OVERVIEW OF $\tan\beta$ DETERMINATION AT A LINEAR e^+e^- COLLIDER

John GUNION[1], Tao HAN[2], Jing JIANG[3], Andre SOPCZAK[4*]

[1]Davis Institute for HEP, U. of California, Davis, CA
[2]Dept. of Physics, U. of Wisconsin, Madison, WI
[3]Argonne National Laboratory, Chicago, IL
[4]Lancaster University, UK

Abstract

The ratio of the vacuum expectation value of the two Higgs doublets, $\tan\beta$, is an important parameter of the general 2-Higgs-Doublet Model (2HDM) and the Minimal Supersymmetric extension of the Standard Model (MSSM). The expected uncertainty on the determination of $\tan\beta$ at a Linear Collider (LC) of at least 500 GeV center-of-mass energy and high luminosity is reviewed based on studies of neutral and charged Higgs boson production.

Introduction

Various methods to determine $\tan\beta$ at a LC exist and they have in common that a physical observable depends on $\tan\beta$:

- The pseudoscalar Higgs boson, A, could be produced via radiation off a pair of b-quarks: $e^+e^- \to b\bar{b} \to b\bar{b}A \to b\bar{b}b\bar{b}$. The $b\bar{b}A$ coupling is proportional to $\tan\beta$ and thus the expected production rate is proportional to $\tan^2\beta$.
- The $b\bar{b}\bar{b}b$ rate from the pair-production of the heavier scalar, H, in association with the pseudoscalar Higgs boson $e^+e^- \to HA \to b\bar{b}b\bar{b}$ can be exploited. While the HA production rate is almost independent of $\tan\beta$ the sensitivity occurs via the variation of the decay branching ratios with $\tan\beta$.
- The value of $\tan\beta$ can also be determined from the H and A decay widths, which can be obtained from the previously described reaction.
- The $t\bar{b}\bar{t}b$ rate from charged Higgs boson production can contribute to the determination of $\tan\beta$ from the reaction $e^+e^- \to H^+H^- \to t\bar{b}\bar{t}b$ because of the charged Higgs boson branching ratio variation with $\tan\beta$.
- In addition, the charged Higgs boson total decay width depends on $\tan\beta$.

[*]speaker

The $b\bar{b}A \rightarrow b\bar{b}b\bar{b}$ bremsstrahlung process

The experimental challenge of this study is the low expected production rate and the large irreducible background for a four-jet final state, as discussed in a previous simulation [1]. The expected background rate for a given $b\bar{b}A \rightarrow b\bar{b}b\bar{b}$ signal efficiency is shown in Fig. 1. Taking a working point of 10% efficiency, we estimate the statistical error in determining $\tan\beta$ by $\Delta\tan^2\beta/\tan^2\beta = \Delta S/S = \sqrt{S+B}/S = \sqrt{200}/100 \approx 0.14$, resulting in an error on $\tan\beta = 50$ of 7%. In the MSSM, the $b\bar{b}h$ signal would essentially double the number of signal events and have exactly the same $\tan\beta$ dependence, yielding $\Delta\tan^2\beta/\tan^2\beta \approx \sqrt{300}/200 \approx 0.085$ for $\tan\beta = 50$ and the $\tan\beta$ error would be about 4%. Systematic errors arising from interference with the $hA \rightarrow b\bar{b}b\bar{b}$ reaction can be controlled [2].

