhile, the $BR(H \to H^\pm W^\mp)BR(H^\pm \to c\bar{c})$ values are similar to those quoted for the $A$. Thus, for the preferred $m_H \in [250 - 300]$ GeV mass range, the $H$ would yield a $Wjj$ signal of order $30\% - 40\%$ of the $A$ result. If the $H$ and $A$ are not fairly degenerate, this would yield a somewhat spread out net $Wjj$ signal, despite the $\lesssim 1$ GeV total widths of the $A$ and $H$ (for the $\tan\beta$ values being discussed), given the experimental $M_{ij}$ resolution of order 15 GeV. This is perhaps suggested by the absence of any distinct peaking in the $Wjj$ mass in the data. Another interesting point is that in this model with $m_H$ not very different from $m_A$, there would be no signal in the $Zjj$ channel due to the absence of $H \to AZ$ and $A \to HZ$ decays.

Other signals should be seen if the model is correct. In particular, as pointed out in $[24]$, there is a very large $A \to \gamma\gamma$ signal for small $\tan\beta$. A plot of $R_{ij} \equiv [\Gamma_{ij}^{A}/\Gamma_{ij}^{H}] / [\Gamma_{ij}^{SM}/\Gamma_{ij}^{M_{ij}}]$ is given in Fig. $5$. For $\tan\beta \sim 1/3, 1/5$ and $m_A \sim 250$ GeV, $R_{ij} \sim 10^2, 10^3$, respectively! Such a signal will soon be observed at the LHC if present and might also be observable with current Tevatron data. To assess actual event rates one can combine the actual branching ratio for $A \to \gamma\gamma$, plotted in Fig. $6$ with the cross sections for $gg \to A$ plotted in Fig. $1$.

For example, for $\tan\beta = 1/5$ and $m_A = 250$ GeV, in the case of the Tevatron one finds $\sigma(gg \to A)/BR(A \to \gamma\gamma) \sim 3.9 \times 4.8 \times 10^{-4} \approx 1.9 \times 10^{-3}$ pb, yielding $\sim 10$ events for $L = 5.4$ fb$^{-1}$. This must be compared to the number of events expected in the SM. Ref. $[29]$ performs an analysis for $L = 5.4$ fb$^{-1}$. Their net efficiency times acceptance is $\sim 0.12$, implying a predicted number of $A \to \gamma\gamma$ events of order 1.2. The actual number of observed events is consistent with the SM prediction, as shown in their Fig. 2. They set a $95\%$ CL limit of $\sigma BR(\gamma\gamma) \lesssim 0.05$ pb at $M_{\gamma\gamma} = 250$ GeV, a factor of $\sim 25$ above our typical prediction. At the LHC, the corresponding calculation is $\sigma(gg \to A)/BR(A \to \gamma\gamma) \sim 164 \times 4.8 \cdot 10^{-4} = 0.08$ pb. For $L = 36$ pb$^{-1}$, this yields $\sim 3,800$ events, respectively. Ref. $[20]$ uses $L = 36$ pb$^{-1}$ data to set a limit of $\sigma \times BR(\gamma\gamma) \lesssim 0.7$ pb at $M_{\gamma\gamma} = 250$ GeV, a factor of about 8 above the prediction for the present scenario. This shows that the present scenario for obtaining a $Wjj$ excess will be strongly tested once the currently available LHC data sets with $L = 1$ fb$^{-1}$ are analyzed.

Of course, the $H$ also yields a large $\gamma\gamma$ signal (again of order $30\% - 40\%$ that of the $A$) that most probably would be detected as a separate peak if $m_H$ differs from $m_A$. 

![FIG. 4: $BR(H \to H^\pm W^\mp)$ as a function of $m_A$ for $m_H = 140$ GeV and Model II couplings. In this and subsequent plots for the $H$, we have taken $m_A = 200$ GeV. The legend is as in Fig. $1$.](image1)

![FIG. 5: $R_{ij}$ for the 2HDM-II $A$. The legend is as in Fig. $3$. This figure takes account of all the $A$ decay modes, including especially $A \to H^\pm W^\mp$ as well as $A \to H$ (off-shell) decays.](image2)

![FIG. 6: $BR(A \to \gamma\gamma)$ for the 2HDM-II $A$ after including $A \to H^\pm W^\mp$ and $A \to H$ off-shell decays in the present scenario. The legend is as in Fig. $3$.](image3)
$m_A$ by more than 10 GeV, given the excellent $\sim 2$ GeV mass resolution in $M_\gamma$ for the LHC detectors and given that the total $A$ and $H$ widths are of order 1 GeV.

Finally, there is an interesting signal in the $gg \to A \to H^\pm W^\mp \to t\bar{t}^\pm W^\mp + t\bar{t}^\pm W^+\mp$ final state deriving from $BR(H^+ \to t\bar{t}^0) \sim 0.7$ (off-shell) decays, see Fig. 2, where $t^* \to W^+b$. The resulting final states of $W^*W^-b\bar{b}$ will not peak in either $Wb$ mass combination. The cross section for this final state is, however, significant: for $m_A = 250$ GeV and $\tan \beta = 1/5$, one finds $\sigma(WWbb) \sim 2.8$ pb compared to $\sigma_{t\bar{t}Wjj} \sim 0.75$ pb and $\sigma_{t\bar{t}Wjj}^{\mu} \sim 0.28$ pb. Although this $\sigma(WWbb)$ is somewhat smaller than that for direct $t\bar{t} \to W^+W^-b\bar{b}$ production, it is still sizable and might lead to some “anomalies” in the $W^*W^-b\bar{b}$ final state. It would be very interesting to determine whether or not such anomalies in the $W^*W^-b\bar{b}$ final state would have been noticed in current data and, if not, how much LHC integrated luminosity would be needed to detect them. One should note that for this model to achieve the CDF $Wjj$ cross section of $\sim 0.4$ pb would imply an anomalous $W^*W^-b\bar{b}$ final state cross section that is larger than that coming directly from $t\bar{t} \to W^+W^-b\bar{b}$ production.

