CERN, February 2002

LC-LHC: on the Determination of $\tan\beta$ at a Future e^+e^- LC

Jack Gunion[1]
Tao Han[2]
Jing Jiang[3]
André Sopczak[4]

1...U.C. Davis, 2...University of Wisconsin, 3...Argonne N.Lab
4...Lancaster University

Outline

- Introduction
- $HA \to b\bar{b}b\bar{b}$ event rate
- H and A width from $HA \to b\bar{b}b\bar{b}$
- New aspect: $H^+H^- \to t\bar{b}\bar{t}b$
- Conclusions

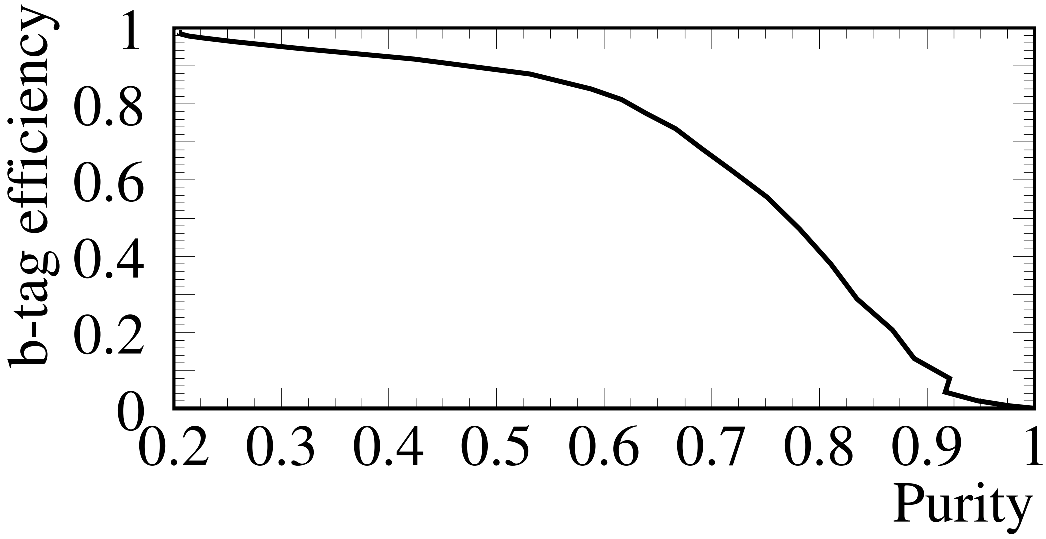
Introduction

- Framework:
  Two-Higgs Doublet Model or MSSM.
- Production and Decay of A, h, H, and $H^{\pm}$.
- Considered reactions for TESLA:
  strong dependence on $\tan\beta$.
- Extrapolation $\mathrm{b\bar{b}A} \to \mathrm{b\bar{b}b\bar{b}}$ for
  $100 < m_\mathrm{A} < 200$ GeV.
- $\mathrm{HA} \to \mathrm{b\bar{b}b\bar{b}}$ event rate.
- H and A width determination.
- Charged Higgs bosons rate.
- Charged Higgs bosons decay width.

b-tagging

Experimental potential depends strongly on the b-tagging performance.

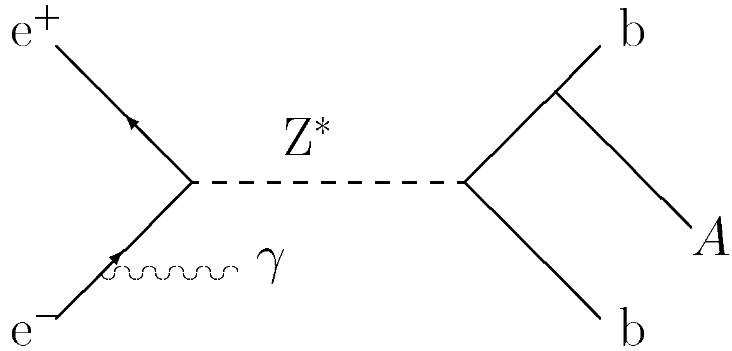
Hadronic events $e^+e^- \to q\bar{q}$ (5 flavors).



Efficiency: Ratio of simulated $b\overline{b}$ events after the selection to all simulated $b\overline{b}$ events.

Purity: Ratio of simulated $b\overline{b}$ events after the selection to all selected $q\overline{q}$ events.