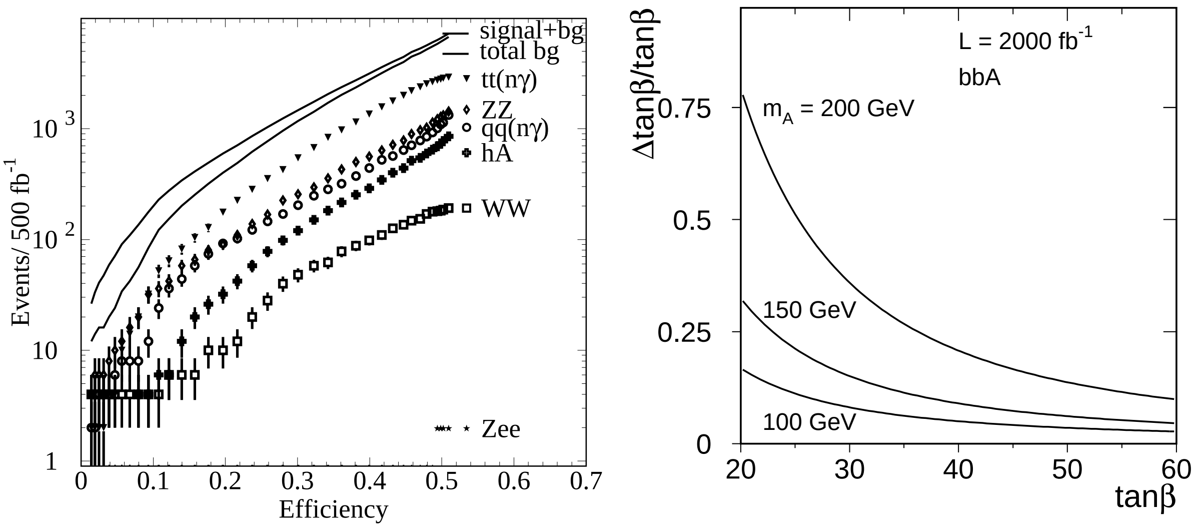

Figure 1: Left: Final background rate versus $b\bar{b}A$ signal efficiency for $m_A = 100$ GeV, $\sqrt{s} = 500$ GeV and $\mathcal{L} = 500$ fb^{-1}. Right: Corresponding $\tan\beta$ statistical error for $\mathcal{L} = 2000$ fb^{-1} and $m_A = 100, 150, 200$ GeV. For both plots, we take a fixed value of $m_b = 4.62$ GeV.

HA production: branching ratios and decay widths

The branching ratios for H, A decay to various allowed modes vary rapidly with $\tan\beta$ in the MSSM when $\tan\beta$ is below 20. Consequently, if these branching ratios can be measured accurately, $\tan\beta$ can be determined with good precision in this range. As the H and A decay rates depend on the MSSM parameters, two cases are considered. In scenario (I), SUSY decays of the H and A are kinematically forbidden. Scenario (II) is taken from [3] in which SUSY decays (mainly to $\tilde{\chi}_1^0\tilde{\chi}_1^0$) are allowed. We assume event selection criteria with an event selection efficiency of 10% and negligible background, based on the expected b-tagging performance and kinematic event selection. The expected $HA \rightarrow b\bar{b}b\bar{b}$ event rates and 1σ statistical bounds are shown in Fig. 2 as a function of $\tan\beta$ for $\sqrt{s} = 500$ GeV and $\mathcal{L} = 2000$ fb^{-1}. The resulting bounds for $\tan\beta$ are plotted in Fig. 3 (right) for MSSM scenarios (I) and (II).

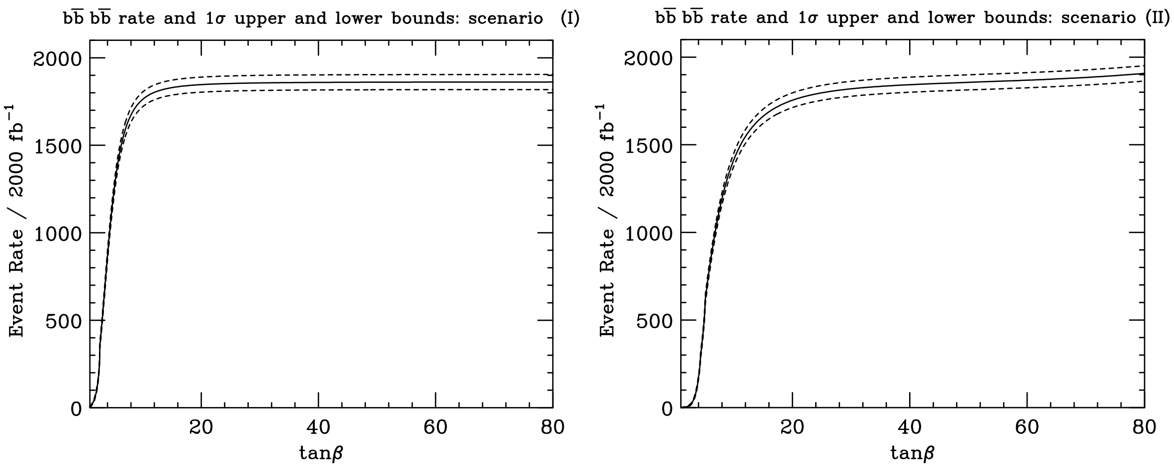

Figure 2: Expected $e^+e^- \to HA \to b\overline{b}b\overline{b}$ event rates for 10% efficiency and $\pm 1\sigma$ bounds in scenarios (I) and (II) in the MSSM for $m_A = 200$ GeV, $\sqrt{s} = 500$ GeV and $\mathcal{L} = 2000\ \mathrm{fb}^{-1}$.

