

## Rapid Communications

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### Mass limits of charged Higgs boson at large $\tan\beta$ from $e^+e^-$ annihilations at $\sqrt{s} = 50-60.8$ GeV

J. R. Smith,<sup>a</sup> R. R. McNeil,<sup>b</sup> R. E. Breedon,<sup>a,g</sup> G. N. Kim,<sup>a,g</sup> Winston Ko,<sup>a</sup> R. L. Lander,<sup>a</sup> K. Maeshima,<sup>a</sup> R. L. Malchow,<sup>a</sup> J. Rowe,<sup>a</sup> D. Stuart,<sup>a</sup> R. Imlay,<sup>b</sup> P. Kirk,<sup>b</sup> J. Lim,<sup>b</sup> W. Metcalf,<sup>b</sup> S. S. Myung,<sup>b</sup> C. P. Cheng,<sup>c</sup> P. Gu,<sup>c</sup> J. Li,<sup>c</sup> Y. K. Li,<sup>c,e</sup> M. H. Ye,<sup>c</sup> Y. C. Zhu,<sup>c</sup> A. Abashian,<sup>d</sup> K. Gotow,<sup>d</sup> K. P. Hu,<sup>d</sup> E. H. Low,<sup>d</sup> M. E. Mattson,<sup>d</sup> L. Piilonen,<sup>d</sup> K. L. Sterner,<sup>d</sup> S. Lusin,<sup>e</sup> C. Rosenfeld,<sup>e</sup> A. T. M. Wang,<sup>e</sup> S. Wilson,<sup>e</sup> M. Frautschi,<sup>f</sup> H. Kagan,<sup>f</sup> R. Kass,<sup>f</sup> C. G. Trahern,<sup>f</sup> K. Abe,<sup>g</sup> Y. Fujii,<sup>g</sup> Y. Higashi,<sup>g</sup> S. K. Kim,<sup>g</sup> Y. Kurihara,<sup>g</sup> A. Maki,<sup>g</sup> T. Nozaki,<sup>g</sup> T. Omori,<sup>g</sup> H. Sagawa,<sup>g</sup> Y. Sakai,<sup>g</sup> Y. Sugimoto,<sup>g</sup> Y. Takaiwa,<sup>g</sup> S. Terada,<sup>g</sup> R. Walker,<sup>g,o</sup> F. Kajino,<sup>i</sup> D. Perticone,<sup>j</sup> R. Poling,<sup>j</sup> T. Thomas,<sup>j</sup> Y. Ishi,<sup>k</sup> K. Miyano,<sup>k</sup> H. Miyata,<sup>k</sup> T. Sasaki,<sup>k</sup> Y. Yamashita,<sup>l</sup> A. Bacala,<sup>m,n</sup> J. Liu,<sup>m</sup> I. H. Park,<sup>m</sup> F. Sannes,<sup>m</sup> S. Schnetzer,<sup>m</sup> R. Stone,<sup>m</sup> J. Vinson,<sup>m</sup> P. Auchincloss,<sup>o</sup> D. Blanis,<sup>o</sup> A. Bodek,<sup>o</sup> H. Budd,<sup>o</sup> S. Eno,<sup>o</sup> C. A. Fry,<sup>o,g</sup> H. Harada,<sup>o</sup> Y. H. Ho,<sup>o</sup> B. J. Kim,<sup>o</sup> Y. K. Kim,<sup>o</sup> T. Kumita,<sup>o</sup> T. Mori,<sup>o</sup> S. L. Olsen,<sup>o,h</sup> N. M. Shaw,<sup>o</sup> A. Sill,<sup>o</sup> E. H. Thorndike,<sup>o</sup> K. Ueno,<sup>o</sup> C. Velissaris,<sup>o</sup> H. W. Zheng,<sup>o</sup> S. Kobayashi,<sup>p</sup> A. Murakami,<sup>p</sup> J. S. Kang,<sup>q</sup> H. J. Kim,<sup>q</sup> M. H. Lee,<sup>q</sup> D. H. Han,<sup>r</sup> E. J. Kim,<sup>r</sup> D. Son,<sup>r</sup> T. Kojima,<sup>s</sup> S. Matsumoto,<sup>s</sup> R. Tanaka,<sup>s</sup> Y. Yamagishi,<sup>s</sup> T. Yasuda,<sup>s</sup> T. Ishizuka,<sup>t</sup> and K. Ohta<sup>t</sup>