$\mathbf{b\bar{b}A}$ Simulation



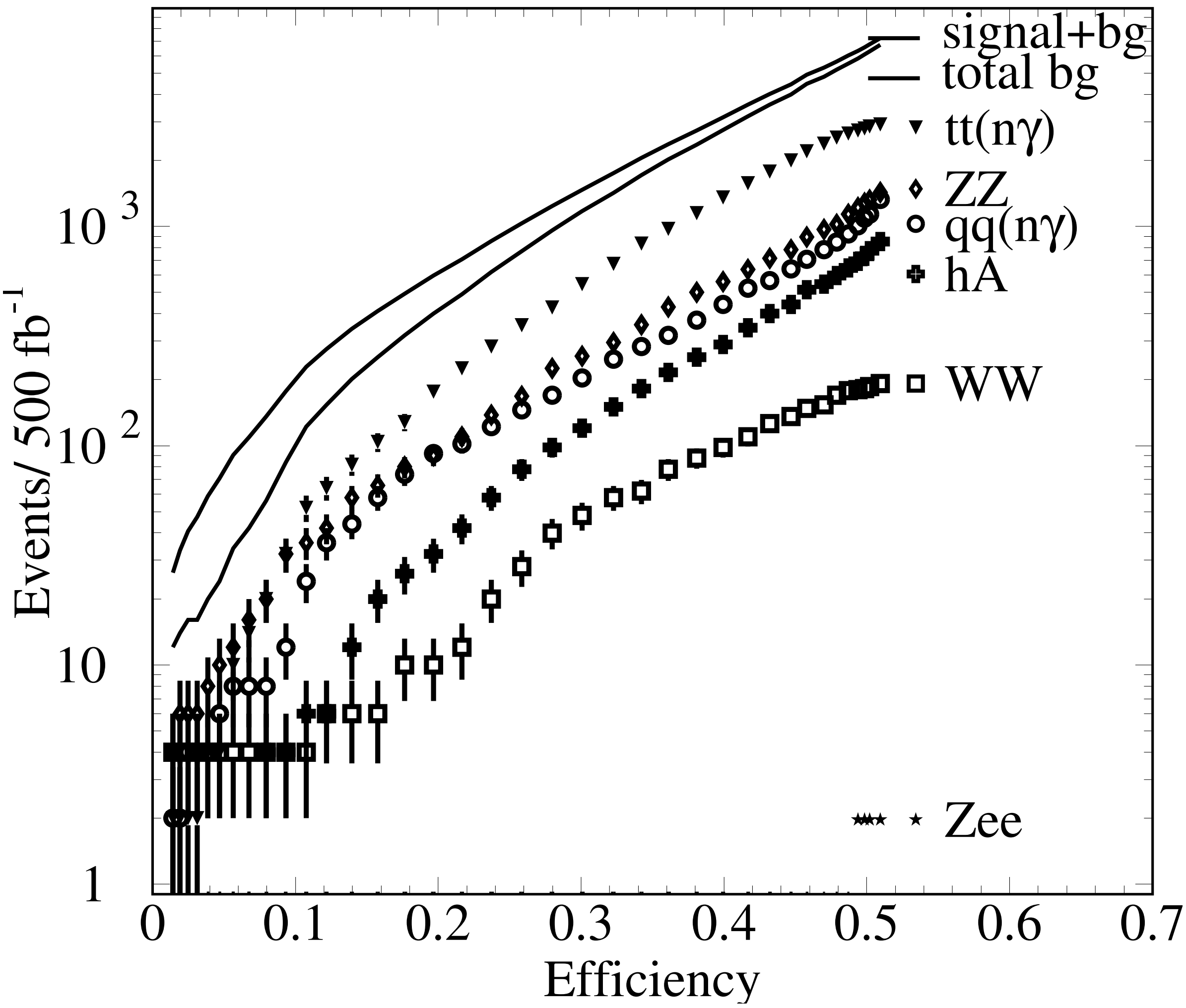
Simulated Higgs boson mass: 100 GeV

Channel	bbA	qq	WW	eWν	tt	ZZ	eeZ	hA	sum
(in 1000)	50	6250	3500	2500	350	300	3000	50	16000
After Presel.	73%	20991	7481	0	89983	10278	145	12665	141544

Simulated hA rate corresponds to twice the luminosity (maximum cross section in general Two-Higgs Doublet Model).

A. Sopczak

Signal and Background



A. Sopczak

Interference: $\mathbf{b\overline{b}A}$ $\mathbf{hA \to b\bar{b}b\bar{b}}$

Expectation before event selection:

$$\sigma_{\mathrm{bbA}} \equiv \sigma(\mathrm{e^+e^-} \to \mathrm{bbA} \to \mathrm{b\bar{b}b\bar{b}})$$

$$\sigma_{\mathrm{hA}} \equiv \sigma(\mathrm{e^+e^-} \to \mathrm{hA} \to \mathrm{b\bar{b}b\bar{b}})$$

$$\sigma_{\mathrm{b\overline{b}A+hA}} \equiv \sigma(\mathrm{e^+e^-} \to \mathrm{b\overline{b}A, hA} \to \mathrm{b\bar{b}b\bar{b}})$$

$$\sigma_{\mathrm{interf}} = \sigma_{\mathrm{b\overline{b}A+hA}} - \sigma_{\mathrm{b\overline{b}A}} - \sigma_{\mathrm{hA}}.$$

For $m_{\mathrm{b}} = 4.62$ GeV:

$$\sigma_{\mathrm{b\overline{b}A}} = 1.83 \pm 0.01 \text{ fb}$$

$$\sigma_{\mathrm{hA}} = 36.85 \pm 0.10 \text{ fb}$$

$$\sigma_{\mathrm{b\overline{b}A+hA}} = 39.23 \pm 0.12 \text{ fb}$$

$$\sigma_{\mathrm{interf}} = 0.55 \pm 0.16 \text{ fb}$$

Positive interference,

reduction in statistical error.

Systematic errors:
$\mathbf{b\bar{b}A}$ $\mathbf{hA \to b\bar{b}b\bar{b}}$

Interference events:

background-like: small systematic error.

signal-like: large systematic error.

Solution: fit signal and background to data for various $\tan\beta$.

Another systematic error is the running b-mass. Higher-order corrections should be very precisely known by the time the LC is constructed.

2HDM: $\mathrm{b\bar{b}A}$ 500 fb^{-1} Results

For $\tan\beta = 50$ and $m_{\mathrm{A}} = 100$ GeV:

$\Delta\tan\beta/\tan\beta = 0.07.$

$$\Delta\tan^2\beta/\tan^2\beta = \Delta N_{\mathrm{signal}}/N_{\mathrm{signal}}$$

$$= \sqrt{N_{\mathrm{signal}} + N_{\mathrm{background}}}/N_{\mathrm{signal}} = 0.14.$$

Smaller values of $\tan\beta$, the sensitivity decreases rapidly. 5σ signal detection for $\tan\beta = 35$.

MSSM: $\mathrm{b\bar{b}A}$ 500 fb^{-1} Results

$\mathrm{b\bar{b}h}$ would double the number of signal events and have the same $\tan\beta$ dependence:

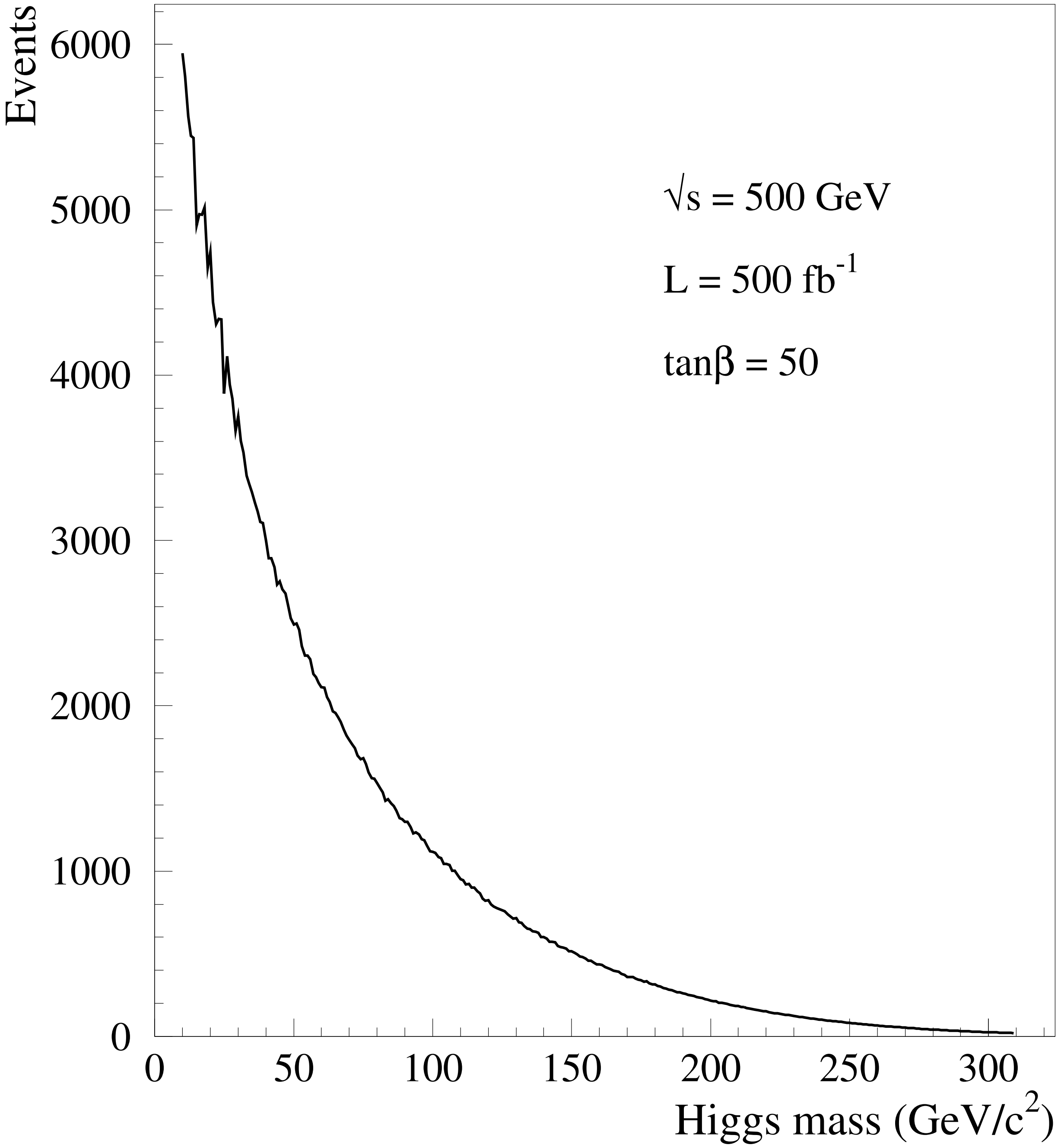
$$\Delta\tan^2\beta/\tan^2\beta \sim \sqrt{300}/200 \approx 0.085$$

For $\tan\beta = 50$ and $m_\mathrm{A} = m_\mathrm{h} = 100$ GeV: $\Delta\tan\beta/\tan\beta = 0.04$.

(For heavier A, $\mathrm{b\bar{b}H}$ will contribute).

Experimental challenge:
at 10% efficiency, $\Delta\tan\beta/\tan\beta < 0.05$ requires $\Delta\epsilon/\epsilon < 0.1$, thus $\Delta\epsilon < 1\%$.

$e^+e^- \to b\bar{b} \to b\bar{b}A$ Rate

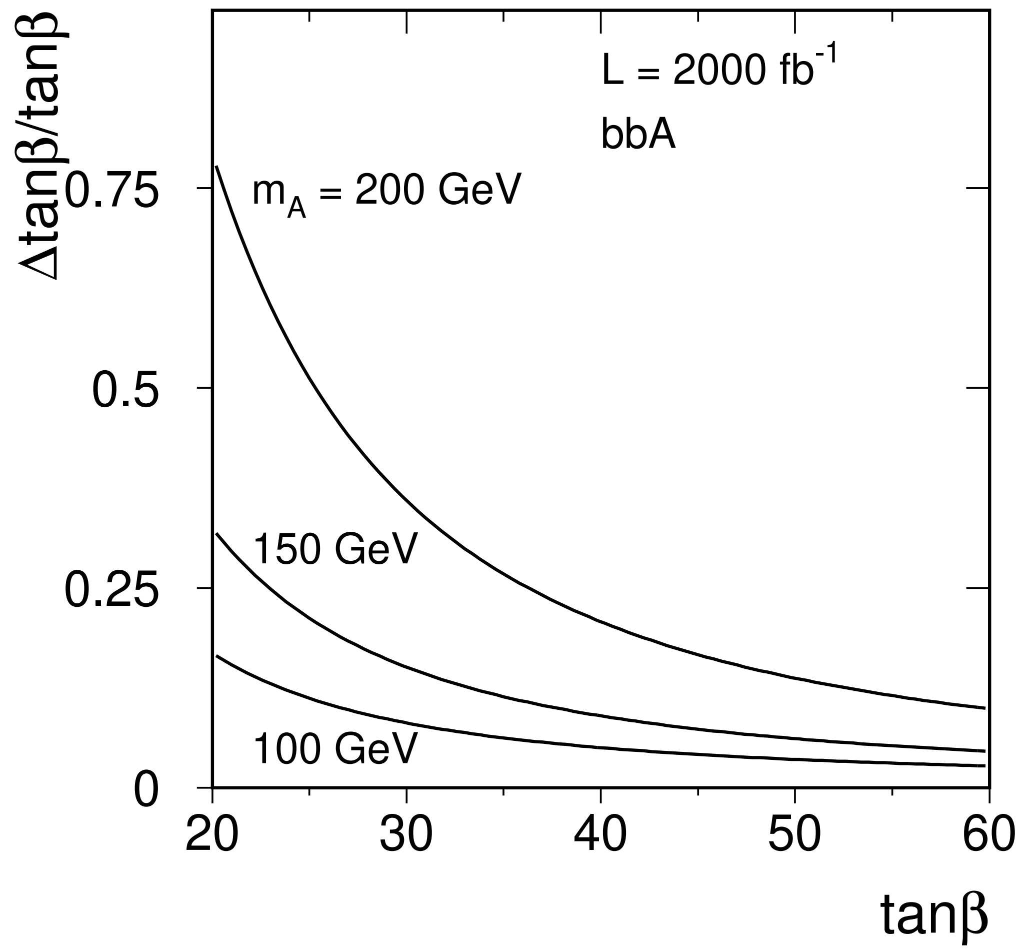


At 100 GeV: 1000 events.

At 200 GeV: 200 events.

A. Sopczak

$\mathbf{b\bar{b}A}$ Results for 2000 $\mathbf{fb^{-1}}$



A. Sopczak

$\mathbf{HA \to b\bar{b}b\bar{b}}$ Event Rate

Assume b-tagging purity 80% per $b\bar{b}$ pair, thus 40% signal efficiency.
For $b\bar{b}b\bar{b}$: 16% efficiency.