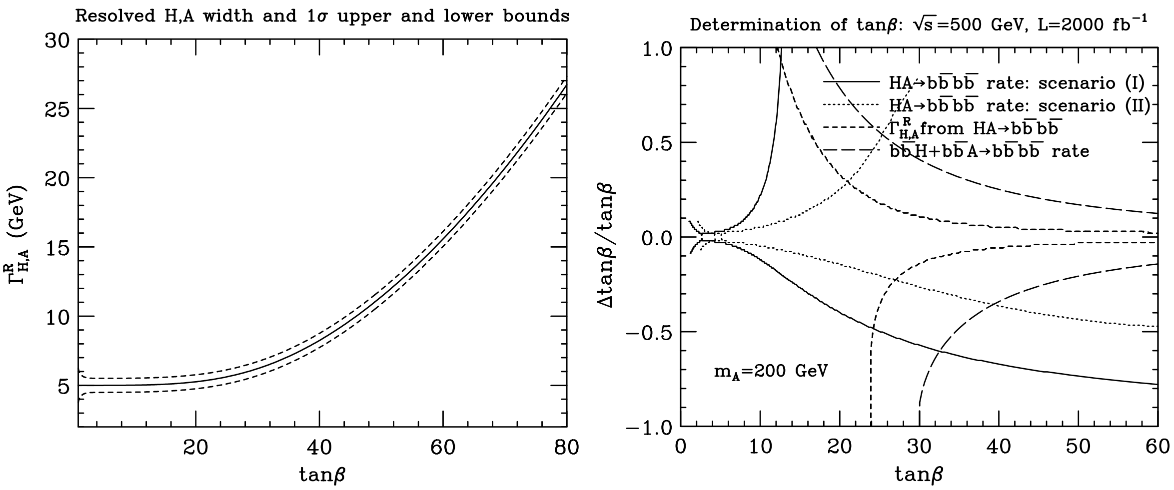

Figure 3: Left: Expected resolved width $\Gamma^{R}_{H,A}$, Eq. (1), for scenario (I) and 1σ upper and lower bounds with 10% selection efficiency. The statistical bounds include an additional efficiency factor of 0.75 for keeping only events in the central mass peak and assume a detector resolution of $\Gamma_{res} = 5$ GeV with a 10% uncertainty. Right: Expected precision on $\tan\beta$ (1σ bounds) for $m_A = 200$ GeV, $\sqrt{s} = 500$ GeV and $\mathcal{L} = 2000\ \mathrm{fb}^{-1}$ based on the $e^+e^- \to b\overline{b}A + b\overline{b}H \to b\overline{b}b\overline{b}$ rate, the $e^+e^- \to HA \to b\overline{b}b\overline{b}$ rate and $\Gamma^{R}_{H,A}$.

A previous HA simulation [5] indicates that about 25% of the time wrong jet-pairings are made, which are attributed to the wings of the mass distribution. The $m_{b\overline{b}}$ values from H and A decays are binned in a single distribution, since the H and A mass splitting is typically substantially smaller than the detector resolution of $\Gamma_{res} = 5$ GeV for the large $\tan\beta$ values considered. Our effective observable is the resolved average width defined by

$$\Gamma^{R}_{H,A} = \frac{1}{2}\left[\sqrt{[\Gamma^{H}_{tot}]^2 + [\Gamma_{res}]^2} + \sqrt{[\Gamma^{A}_{tot}]^2 + [\Gamma_{res}]^2}\right]. \qquad (1)$$

Its dependence on $\tan\beta$ is shown in Fig. 3 for $m_H \approx m_A = 200$ GeV in MSSM scenario (I) and it is very similar for scenario (II).

