Light MSSM Higgs boson scenario and its test at hadron colliders

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We show that in the Minimal Supersymmetric Standard Model, the possibility for the lightest CP-even Higgs boson to be lighter than Z boson (as low as about 60 GeV) is, contrary to the usual belief, not yet excluded by LEP2 data or any other existing experimental data. The characteristic of the light Higgs boson scenario (LHS) is that the ZH coupling and the decay branching ratio Br(h/A → b); are simultaneously suppressed as a result of generic supersymmetric loop corrections. Consequently, the W±H±h coupling has to be large due to the sum rule of Higgs couplings to weak gauge bosons. In addition to discussing the potential of the Tevatron and B-factories to test the LHS, we show that the associate neutral and charged Higgs boson production process, pp → H±h(A), can completely probe LHS at the CERN Large Hadron Collider.

While the Standard Model (SM) of particle physics is consistent with existing data, there is a strong belief to a more complete description of the underlying physics. Supersymmetry (SUSY), as a good candidate for theory beyond the SM, solves principal theoretical problems of the SM such as hierarchy and fine tuning, as well as provides good dark matter candidate and potentially solves the problem of baryogenesis. In the minimal supersymmetric standard model (MSSM) (for example, see [1]), the Higgs sector consists of two doublet fields h_d and h_u to generate masses for down- and up-type fermions, respectively, and to provide an anomaly-free theory. After spontaneous symmetry breaking, there remain five physical Higgs bosons: a pair of charged Higgs bosons H±, two neutral CP-even scalars H (heavier) and h (lighter), and a neutral CP-odd pseudoscalar A. Higgs potential is constrained by supersymmetry such that all the tree-level Higgs boson masses and self-couplings are determined by only two independent unknown parameters, commonly chosen to be the mass of the CP-odd pseudoscalar (M_A) and the ratio of vacuum expectation values of neutral Higgs fields, denoted as tan β ≡ ⟨h_u⟩/⟨h_d⟩.

The MSSM predicts a light neutral Higgs boson which is lighter than Z-boson at the tree level, since the Higgs quartic coupling is determined by the SM gauge couplings. However, large top quark and squark (stop) loop contributions induce significant radiative correction to the Higgs quartic coupling, such that the lighter neutral Higgs boson mass can be as large as 130 GeV [2, 3, 4, 5] and avoid the LEP2 limit. The negative result of Higgs boson mass can be as large as 130 GeV [2, 3, 4, 5] and avoid the LEP2 limit. The negative result of Higgs boson mass can be as large as 130 GeV [2, 3, 4, 5] and avoid the LEP2 limit. The negative result of Higgs boson mass can be as large as 130 GeV [2, 3, 4, 5] and avoid the LEP2 limit. The negative result of Higgs boson mass can be as large as 130 GeV [2, 3, 4, 5] and avoid the LEP2 limit. The negative result of Higgs boson mass can be as large as 130 GeV [2, 3, 4, 5] and avoid the LEP2 limit.

The LEP2 collaborations performed analyses for the MSSM using several benchmark scenarios that were considered as typical cases for MSSM parameter space. In this Letter, we propose a different branch of the MSSM parameter space which has not been previously studied with deserved attention. We call this possibility light Higgs boson scenario (LHS), in which the lightest Higgs boson is lighter than the Z-boson and generic MSSM radiative corrections induce significantly small ZH coupling so that the LEP2 constraint from e+e− → ZH production channel can be avoided. The similar possibility was previously noted in Ref. [6] but without detailed study of MSSM parameter space. Here we consider only the MSSM without CP-violation (for CP-violating case, see Ref. [7]) and specify the generic MSSM parameter space for LHS scenario to be consistent with the LEP2 and other existing experimental constraints. We discuss the potential of the Fermilab Tevatron and B-factories to test the LHS and show that the CERN Large Hadron Collider (LHC) can completely probe LHS via the neutral and charged Higgs boson associate production process pp → H±h/HzhA.

LEP2 collaborations analyzed especially two complementarity processes for MSSM Higgs boson search: e+e− → Zh/Ah [3, 4], in which the first one occurs via ZZH = sin(β − α)(= s_βα) while the second one via Zuh coupling g_{ZH} = cos(β − α). The obvious sum rule (g_{ZH}^2 + g_{ZAH}^2 = 1) puts strong constraints on the mass and couplings of the MSSM Higgs boson h. For all studied benchmark scenarios at LEP2, M_h below about 90 GeV is excluded [3]. In this study we demonstrate that LEP2 has missed the generic parameter space, outside of the benchmark points, with 60 GeV < M_h < M_Z.