(The AMY Collaboration)

<sup>a</sup>University of California, Davis, California 95616

<sup>b</sup>Louisiana State University, Baton Rouge, Louisiana 70803

<sup>c</sup>Institute of High Energy Physics, Beijing 100039

<sup>d</sup>Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

<sup>e</sup>University of South Carolina, Columbia, South Carolina 29208

<sup>f</sup>Ohio State University, Columbus, Ohio 43210

<sup>g</sup>KEK, National Laboratory for High Energy Physics, Ibaraki 305

<sup>h</sup>Tsukuba University, Ibaraki 305

<sup>i</sup>Konan University, Kobe 658

<sup>j</sup>University of Minnesota, Minneapolis, Minnesota 55455

<sup>k</sup>Niigata University, Niigata 950-21

<sup>l</sup>Nihon Dental College, Niigata 951

<sup>m</sup>Rutgers University, Piscataway, New Jersey 08854

<sup>n</sup>University of the Philippines, Quezon City 3004

<sup>o</sup>University of Rochester, Rochester, New York 14627

<sup>p</sup>Saga University, Saga 840

<sup>q</sup>Korea University, Seoul 136-701

<sup>r</sup>Kyungpook National University, Taegu 702-701

<sup>s</sup>Chuo University, Tokyo 112

<sup>t</sup>Saitama University, Urawa 338

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A search for the pair production of charged Higgs particles decaying via the  $H^\pm \rightarrow \tau \bar{\nu}$  mode has been made in  $e^+e^-$  annihilations at center-of-mass energies between 50 and 60.8 GeV using the AMY detector at the KEK collider TRISTAN. No evidence for their existence is observed and 95%-C.L. mass limits are presented. The result has been interpreted in terms of the  $\tan\beta$  parameter in the Higgs sector.

The two-Higgs-doublet model<sup>1</sup> allows three neutral<sup>2</sup> and a pair of charged Higgs bosons. In the model ("model II") in which one neutral Higgs field  $\phi_1^0$  couples exclusively to  $d$ -type quarks and leptons, while the other  $\phi_2^0$  couples exclusively to  $u$ -type quarks and leptons, the charged-Higgs-boson decay modes are determined by a matrix element that depends on the ratio of the vacuum expectation values,  $\langle\phi_2^0\rangle/\langle\phi_1^0\rangle\equiv\tan\beta$ . Figure 1 is a plot of the predictions for various decay branching ratios for the charged Higgs boson as a function of  $\tan\beta$ . Constituent quark masses have been used in the calculation of the branching ratios. This is a conservative assumption. The use of current quark masses would produce a larger branching ratio for the  $H^- \rightarrow \tau\bar{\nu}$  mode. At small values of  $\tan\beta$  the decay is dominated by  $H^- \rightarrow \bar{c}s$  whereas at large values of  $\tan\beta$  the decay is dominated by  $H^- \rightarrow \tau\bar{\nu}$ . Together the  $H^- \rightarrow \bar{c}s$  and  $H^- \rightarrow \tau\bar{\nu}$  decay modes cover about 88% of the total branching ratio of the charged-Higgs-boson decays while the  $H^- \rightarrow \tau\bar{\nu}$  decay mode never exceeds 72%. The 95%-confidence limit on the mass of a charged Higgs boson from several experiments<sup>3</sup> at the DESY and SLAC storage rings PETRA and PEP is 19 GeV. In grand unification models, a large top/bottom mass ratio motivates a large value for  $\tan\beta$ .<sup>1</sup> We place limits at the larger values of  $\tan\beta$  by concentrating on the  $H^- \rightarrow \tau\bar{\nu}$  decay mode.