Further reduction: kinematic event selection: final efficiency 10%, and negligible background.

Small $\tan\beta$: constant MSSM cross section and large variation of branching fraction.

Typical expected signal rate for 2000 fb^{-1}
and $m_{\mathrm{A}} = m_{\mathrm{H}} = 200$ GeV
for $\tan\beta = 5$: 500 events.

$\Delta\tan\beta/\tan\beta \approx 0.01$
Good overlap with $b\bar{b}A$ results.

MSSM Interpretation

Model (I) Heavy SUSY particles

$m_{\tilde{g}} = 1$ TeV, $\mu = M_2 = 250$ GeV,

$m_{\tilde{t}_L} = m_{\tilde{b}_L} = m_{\tilde{t}_R} = m_{\tilde{b}_R} \equiv m_{\tilde{t}} = 1$ TeV,

$A_b = A_\tau = 0$, $A_t = \mu/\tan\beta + \sqrt{6}m_{\tilde{t}}$

(maximal mixing);

Model (II) Higgs into SUSY decays possible

$m_{\tilde{g}} = 350\,\mathrm{GeV}, \mu = 272\,\mathrm{GeV}, M_2 = 120\,\mathrm{GeV}$,

$m_{\tilde{t}_L} = m_{\tilde{b}_L} = 356$ GeV, $m_{\tilde{t}_R} = 273$ GeV,

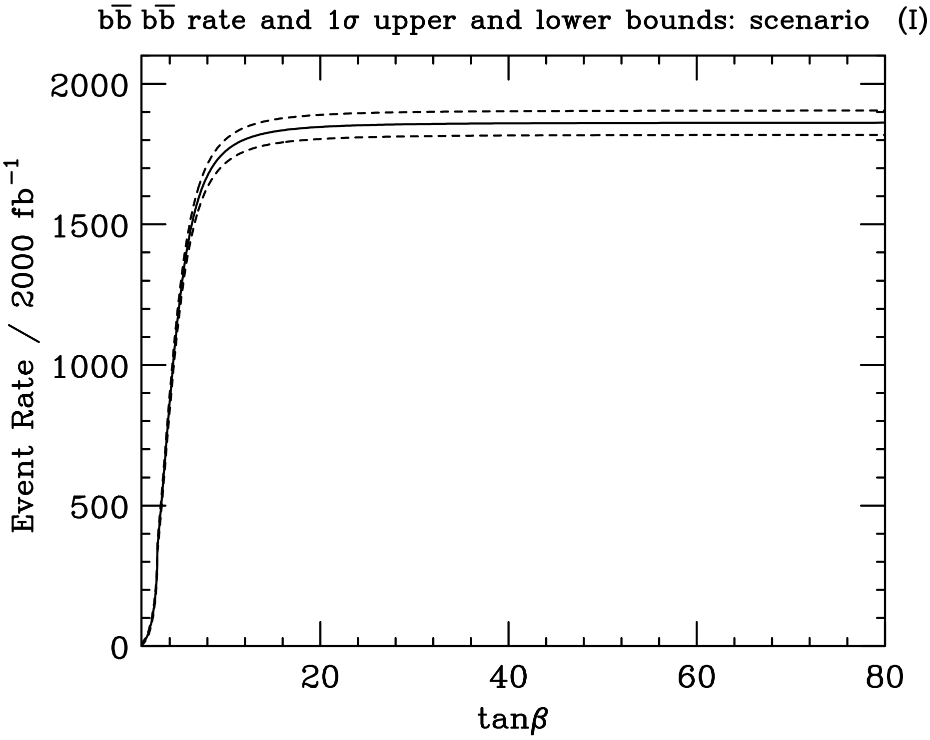
$m_{\tilde{b}_R} = 400$ GeV, $A_\tau = 0$, $A_b = -672$ GeV,

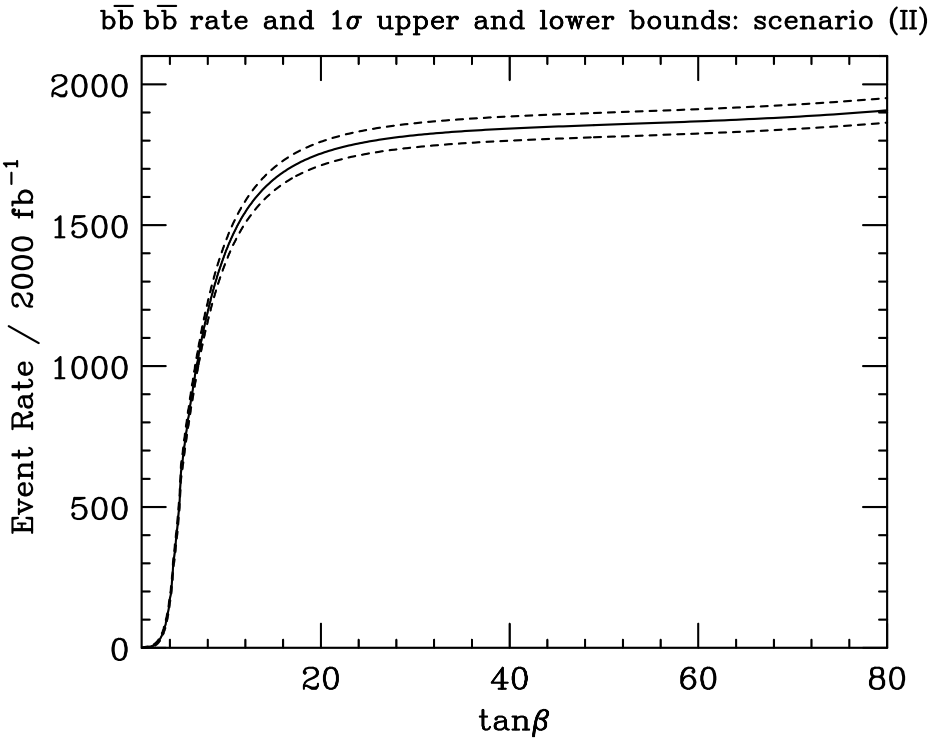
$A_t = -369$ GeV.

bbA and H,A decay widths results almost independent of model (I) or (II).

A. Sopczak

HA → $b\bar{b}b\bar{b}$ Event Rate





A. Sopczak

H and A width from $\mathrm{HA} \rightarrow \mathrm{b\bar{b}b\bar{b}}$

Assumption: 5 ± 0.5 GeV detector resolution ($\Delta E/E = 0.3/\sqrt{E}$ and conservative error).

Reconstruction of mean H and A widths from $\mathrm{b\bar{b}}$-mass.