In order to satisfy the LEP2 constraint derived from the production channel e+e− → Zh with M_h < M_Z, the coupling g_{ZH} (i.e. s_βα) has to be small. Here, we describe in detail the mechanism for suppressing the g_{ZH} coupling. Let us denote M^2 for a 2 × 2 squared-mass matrix of the CP-even neutral Higgs bosons in the gauge eigenbasis (Re h_0^0, Re h_u^0). The mass eigenstates (h, H) are given by the diagonalization of the matrix M^2 with the definition:

\[
\begin{pmatrix}
\frac{h}{H}
\end{pmatrix} = \begin{pmatrix}
-s_\alpha & c_\alpha \\
c_\alpha & s_\alpha
\end{pmatrix} \begin{pmatrix}
\text{Re } h_0^0 \\
\text{Re } h_u^0
\end{pmatrix},
\]

where c_α ≡ cos α and s_α ≡ sin α (where −π/2 ≤ α ≤ π/2). Using the components of matrix M_{ij}, s_{βα} can be
analytically expressed as
\[ s_{\beta \alpha} = \frac{(D + x)^{1/2} s_{\beta} \pm (D - x)^{1/2} c_{\beta}}{\sqrt{2D}}, \tag{2} \]
where \( s_{\beta} \equiv \sin \beta \), \( c_{\beta} \equiv \cos \beta \), \( x = M_{\tilde{t}_1}^2 - M_{\tilde{t}_2}^2 \), \( y = M_{\tilde{g}}^2 \), \( D \equiv \sqrt{x^2 + 4y^2} \), and the signs \( \pm \) correspond to negative and positive \( y \), respectively. As to be shown below, the LHS requires \( \tan \beta > 1 \) to be consistent with experimental data. For relatively large tan \( \beta \) \( (s_{\beta} \gg c_{\beta}) \) and \( y/x \simeq 0 \), we obtain \( s_{\beta \alpha} \simeq \frac{(1 \pm |x|)^{1/2}}{\sqrt{2|x|}} = 0 \) which takes place for \( x < 0 \). Therefore, conditions \( y/x \simeq 0 \) and \( x < 0 \) provide small values of \( s_{\beta \alpha} \). We note that when \( M_{A} > M_{Z} \) and \( \tan \beta > 1 \), \( x = (M_{A}^2 - M_{Z}^2) \left( - \cos 2\beta \right) > 0 \) and \( y = \frac{M_{A}^2 + M_{Z}^2}{2} \sin 2\beta \) at tree level. Therefore, the loop corrections to \( x \) and \( y \) are very important and have to be as large as the tree-level values in order to satisfy the conditions \( y/x \simeq 0 \) and \( x < 0 \), which yield a small value of \( s_{\beta \alpha} \). It is important to mention, however, that tree-level values of \( x \) and \( y \) are naturally suppressed when \( M_{A} \simeq M_{Z} \) and \( \tan \beta \) is large. When \( y/x \simeq 0 \) and \( x < 0 \), the lightest neutral Higgs boson \( h \) mainly consists of \( h_{0}^{0} \), and the neutral Higgs bosons are approximately given by \( M_{h}^2 \simeq M_{\tilde{t}_1}^2 \) and \( M_{H}^2 \simeq M_{\tilde{t}_2}^2 \), which is different from the usual scenarios. As it is well-known, the \( M_{Z}^2 \) (i.e. \( h_{u} \)-component) receives large positive logarithmic correction from top and stop contributions, \( \delta M_{Z}^2 \simeq y_{t}^2 \sin^2 \beta \) in \( \left( \frac{M_{Z}^2}{m_f^2} \right) \), where \( y_{t} \) is the top Yukawa coupling and \( M_{S} \) is the average stop mass \( 2, 2, 2 \). This correction, which helps to significantly increase the mass of \( h \) in the usual scenarios, increases the mass of \( H \) in the LHS case. Therefore, even though \( x < 0 \) at tree level, the condition \( x < 0 \) can be easily realized in the LHS because the large logarithmic correction to \( M_{\tilde{t}_2}^2 \) at the one-loop level can overcome its tree-level value when \( M_{A} \simeq M_{Z} \). In order to realize the condition \( y/x \simeq 0 \), certain values of the trilinear A-term of the stop \( (A_{3}) \) and the supersymmetric Higgs mass \( \mu \)-parameter \( \mu \) are usually required, depending on \( M_{A} \), \( \tan \beta \) and other SUSY breaking parameters. Typically, \( |A_{3}| > 400 \text{ GeV} \) and \( \mu > 300 \text{ GeV} \), as we will show later.