In order to extract the implied $\tan\beta$ bounds, we must account for the fact that the detector resolution will not be precisely determined. There will be a systematic uncertainty which we have estimated at 10% of $\Gamma_{\rm res}$, i.e. 0.5 GeV. This systematic uncertainty considerably weakens our ability to determine $\tan\beta$ at the lower values of $\tan\beta$ for which $\Gamma^{\rm H}_{\rm tot}$ and $\Gamma^{\rm A}_{\rm tot}$ are smaller than $\Gamma_{\rm res}$. This systematic uncertainty should be carefully studied as part of future experimental analyses. Figure 3 shows also the expected $\pm 1\sigma$ experimental errors based on the measurement of $\Gamma^{\rm R}_{\rm H,A}$. An excellent determination of $\tan\beta$ will be possible at high $\tan\beta$. The $\rm b\bar{b}H/A$ and H/A width methods are nicely complementary in their $\tan\beta$ coverage to the $\tan\beta$ determination based on the $\rm HA \to b\bar{b}b\bar{b}$ rate method at lower $\tan\beta$.

$\rm H^+H^-$ production: branching ratios and decay widths

The reaction $\rm e^+e^- \to H^+H^- \to t\bar{b}\,\bar{t}b$ can be observed at a LC [6] and recent high-luminosity simulations [7] show that precision measurements can be performed. As soon as the charged Higgs boson decay into tb is allowed this decay mode is dominant. Nonetheless, $\rm BR(H^\pm \to tb)$ varies significantly with $\tan\beta$, especially for small values of $\tan\beta$ where the tb mode competes with the $\tau\nu$ mode. The $\rm H^+ \to t\bar{b}$ branching ratio and width are sensitive to $\tan\beta$ in the form $\Gamma(\rm H^\pm \to tb) \propto m_{\rm t}^2 \cot^2\beta + m_{\rm b}^2 \tan^2\beta$. As in the previous section, we use HDECAY [4] (which incorporates the running of the b-quark mass) to evaluate the charged Higgs boson branching ratios and decay widths. The tb partial width and the corresponding branching ratio have a minimum in the vicinity of $\tan\beta \approx 6-8$. In contrast to the variation of the branching ratio, the cross section for $\rm e^+e^- \to H^+H^-$ production is largely independent of $\tan\beta$.

Our procedures for estimating errors for the $\rm t\bar{b}\,\bar{t}b$ rate and for the total width are similar to those given earlier for HA production rate and width in the $\rm b\bar{b}b\bar{b}$ channel. For $m_{\rm H^\pm} = 300$ GeV at $\sqrt{s} = 800$ GeV, a $\rm H^+H^-$ study [7] finds that the $\rm t\bar{b}\,\bar{t}b$ final state can be isolated with an efficiency of 2.2%. For $m_{\rm H^\pm} = 200$ GeV and $\sqrt{s} = 500$ GeV, we have adopted the same 2.2% efficiency and negligible background. Figure 4 shows the resulting $\rm t\bar{b}\,\bar{t}b$ rates and 1σ bounds for MSSM scenarios (I) and (II). The corresponding bounds on $\tan\beta$ are shown in Fig. 5 (right).

For the total width determination, we assume that we keep only 75% of the events after cuts (i.e. a fraction 0.75×0.022 of the raw event number), corresponding to throwing away wings of the mass peaks, and each $\rm t\bar{b}\,\bar{t}b$ event is counted twice since we can look at both the $\rm H^+$ and the $\rm H^-$ decay. We define a resolved width which incorporates the detector resolution $\Gamma_{\rm res} = 5$ GeV:

$$\Gamma^{\rm R}_{\rm H^\pm} = \sqrt{[\Gamma^{\rm H^\pm}_{\rm tot}]^2 + [\Gamma_{\rm res}]^2}. \tag{2}$$

Estimated errors are based on the width measurement for 10% systematic error in $\Gamma_{\rm res} = 0.5$ GeV. The resolved width $\Gamma^{\rm R}_{\rm H^\pm}$ for scenario (I) is given in Fig. 5 and it is very similar for scenario (II). It also shows resulting $\tan\beta$ bounds. In comparison to the neutral Higgs boson methods (Fig. 3), we observe that for MSSM scenario (I) the $\rm t\bar{b}\,\bar{t}b$ rate measurement gives a $\tan\beta$ determination that is quite competitive with that from HA production in