There are two $\mathrm{b\bar{b}}$ masses per event.

Wrong jet-jet pairings: 25%.

Available statistics for mass reconstruction: 1.5 $\mathrm{HA} \rightarrow \mathrm{b\bar{b}b\bar{b}}$ rate.

Determination of intrinsic Higgs width by convolution with detector resolution.

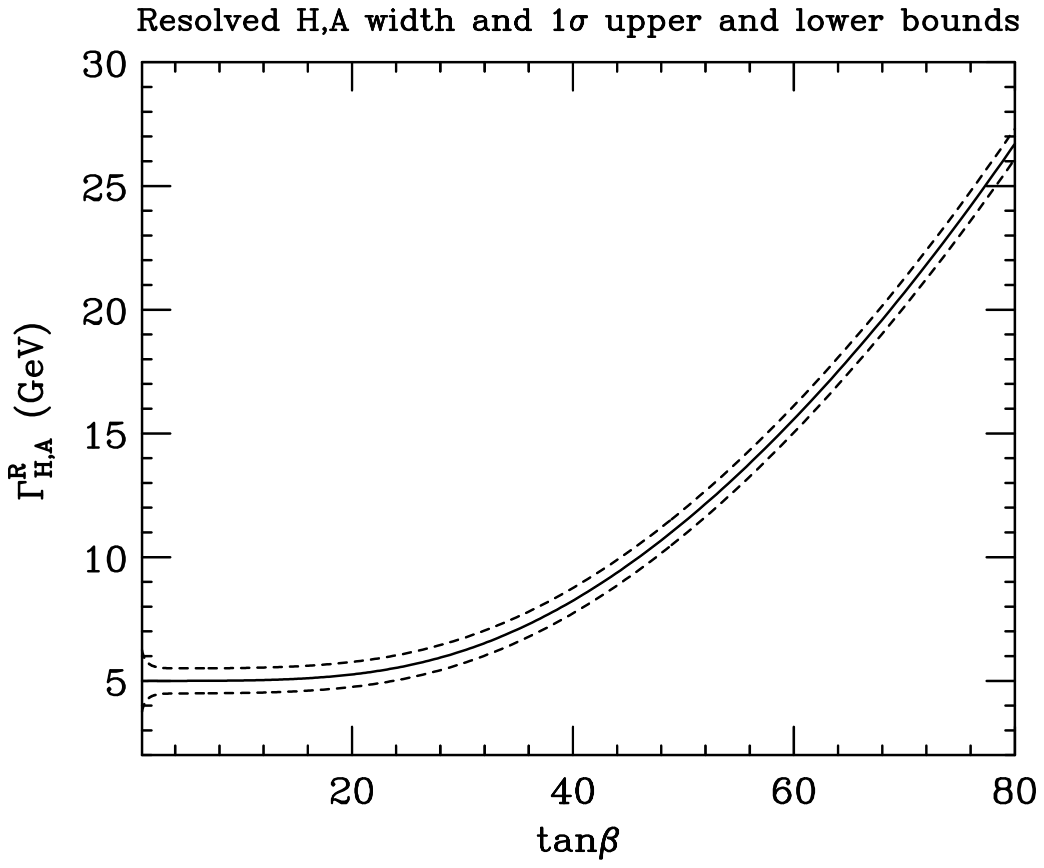
$0.5(\Gamma_\mathrm{H} + \Gamma_\mathrm{A}) = 12.5 \pm 0.54$ GeV, dominated by error on detector resolution.

$\Delta \tan\beta / \tan\beta < 0.02$ for $\tan\beta = 55$.

Resolved Average H/A Width

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

$$\Delta\Gamma^{\mathrm{R}}_{H,A} = \left[\left(\frac{\Gamma^{\mathrm{R}}_{H,A}}{\sqrt{2N_{\mathrm{entries}}}}\right)^2 + (\Delta\Gamma^{\mathrm{sys}}_{\mathrm{res}})^2\right]^{1/2}$$



A. Sopczak

H,A Decay Width

$\tan\beta$	15	20	50	55	60
$\langle \Gamma^H_{\rm tot}, \Gamma^A_{\rm tot} \rangle_{\rm th}$ (GeV)	0.935	1.64	10.4	12.5	14.9
$\langle \Gamma^H_{\rm tot}, \Gamma^A_{\rm tot} \rangle_{\rm effective}$ (GeV)	5.09	5.26	11.5	13.4	15.7
sensitivity (GeV)	0.57	0.57	0.54	0.54	0.54

Strong $\tan\beta$ sensitivity only for large $\tan\beta$.