We present one of our sample points for the LHS in Table I. For simplicity, we assume \( M_{Z} = 2 M_{1} \) for gaugino masses, the universal soft-breaking sfermion mass \( (M_{Q}) \) and trilinear A-term \( (A_{3}) \) for the third-generation at the weak scale. For our numerical analysis, we use CPsuperH program \( \text{[10]} \) and assume CP is conserved. Although at tree level, for the sample point, \( x = 0 \), \( y/x \simeq -0.22 \) and \( s_{\beta \alpha} \simeq 0.98 \), the Higgs mass matrix elements in the effective potential become \( M_{h}^2 \simeq (82.0 \text{ GeV})^2 \), \( M_{w}^2 \simeq (120 \text{ GeV})^2 \), \( M_{\tau}^2 \simeq - (29.1 \text{ GeV})^2 \), and hence \( x < 0 \) and \( y/x \simeq 0.11 \), after including the radiative corrections (we use 172.5 GeV top-quark mass \( \text{[11]} \) in our studies). Consequently, we can obtain small \( s_{\beta \alpha} \) \( (s_{\beta \alpha} \simeq 0.14) \) since both the conditions \( x < 0 \) and \( y/x \simeq 0 \) are realized by including the large radiative corrections. Note that for the LHS the mass term of \( h_{u} \)-component \( M_{h}^2 \) does not receive as large radiative corrections as \( M_{\tilde{t}_2}^2 \) does, and hence the lighter Higgs mass is close to its tree-level value \( M_{h} \simeq \sqrt{M_{\tilde{t}_1}^2 + M_{Z}^2} \) when \( M_{A} \simeq M_{Z} \). This feature is qualitatively very different from those in the commonly discussed MSSM scenarios. On the contrary, the mass of the heavier CP-even Higgs boson receives large radiative corrections to exceed about 114 GeV in order to be in agreement with LEP2 data, since the \( ZZH \) coupling is close to the SM value.

To search for the LHS parameter space, we scan the following set of MSSM parameters: \( \tan \beta [1.1, 50) \), \( (M_{1}/\text{TeV}) [0.05, 1) \), \( (M_{2}/\text{TeV}) [0.05, 1) \), \( (M_{3}/\text{TeV}) [-2, 2) \), \( (M_{Q}/\text{TeV}) [0.05, 1) \) and \( (\mu/\text{TeV}) [0, 3M_{Q}] \), within the range denoted in brackets. Since a too large \( \mu \)-parameter induces not only the color breaking vacuum in the general direction of the scalar potential but also the fine-tuning in the Higgs mass parameter, we require \( \mu \) to be less than \( 3M_{Q} \) in our analysis \( \text{[12]} \). Then, we check the LHS parameter space against the full set of the experimental and theoretical constraints. The relevant constraints are the following: (1) LEP2 \( Zh/ZH \) and \( Ah/AH \) constraints \( \text{[7]} \); (2) Chargino \( (M_{\chi^\pm}) \), stop \( (M_{\tilde{t}_1}) \), sbottom \( (M_{\tilde{b}_1}) \) and gluino \( (M_{1}) \) mass limits: \( M_{\tilde{t}_1} > 103 \text{ GeV} \), \( M_{\tilde{b}_1} > 96 \text{ GeV} \), \( M_{\tilde{b}_1} > 220 \text{ GeV} \) for \( M_{\tilde{t}_1} < 90 \text{ GeV} \) and \( M_{\tilde{b}_1} > 6 \text{ GeV} \) (where \( M_{\tilde{t}_1} \) is the neutralino mass) \( \text{[13]} \) or \( M_{\tilde{b}_1} > 100 \text{ GeV} \) for all other regions \( \text{[13]} \), and \( M_{3} > 270 \text{ GeV} \). For all regions \( \text{[13]} \), \( M_{3} > 270 \text{ GeV} \). For all other regions \( \text{[13]} \); (3) electroweak constraint: one-loop stop contributions to \( \rho \)-parameter \( |\Delta \rho_{\text{stop}}| < 2 \times 10^{-3} \), \( \text{[17]} \); (4) color breaking constraint: \( A_{3}^2 < 3(2M_{Q}^2 + M_{\tilde{t}_1}^2 + \mu^2) \) where \( M_{h_{u}} \) is the soft-breaking mass for Higgs \( h_{u} \) \( \text{[18, 19]} \).