Massive charged-Higgs-boson pairs decay to acoplanar  $\tau$  pairs. The four  $\tau$  neutrinos in the final state will carry away on average about  $\frac{3}{4}$  of the available c.m. energy, providing a signature of missing energy and transverse momentum. We have searched for acoplanar  $\tau$ -pair events with the 1-vs-1 and 1-vs-3 charged-track event topologies.

The AMY detector<sup>4</sup> at the KEK collider TRISTAN is described elsewhere. Events with two and four charged tracks ( $p > 0.5$  GeV/c and  $|\cos\theta| < 0.85$ ) which balance charge are selected. For four-track events, a 3-prong cluster must be found where the sum of the two-track

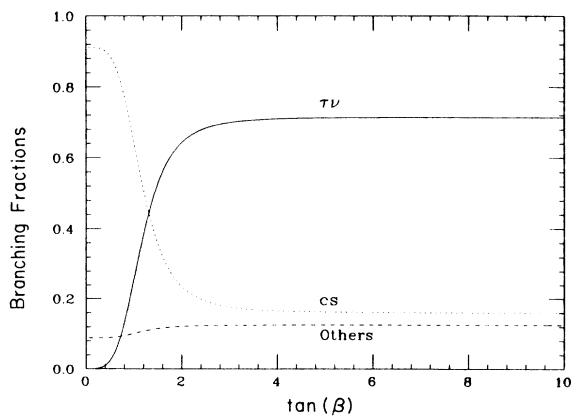


FIG. 1. Effect of  $\tan\beta$  on branching fractions for charged-Higgs-boson decays assuming a charged-Higgs-boson mass of 20 GeV/c<sup>2</sup>. Curves are calculated assuming Kobayashi-Maskawa mixing and quark masses given by  $m_u, m_d = 325$  MeV/c<sup>2</sup>,  $m_s = 500$  MeV/c<sup>2</sup>,  $m_c = 1.6$  GeV/c<sup>2</sup>, and  $m_b = 5.0$  GeV/c<sup>2</sup>.

opening angles for the three combinations is less than 60°. The direction of the  $\tau$  is defined as that of the charged track in the case of 1-prong  $\tau$  events and the vector sum of the charged tracks in the case of 3-prong  $\tau$  events. The  $\tau$ 's are required to be in the barrel region of the detector ( $|\cos\theta| < 0.71$ ). Single- and double-tagged two-photon events are suppressed by rejecting events with more than 5 GeV of energy deposited in the end-cap calorimeters. The background from  $e^+e^- \rightarrow \tau^+\tau^-$  is suppressed by requiring the  $\tau$ 's to have acoplanarity  $\Theta_{\text{acop}} > 20^\circ$ . The background process  $e^+e^- \rightarrow \tau^+\tau^-\gamma$  will produce acoplanar  $\tau$ 's. We suppress this background by rejecting events that have a single neutral-energy cluster greater than  $0.3\sqrt{s}$  (5 GeV in end cap) or have photons of 5 GeV or more with less than 1 GeV of accompanying energy in a cone of half-angle 30° about the photon direction. The process  $e^+e^- \rightarrow e^+e^-\tau^+\tau^-$  (0-tag) will also produce acoplanar  $\tau$ 's, but with low visible energy. We require the visible energy to be  $\frac{1}{3} (\frac{1}{6}) < E_{\text{vis}}/\sqrt{s} < 0.6$  (0.55) for 1-vs-3 (1-vs-1) topologies. Backgrounds are further suppressed by requiring the net transverse momentum in the event to be greater than  $0.05\sqrt{s}$  and  $|\cos\theta_P| < 0.8$ , where  $\theta_P$  is the polar angle of the vector sum of the momentum. To reject two-photon produced electron pairs and muon pairs in the barrel region, we impose the following additional criteria on the 1-vs-1 topology. The momentum of each charged track is required to be more than 2 GeV/c; the invariant mass of the two charged particles must be more than 2 GeV/c<sup>2</sup>; and events where both charged tracks are identified as muons [matched muon-drift-chamber and central-drift-chamber (CDC) track] or electrons ( $E_{\text{SHC}}/P_{\text{CDC}} > 0.5$ ) are rejected.