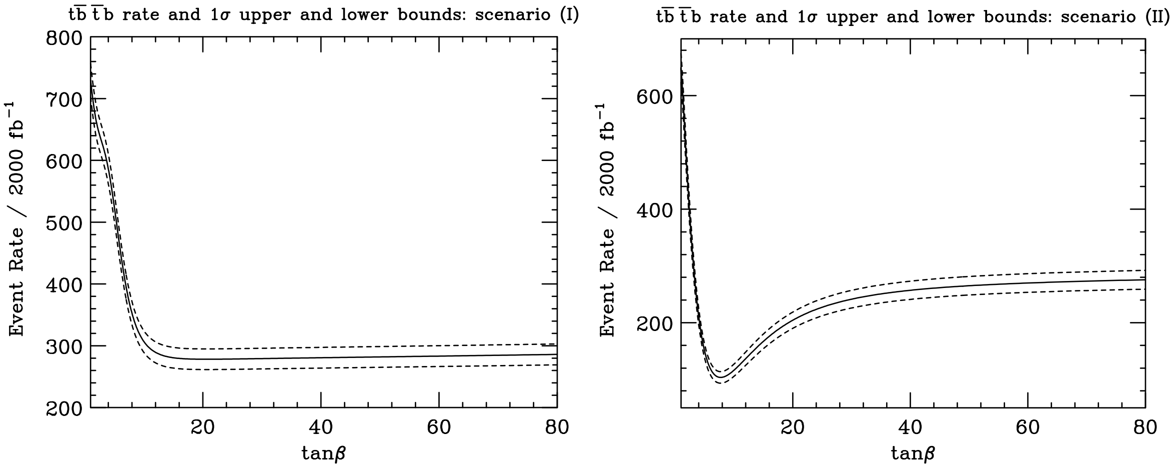

Figure 4: Expected $e^+e^- \to H^+H^- \to t\overline{b}\,\overline{t}b$ event rates for 2.2% efficiency and $\pm 1\sigma$ bounds in scenarios (I) and (II) in the MSSM for $m_A = 200$ GeV, $\sqrt{s} = 500$ GeV and $\mathcal{L} = 2000$ fb^{-1}.

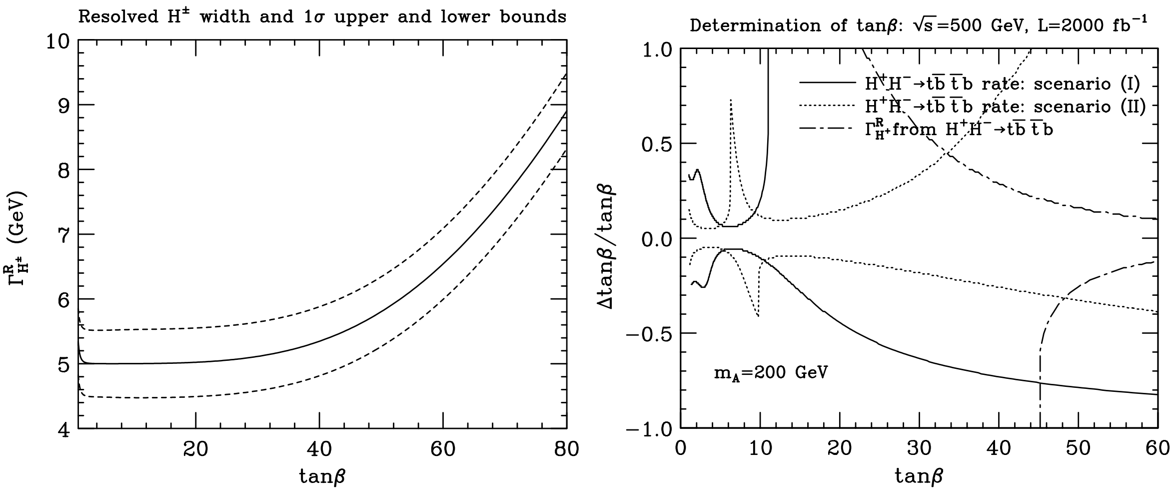

Figure 5: Left: Expected resolved width $\Gamma^R_{H^\pm}$, Eq. (2), for scenario (I) and 1σ upper and lower bounds with 2.2% selection efficiency. The statistical bounds include an additional efficiency factor of 0.75 for keeping only events in the central mass peak and assume $\Gamma_{res} = 5$ GeV with a 10% uncertainty. Right: Expected precision on $\tan\beta$ (1σ bounds) for $m_{H^\pm} \approx m_A = 200$ GeV, $\sqrt{s} = 500$ GeV and $\mathcal{L} = 2000$ fb^{-1} based on the $e^+e^- \to H^+H^- \to t\overline{b}\,\overline{t}b$ rate and $\Gamma^R_{H^\pm}$.