The results shown in Fig. \( \text{[1]} \) unveil that essential
LHS parameter space survives all constraints and the mass of the light Higgs boson can be as low as about 60 GeV. In Fig. 1 green (blue) color indicates allowed parameter space with \( M_h < M_Z \) (\( M_h > M_Z \)). All other colors indicate regions excluded by LEP2 Zh/ZH search (dark red), LEP2 Ah/AH search (red), direct LEP2/Tevatron SUSY searches (yellow) and color breaking constraint (light red). We note that \( \Delta \rho \) constraint does not further limit the parameter space once LEP2 Higgs boson search and SUSY particle search constraints are applied. Fig. 1(c) \( (M_H-M_h \) plane) shows that LHS scenario (green) is realized for low values of charged Higgs boson mass: \( 120 \text{ GeV} < M_{H^+} < 150 \text{ GeV} \), indicating the non-decoupling regime. Much lighter charged Higgses are excluded mainly by the LEP \( Ah \) production constraint. The scenario requires intermediate-to-large values of the \( A \)-term and \( \mu \)-parameter; \( |A_q| > 400 \text{ GeV} \) and \( \mu > 300 \text{GeV} \) (cf. Fig. 1(c): \( A_2(\mu)-M_h \) plane) to make \( g_{Z\text{ZH}} \) small, as indicated in Fig. 1(b). On the other hand, larger positive \( M_3\mu \tan \beta \) product gives rise to larger negative correction to the bottom Yukawa coupling \( y_{\text{bb}} \). This large negative correction to \( y_{\text{bb}} \) is non-universal with respect to the \( \tau \) Yukawa coupling \( y_{\text{\tau \tau}} \) and leads to a suppression in \( \text{Br}(h/A \rightarrow bb) \) large enough to avoid LEP2 constraint from the \( Ah \) channel with low \( M_h \) values. This channel is complementary to the LEP2 Z\( h \) search in excluding light Higgs bosons since \( g_{Z\text{AH}} \) coupling is enhanced when \( g_{Z\text{ZH}} \) is suppressed. In the LHS parameter space \( \text{Br}(h/A \rightarrow bb) \) can be suppressed down to about 50\% (cf. Fig. 1(f)), and consequently \( \text{Br}(h/A \rightarrow \tau \tau) \) is enhanced up to about 50\%, so that \( Ah \) channel is not observed: \( bbb \) decay mode is largely suppressed, while \( bb\tau \) or \( \tau \tau \tau \tau \) signatures are not enhanced enough to exclude \( 60 \text{ GeV} \leq M_h \leq M_Z \). In Fig. 1(e) presents the \( \text{Br}(h \rightarrow bb)-M_h \) correlations. It is interesting to note that the relatively large \( \mu \)-parameter simultaneously suppress both \( s_{\beta\alpha} \) and \( \text{Br}(h/A \rightarrow bb) \) to be consistent with the LEP2 constraints. We also note that as \( \tan \beta \) gets larger, the lighter Higgs becomes possible (Fig. 1(i)). It is worth mentioning that although the heavy Higgs \( H \) couplings to vector bosons are SM-like, its couplings to down-type fermions are further suppressed as compared to those of light and CP-odd Higgs bosons (see Table 1).