HA $\rightarrow$ b$\overline{\text{b}}$b$\overline{\text{b}}$ Model Dependence

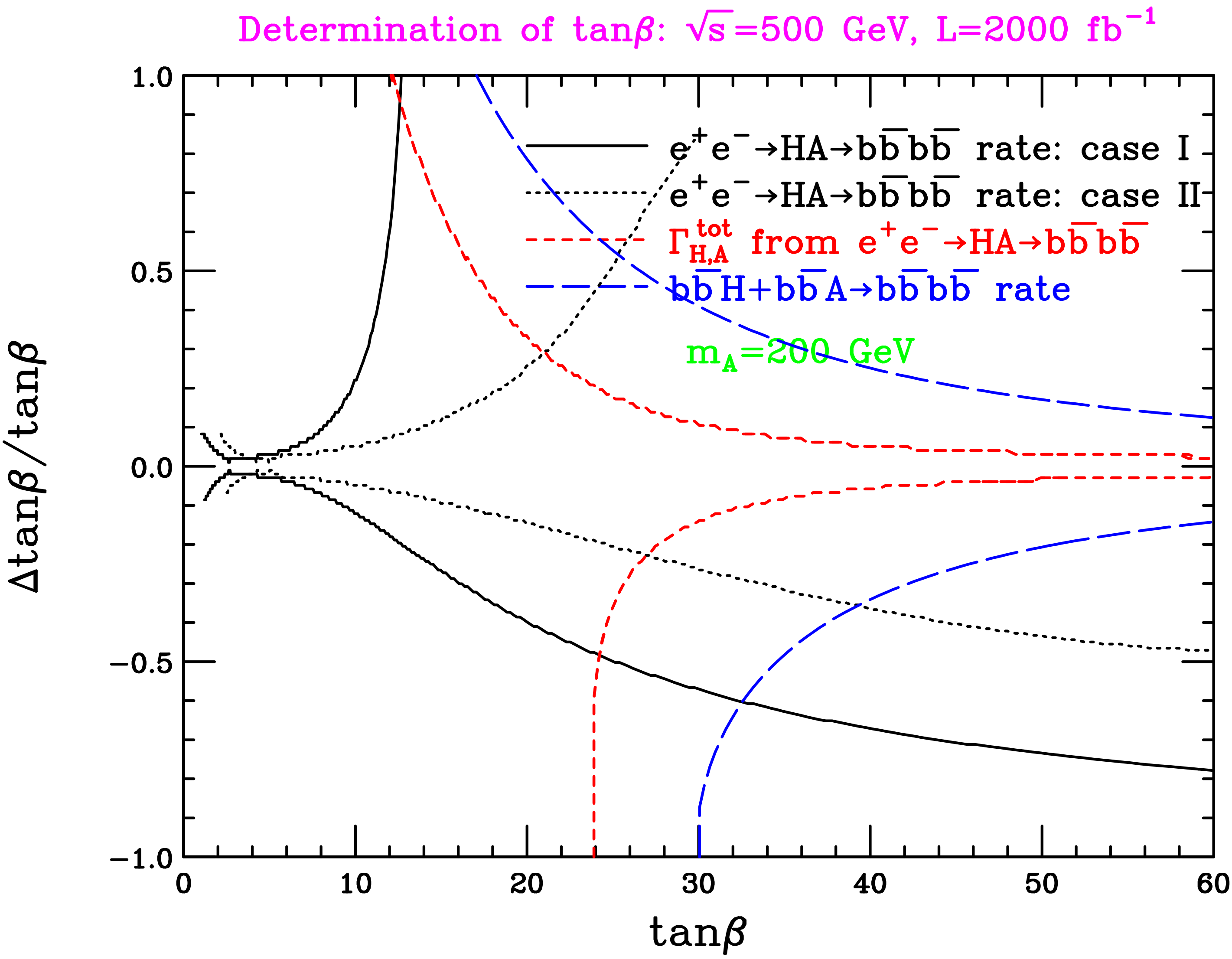
HA $\rightarrow$ b$\overline{\text{b}}$b$\overline{\text{b}}$ results depend on model parameter, owing to large branching variations.

b$\overline{\text{b}}$b$\overline{\text{b}}$ event rate for 10% selection efficiency:

$\tan\beta$	1	2	3	10	40
Model (I)	1	5	34	1415	1842
Model (II)	8	77	464	1762	1859

Significant model parameter dependence on $\tan\beta$ sensitivity.

Complementarity of Different Neutral Higgs Boson Methods



(I) Heavy SUSY particles.

(II) Possible H, A $\rightarrow \chi_1^0 \tilde{\chi}_1^0$ decays.

A. Sopczak

$\mathbf{e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}\bar{t}b}$

- 500 GeV and 10 fb^{-1},

  the charged Higgs can be reconstructed

  Z. Phys. **C 65** (1995) 449.

- 800 GeV and 1000 fb^{-1},

  high precision reconstruction,

  M. Battaglia, A. Ferrari, A. Kiiskinen, T.M. Ki,

  hep-ph/0112015.

- Sensitivity for 500 GeV and 1000 fb^{-1},

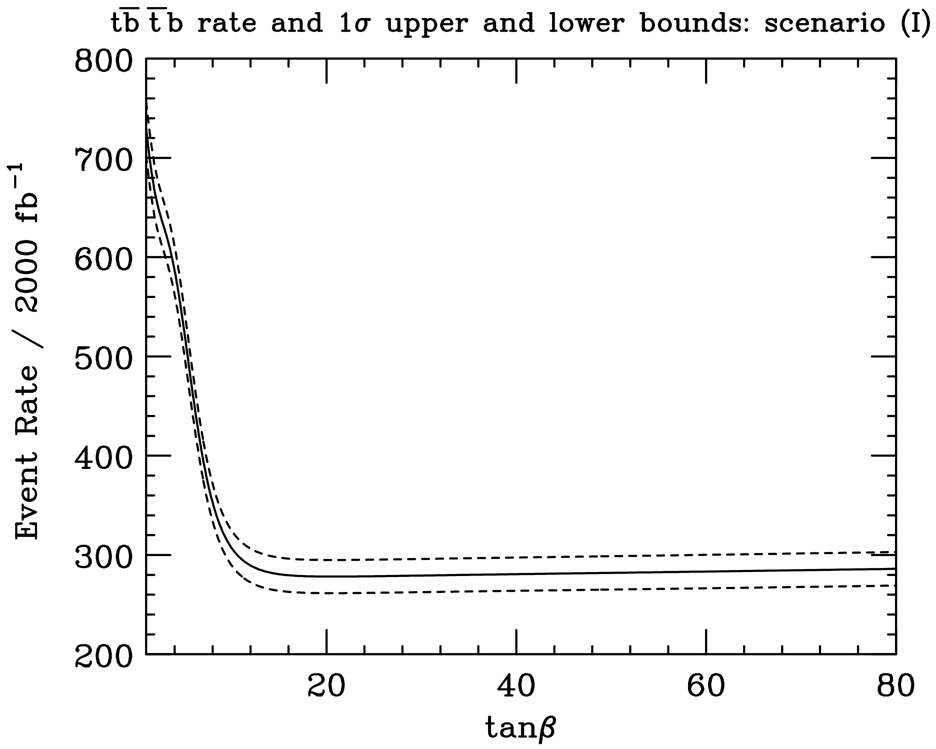
  for a 200 GeV charged Higgs boson mass: small intrinsic width and reconstruction uncertainty dominated by detector resolution.