the $b\overline{b}b\overline{b}$ final state. For MSSM scenario (II), the $t\overline{b}\,\overline{t}b$ rate gives an even better $\tan\beta$ determination than does the $b\overline{b}b\overline{b}$ rate. On the other hand, the width measurement from the $t\overline{b}\,\overline{t}b$ final state of H^+H^- production is much poorer than that from the $b\overline{b}b\overline{b}$ final state of HA production.

By combining the $\tan\beta$ errors from all processes in quadrature we obtain the expected net errors on $\tan\beta$ shown in Fig. 6 for MSSM scenarios (I) and (II). The Higgs sector will provide an excellent determination of $\tan\beta$ at small and large $\tan\beta$ values. However, larger bounds are expected for moderate $\tan\beta$ in scenario (II) where SUSY decays of the A, H, $H^\pm$ are not significant. Further information on $\tan\beta$ could be obtained from the reaction $e^+e^- \to t\bar{t} \to tbH^\pm \to tb\tau\nu$, further Higgs decay branching ratios (e.g. $H \to WW, ZZ, hh$; $A \to Zh$; H, A $\to$ SUSY particles), the H/A decay width from $b\bar{b}H/A$ production, and the polarization of scalar taus.

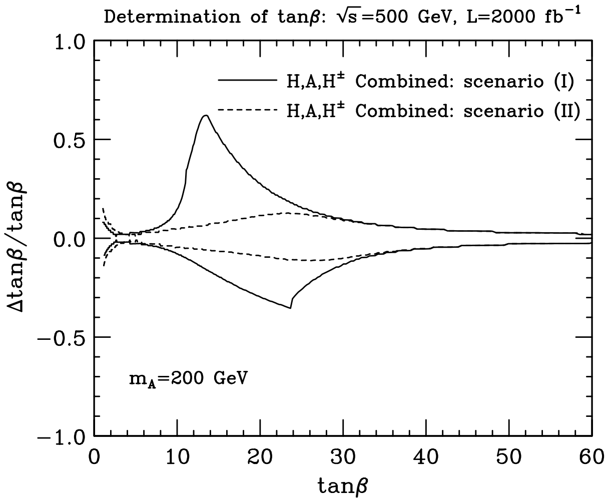

Figure 6: Expected combined precision on $\tan\beta$ (1σ bounds) for $m_{H^\pm} \approx m_A = 200$ GeV, $\sqrt{s} = 500$ GeV and $\mathcal{L} = 2000$ fb^{-1} based on combining (in quadrature) the results shown in Figs. 3 and 5 for the $b\bar{b}H/A$ rate, the $HA \to b\bar{b}b\bar{b}$ rate, $\Gamma^R_{H,A}$, the $t\bar{b}\bar{t}b$ rate and $\Gamma^R_{H^\pm}$. Higher order calculations in the MSSM could influence the combination of the different $\tan\beta$ methods.

Conclusions

A high-luminosity linear e^+e^- collider will provide a precise measurement of the value of $\tan\beta$ throughout most of the large possible $\tan\beta$ range $1 < \tan\beta < 60$. In particular, we have demonstrated the complementarity of employing: a) the $b\bar{b}A + b\bar{b}H \to b\bar{b}b\bar{b}$ rate; b) the $HA \to b\bar{b}b\bar{b}$ rate; c) the average H, A total width from HA production; d) the $H^+H^- \to t\bar{b}\bar{t}b$ rate; and e) the $H^\pm$ total width from $H^+H^- \to t\bar{b}\bar{t}b$ production. Experimental challenges will be the required high total luminosity, an excellent b-tagging performance, and precision detector resolution and selection efficiency determinations.

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