With these selection criteria, the expected background level from  $e^+e^- \rightarrow eeee$ ,  $e^+e^- \rightarrow ee\mu\mu$ ,  $e^+e^- \rightarrow ee\tau\tau$ ,  $e^+e^- \rightarrow \tau\tau$ ,  $e^+e^- \rightarrow q\bar{q}$ , and  $e^+e^- \rightarrow eeq\bar{q}$ , taken together are  $1.8 \pm 0.3$  (0.14  $\pm$  0.14) events for 1-vs-1 (1-vs-3) selection. One candidate event is found of the 1-vs-1 topology and none for the 1-vs-3 topology in a 27.5-pbs<sup>-1</sup> data sample. The selection efficiency for  $e^+e^- \rightarrow H^+H^- \rightarrow \tau^+\nu_\tau\tau^-\nu_\tau$  varies from 1.8%  $\pm$  0.25% for a Higgs-boson mass of 5 GeV to 15.6%  $\pm$  0.35% for a Higgs-boson mass of 25 GeV. Given one observed event

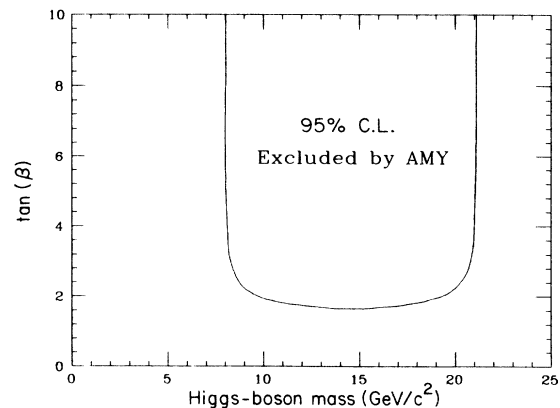


FIG. 2. Region in the  $\tan\beta$  vs charged-Higgs-boson-mass space excluded at the 95% C.L. by this experiment.

with an expected mean of 1.9 events total background, we conservatively estimate the 95%-C.L. limit to be four charged-Higgs-boson events.<sup>5</sup> Figure 2 shows the 95%-C.L. limit on  $\tan\beta$  as a function of charged-Higgs-boson mass. The region between 10 and 20  $\text{GeV}/c^2$  and  $\tan\beta > 2$  is excluded.

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<sup>1</sup>See John F. Gunion *et al.*, *The Higgs Hunter's Guide* (Addison-Wesley, Reading, MA, 1989), and the references therein.

<sup>2</sup>AMY Collaboration, E. Low *et al.*, Phys. Lett. B **228**, 548 (1989).

<sup>3</sup>CELLO Collaboration, H.-J. Behrend *et al.*, Phys. Lett. **114B**, 287 (1982); Phys. Lett. B **193**, 376 (1987); TASSO Collaboration, M. Althoff *et al.*, Phys. Lett. **122B**, 95 (1983); JADE Collaboration, W. Bartel *et al.*, *ibid.* **114B**, 211

(1982); Z. Phys. C **31**, 359 (1986); Mark II Collaboration, C. A. Blocker *et al.*, Phys. Rev. Lett. **49**, 517 (1982); Mark J Collaboration, B. Adeva *et al.*, Phys. Lett. **115B**, 345 (1982); **152B**, 439 (1985).

<sup>4</sup>AMY Collaboration, H. Sagawa *et al.*, Phys. Rev. Lett. **60**, 93 (1988); A. Bacala *et al.*, Phys. Lett. B **218**, 112 (1989).

<sup>5</sup>See Particle Data Group, G. P. Yost *et al.*, Phys. Lett. B **204**, 1 (1988), p. 81, section on "Poisson processes with background."