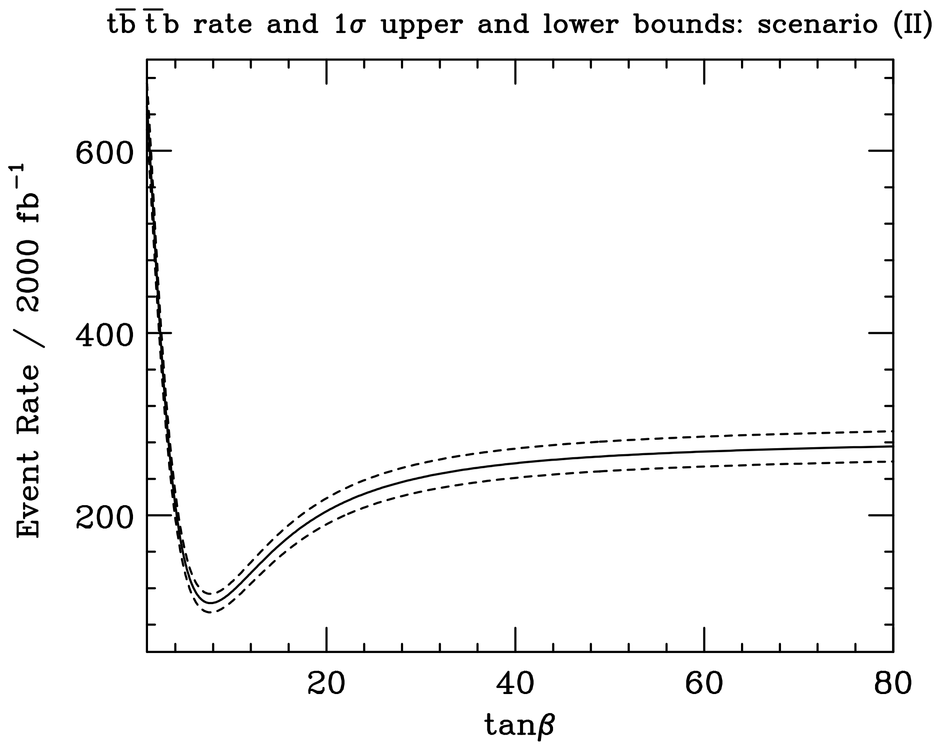
- 2.2% selection efficiency.

$H^+ \rightarrow t\bar{b}$ branching ratio is sensitive to $\tan\beta$:

$$\Gamma(H^\pm \rightarrow tb) \propto m_\tau{}^2 \cot^2\beta + m_\mathrm{b}{}^2 \tan^2\beta$$