If a 4th generation is present with $m_{l^4} \sim 400$ GeV, then $\Gamma_{A}^{\mu}$ and, therefore, $\sigma_{t\bar{t}Wjj}^{\mu}$ is increased substantially at any fixed $\tan \beta$. However, $\tan \beta$ is restricted to lie in the range $\tan \beta \in [1/2, 2]$ in order to keep $\lambda_{l^4 l^4 W}^2/(4\pi) \leq 1$. The resulting $gg \to A$ rate is then more or less the same as for $t\bar{t} \to W^+W^-b\bar{b}$ production, if $\tan \beta < 1$. However, the enhancement is not quite as great as for Model II. In addition, $BR(H^+ \to c\bar{s}) \sim 0.13$ for $\tan \beta \in [1/3, 1/10]$. As a result, the $Wjj$ cross section that can be achieved in Model I is smaller by about a factor of three as compared to that achieved for the $Wjj$ final state of the case of Model II.

To summarize, we have shown that if $\tan \beta$ is small then a Model II two-Higgs-doublet sector with $m_A$, and possibly $m_H$, of order 250 GeV – 300 GeV can lead to a very interesting signal in the $Wjj$ final state that could match that seen by CDF at the Tevatron. To get a cross section as large as that originally claimed by CDF would force one to $\tan \beta \lesssim 1/10$, values for which the top-quark Yukawa coupling is quite large and moderately non-perturbative. However, a $Wjj$ signal with cross section of order 1 pb, as possibly consistent with a combination of CDF and D0 data, is quite possible without entering into the domain of non-perturbative top-quark Yukawas. Correlated signals in the $W^*W^-b\bar{b}$ and $\gamma\gamma$ final states are expected. These final states are interesting targets for exploration in their own right. The predicted correlations between the $Wjj$, $W^*W^-b\bar{b}$ and $\gamma\gamma$ signals makes the model proposed herein highly testable and points out the importance of taking into account the latter types of signals in order to fully assess the consistency of the model. At the LHC, the predicted $Wjj$ cross sections and those for the correlated signals are of order 40 times as large as at the Tevatron. As the integrated LHC luminosity approaches $L = 1 fb^{-1}$ the model will most probably be definitively eliminated or confirmed. As a final note, the masses for the $m_{H^\pm}$, $m_A$ and $m_{l^4}$ needed to explain the possible $Wjj$ excess using the approach described here cannot be achieved within the minimal supersymmetric model context.

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[1] T. Aaltonen et al. [ CDF Collaboration ], Phys. Rev. Lett. 106, 171801 (2011), arXiv:1104.0699
[2] V. M. Abazov et al. [ D0 Collaboration ], arXiv:1106.1457
[3] Q. H. Cao, M. Carena, S. Gori, A. Menon, P. Schwaller, C. E. M. Wagner and L. T. M. Wang, arXiv:1104.4776
[4] K. S. Babu, M. Frank, S. K. Rai, arXiv:1104.4782
[5] B. Dutta, S. Khalil, Y. Mimura, Q. Shafi, arXiv:1104.5209
[6] G. Segre, B. Kayser, arXiv:1105.1808.
[7] C. H. Chen, C. W. Chiang, T. Nomura and Y. Fusheng, arXiv:1105.2870
[8] M. R. Buckley, D. Hooper, J. Kopp and E. Neil, arXiv:1103.6035
[9] K. Cheung and J. Song, arXiv:1103.1379
[10] X. P. Wang, Y. K. Wang, B. Xiao, J. Xu and S. h. Zhu, arXiv:1104.1917
[11] B. A. Dobrescu and G. Z. Krnjaic, arXiv:1104.2893
[12] L. M. Carpenter, S. Mantry, arXiv:1104.5528
[13] C. Kilic and S. Thomas, arXiv:1104.1002
[14] R. Sato, S. Shirai and K. Yonekura, arXiv:1104.2014
[15] E. J. Eichten, K. Lane and A. Martin, arXiv:1104.0976
[16] L. A. Anchordoqui, H. Goldberg, X. Huang, D. Lust and T. R. Taylor, arXiv:1104.2302
[17] X. G. He and B. Q. Ma, arXiv:1104.1894
[18] Z. Sullivan, A. Menon, arXiv:1103.3790
[19] T. Plehn, M. Takeuchi, arXiv:1104.4087
[20] The Higgs Hunters Guide, John F. Gunion, Howard E. Haber, Gordon Kane, Sally Dawson. 1990. Series: Frontiers in Physics, 80; QCD161:G78
[21] J. F. Gunion, H. E. Haber, Phys. Rev. D67, 075019 (2003), hep-ph/0207010.
[22] M. Spira, Nucl. Instrum. Meth. A 389, 357 (1997) arXiv:hep-ph/9610350, arXiv:hep-ph/9510347
[23] A. Djouadi, J. Kalinowski, M. Spira, Comput. Phys. Commun. 108, 56-74 (1998), hep-ph/9704448.
[24] J. F. Gunion, arXiv:1105.3965
[25] T. Aaltonen et al. [ CDF Collaboration ], Phys. Rev. D83, 011102 (2011), arXiv:1012.2795.
[26] CMS Collaboration, CMS PAS EXO-10-019.