Since in LHS \( g_{Z\text{ZH}}(= s_{\beta\alpha}) \) is suppressed, \( H^+ W^- h \) coupling is inevitably enhanced due to the sum rules in Higgs boson couplings to weak gauge bosons, i.e., \( g_{Z\text{ZH}}^2 + g_{Z\text{H}^+ W^- h}^2 = 1 = g_{Z\text{H}^+ W^- A}^2 \). Therefore, \( q\bar{q} \rightarrow H^+ h(A) \) production via \( W \) boson exchange could be sizable with the production cross section \( \sim 10 \text{ fb} \) at the Tevatron and \( \sim 100 \text{ fb} \) at the LHC for \( M_{h/A} \sim 100 \text{ GeV} \) [21, 22]. In Fig. 2 we present the inclusive cross section of the \( p\bar{p}, pp \rightarrow H^+ h(A) \rightarrow \tau^+ \nu b\bar{b} \rightarrow \pi^+ \nu b\bar{b} \).
signature at the Tevatron and the LHC in the $M_{H^\pm}$-$M_t$ plane. For simplicity, we have combined the $H^+h$ and $H^+A$ production rates. As clearly shown in Fig. 4, the LHC can be sensitive to the entire LHS parameter space, assuming that the above signal event signature can be measured at the 1 fb level \[22\]. The potential of the Tevatron to observe $H^+A/H^+h$ process deserves special investigation and will be reported elsewhere \[23\]. We also note that when $s_{\beta\alpha}$ is small, the tree level bottom- and tau Yukawa couplings are enhanced by a factor of $(\sin \alpha / \cos \beta) \approx \tan \beta$, compared with the SM values. Therefore, the LHS, which is realized in intermediate-to-high-$\tan \beta$ region, can be potentially probed even at the Tevatron via several $\tan \beta$-enhanced processes, such as $p\bar{p} \to h(A)$ with $h/A \to \tau\bar{\tau}$ (produced via gluon-gluon fusion process), $p\bar{p} \to b\bar{b}h(A)$, as well as $p\bar{p} \to t\bar{t}$ with $t \to H^+b$. At present luminosity, these processes are sensitive only to very high values of $\tan \beta \gtrsim 45-50$, while at 10 fb$^{-1}$ $\tan \beta \gtrsim 30$ could be probed \[24\]. Finally, we note that in the LHS, the flavor physics processes at $B$-factors and Tevatron, such as $b \to s\gamma$ \[26\], $B^- \to \tau^-\nu$, $B_{ds} \to \mu^+\mu^-$ \[31\] and $B_s - B_s$ oscillation measurements \[23\] can be largely modified due to the sizable contributions generated by light Higgs bosons, although the predictions may strongly depend on the flavor structure of the SUSY breaking terms.\[1\]\ Conclusion: We have found that in the MSSM the possibility for the lightest CP-even Higgs boson to be lighter than $Z$-boson (as low as about 60 GeV) is, contrary to the usual belief, not yet excluded by existing experiments. The characteristic of the light Higgs boson scenario is the $ZZh$ coupling and the decay branching ratio $\text{Br}(h/A \to b\bar{b})$ are simultaneously suppressed as a result of SUSY loop corrections. We would like to note that the region of the MSSM parameters used for explanations of non-conclusive LEP2 excess of about 98 GeV 'Higgs-like' events \[12\] studied in the literature (see e.g. \[12\]) is the subset of the more generic LHS parameter space we have found in this paper. Our result would be useful for clarifying the parameter space responsible for this excess.\[2\]\ The key-test of the light Higgs boson scenario is the $pp(p\bar{p}) \to H^\pm h(A)$ production at hadron colliders: if LHS is indeed realized in nature, then it will be unambiguously discovered or excluded at the LHC. Meanwhile, this scenario can be tested at the Tevatron through various production and decay processes with large $\tan \beta$ enhancement such as $p\bar{p} \to h(A)$ with $h/A \to \tau\bar{\tau}$, $p\bar{p} \to b\bar{b}h(A)$ and $p\bar{p} \to t\bar{t}$ with $t \to H^+b$. Current and future $B$-factories could also provide important tests of LHS via $b \to s\gamma$, $B^- \to \tau^-\nu$, $B_{ds} \to \mu^+\mu^-$ and $B_s - B_s$ oscillation measurements.\[3\] Acknowledgments: We thank M. Dress, G. Kane, N. Maekawa and C. Wagner for useful discussions. C.P.Y. and K.T. thank the National Center for Theoretical Sciences in Taiwan for its hospitality, where part of the work was done. This work was supported in part by the US National Science Foundation under award PHY-0555545 and the US Department of Energy under Grant No. DE-FG03-94ER40837.

\begin{thebibliography}{99}
\bibitem{Haber} H. E. Haber and G. L. Kane, Phys. Rept. \textbf{117}, 75 (1985).
\bibitem{Okada} Y. Okada, M. Yamaguchi, and T. Yanagida, Prog. Theor. Phys. \textbf{85}, 1 (1991).
\bibitem{Haber2} H. E. Haber and R. Hempfling, Phys. Rev. Lett. \textbf{66}, 1815 (1991).
\bibitem{Ellis} J. R. Ellis, G. Ridolfi, and F. Zwirner, Phys. Lett. \textbf{B257}, 83 (1991).
\bibitem{Barbieri} R. Barbieri, M. Frigeni, and F. Caravaglios, Phys. Lett. \textbf{B258}, 167 (1991).
\bibitem{Barate} R. Barate \textit{et al.} (LEP Higgs Working Group), Phys. Lett. \textbf{B565}, 61 (2003), hep-ex/0306033.
\bibitem{ALEPH} The ALEPH, DELPHI, L3, OPAL collaborations and LEP Higgs Working Group, hep-ex/0602042 (2006).
\bibitem{Kane} G. L. Kane, T. T. Wang, B. D. Nelson, and L.-T. Wang, Phys. Rev. \textbf{D71}, 035006 (2005).
\bibitem{Carena} M. Carena, J. R. Ellis, A. Pilafptsis, and C. E. M. Wagner, Phys. Lett. \textbf{B495}, 155 (2000), hep-ph/0009212.
\bibitem{Lee} J. S. Lee \textit{et al.}, Comput. Phys. Commun. \textbf{156}, 283 (2004).
\bibitem{Tevatron} Tevatron Electroweak Working Group, hep-ex/0604053.
\bibitem{M. Drees} M. Drees, Phys. Rev. \textbf{D71}, 115006 (2005).
\bibitem{Yao} W. M. Yao \textit{et al.} (Particle Data Group), J. Phys. \textbf{G33}, 1 (2006).
\bibitem{Abazov} V. M. Abazov \textit{et al.} (D0) (2006), hep-ex/0608013.
\bibitem{Abulencia} A. Abulencia \textit{et al.} (CDF), Phys. Rev. Lett. \textbf{96}, 171802 (2006), hep-ex/0512072.
\bibitem{Abazov2} V. M. Abazov \textit{et al.} (D0), Phys. Lett. \textbf{B638}, 119 (2006).
\bibitem{Drees2} M. Drees and K. Hagiwara, Phys. Rev. \textbf{D42}, 1709 (1990).
\bibitem{Frere} J. M. Frere, D. R. T. Jones, and S. Raaby, Nucl. Phys. \textbf{B222}, 11 (1983).
\bibitem{Claudson} M. Claudson, L. J. Hall, and I. Hinchliffe, Nucl. Phys. \textbf{B228}, 501 (1983).
\bibitem{Carena2} M. Carena, S. Mrenna, and C. E. M. Wagner, Phys. Rev. \textbf{D60}, 075010 (1999).
\bibitem{Kanemura} S. Kanemura and C. P. Yuan, Phys. Lett. \textbf{B530}, 188 (2002), hep-ph/0112165.
\bibitem{Cao} Q.-H. Cao, S. Kanemura, and C. P. Yuan, Phys. Rev. \textbf{D69}, 075008 (2004).
\bibitem{Belyaev} A. Belyaev, Q.H. Cao, D. Nomura, K. Tobe and C.-P. Yuan, in preparation.
\bibitem{Maarten} M. Carena \textit{et al.} (Higgs Working Group) (2000), hep-ph/0010338.
\bibitem{Belyaev2} A. Belyaev, T. Han, and R. Rosenfeld, JHEP \textbf{07}, 021 (2003).
\bibitem{Degrassi} G. Degrassi, P. Gambino, and G. F. Giudice, JHEP \textbf{12}, 009 (2000), hep-ph/0009337.
\bibitem{Carena3} M. Carena, D. Garcia, U. Nierste, and C. E. M. Wagner, Phys. Lett. \textbf{B499}, 141 (2001), hep-ph/0010003.
\bibitem{Iado} K. Iado \textit{et al.} (2006), hep-ex/0604018.
\bibitem{Browder} T. Browder’s talk at ICHEP 2006, August 2006.
\bibitem{K. Babu} K. S. Babu and C. F. Kolda, Phys. Rev. Lett. \textbf{84}, 228 (2000), hep-ph/9909476.
\bibitem{PhysRev} Phys. Rev. Lett. \textbf{97}, 062003 (2006), hep-ex/0606027.
\bibitem{Abazov3} V. M. Abazov \textit{et al.} (D0), Phys. Rev. Lett. \textbf{97}, 021802 (2006), hep-ex/0603029.
\bibitem{Kim} S. Kim, N. Maekawa, A. Matsuzaki, K. Sakurai, K. Tobe and C.-P. Yuan, in preparation.
\end{thebibliography}
A.I. Sanda, and T. Yoshikawa, in preparation.