$e^+e^- \to H^+H^- \to t\bar{b}\bar{t}b$ Rate



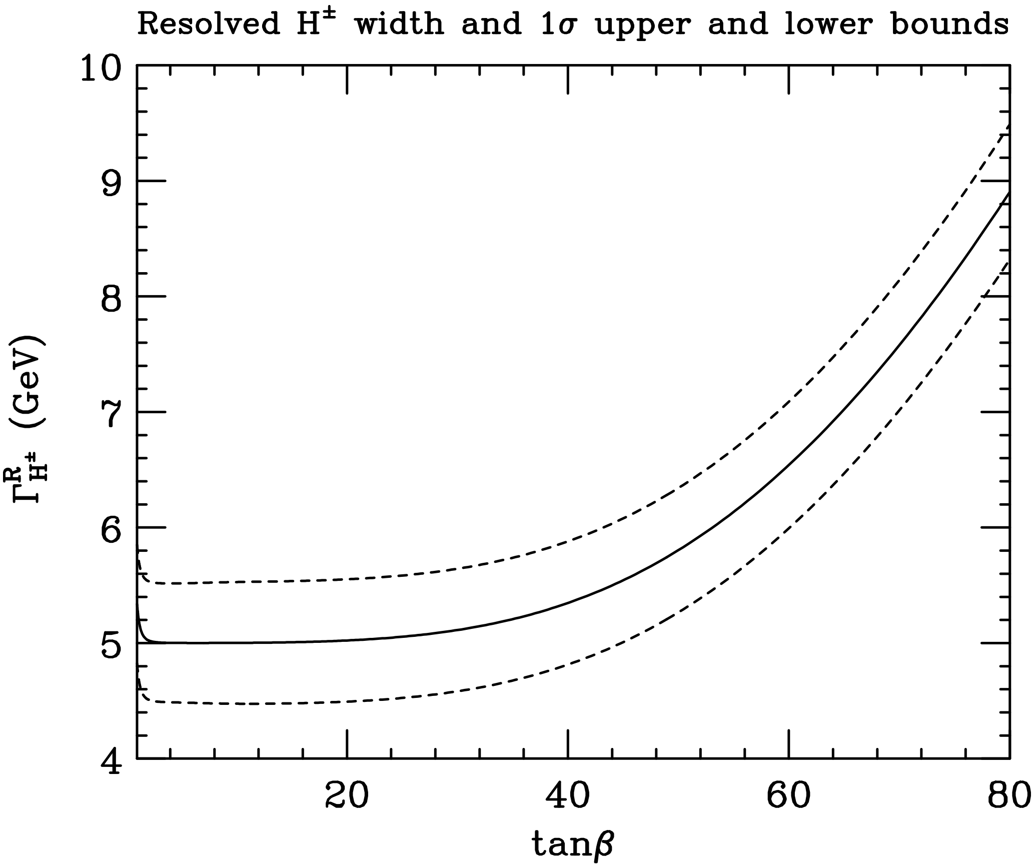


A. Sopczak

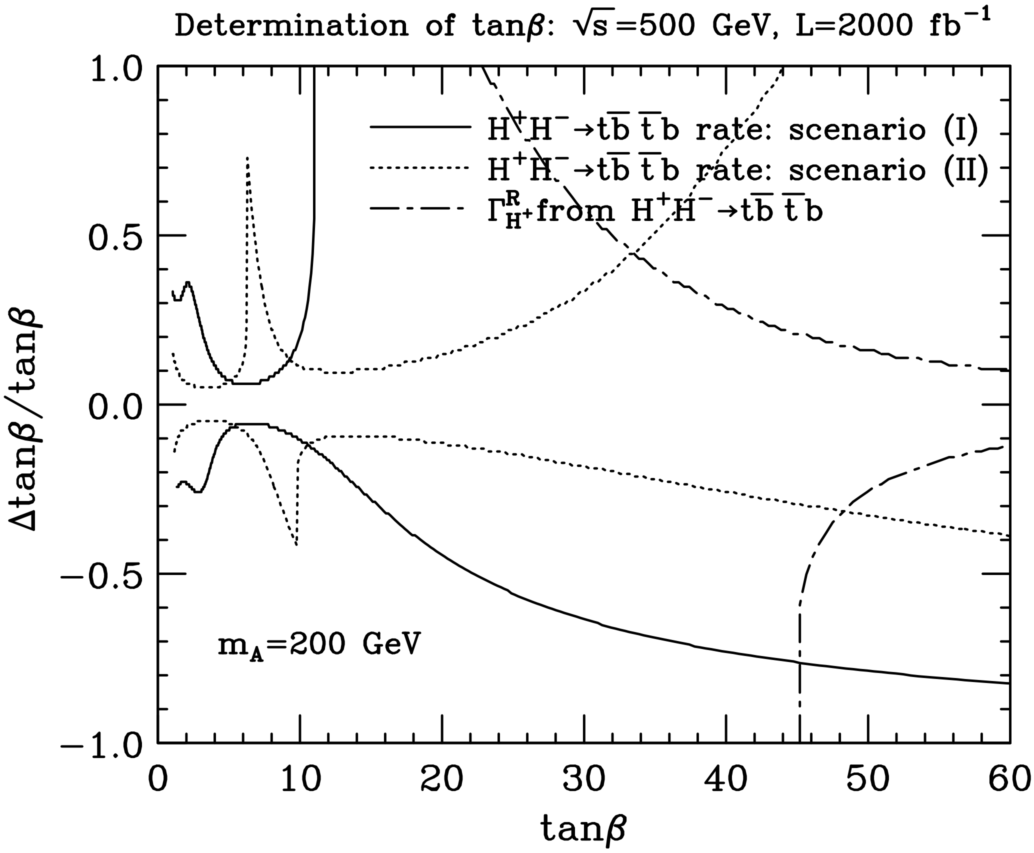
Resolved $H^{\pm}$ Width

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

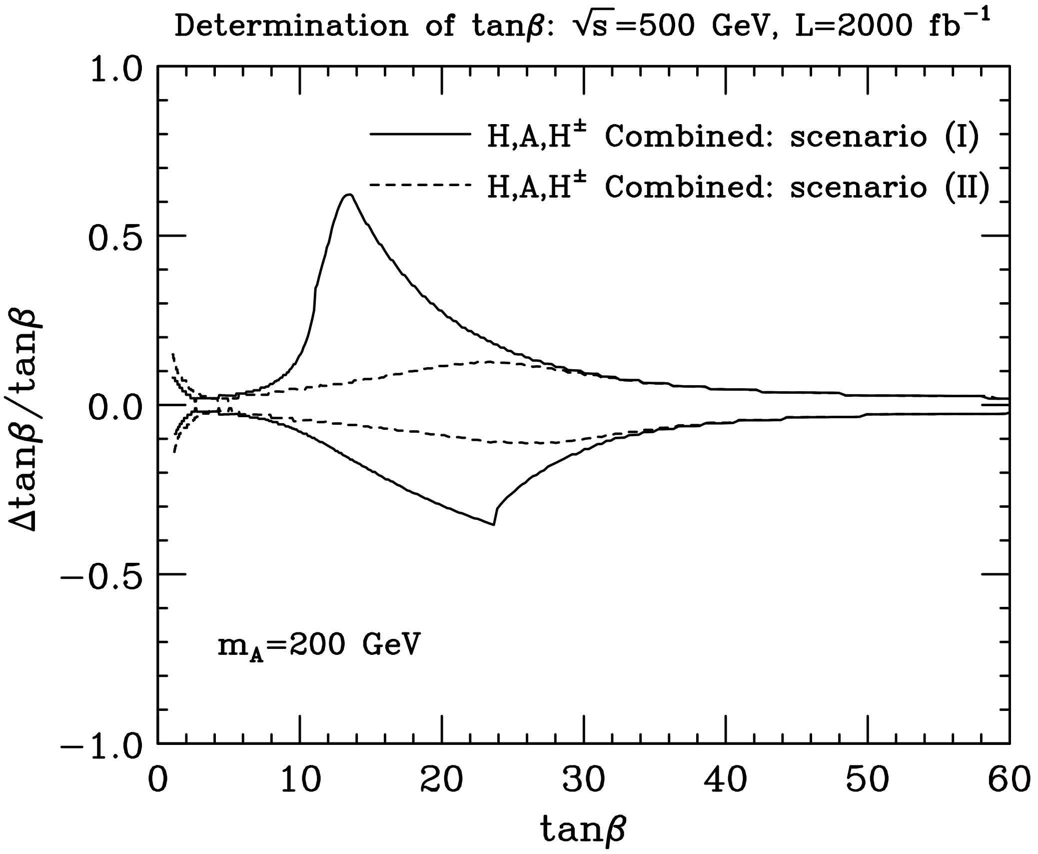
Intrinsic resolution $\Gamma_{\rm res} = 5$ GeV.



Combined $H^{\pm}$ Results



H/A and $H^{\pm}$ Combined Results



A. Sopczak

LHC-LC Relation

LHC ATLAS results based on $H, A, H^{\pm}$ production and decay processes.

Note that there is a wedge-shaped window of moderate $\tan\beta$ and $(m_{\rm h}, m_{\rm A}) \gtrsim 200$ GeV for which the A, H and $H^{\pm}$ are all unobservable.

In this wedge, the only Higgs boson that is detectable at the LHC is the light SM-like Higgs boson, h. Precision measurements of the properties of the h typically only provide weak sensitivity to $\tan\beta$, and will not be considered here.

The lower $\tan\beta$ bound of this moderate-$\tan\beta$ wedge is defined by the LEP-2 limits, $\tan\beta \sim 3$ for $(m_{\rm h}, m_{\rm A}) \sim 200$ GeV, falling to $\tan\beta \sim 2.5$ for $(m_{\rm h}, m_{\rm A}) \gtrsim 250$ GeV (maximal mixing scenario).

The upper $\tan\beta$ limit of the wedge is at $\tan\beta \sim 7$ for ($m_{\rm h}$,$m_{\rm A}$) $\sim$ 200 GeV rising to $\tan\beta \sim 15$ at ($m_{\rm h}$,$m_{\rm A}$) $\sim$ 500 GeV. For either smaller or larger $\tan\beta$ values, the heavy MSSM Higgs bosons can be detected and their production rates and properties will provide sensitivity to $\tan\beta$.

Summary of current LHC results: The reactions that have been studied at the LHC are the following.

1. $H \to ZZ \to 4\ell$

   The best accuracy that can be achieved at low $\tan\beta$ is obtained from the $H \to ZZ \to 4\ell$ rate: $\Delta\tan\beta/\tan\beta = \pm 0.1$ at $\tan\beta = 1$ rising to $> \pm 0.3$ by $\tan\beta = 1.5$ for $m_H = 300$ GeV. For $m_H < 2m_Z$, $\tan\beta$ cannot be measured via this process.

2. $gg \to H + gg \to A \to \tau^+\tau^-, \mu^+\mu^-$ and $gg \to b\bar{b}H + b\bar{b}A \to \mathrm{b\bar{b}}\tau^+\tau^-, \mathrm{b\bar{b}}\mu^+\mu^-$

At high $\tan\beta$ and taking $(m_{\mathrm{h}}, m_{\mathrm{A}}) = 150$ GeV, $gg \to H \to \tau^+\tau^-$, $gg \to A \to \tau^+\tau^-$, and $gg \to \mathrm{b\bar{b}}A + \mathrm{b\bar{b}}H \to \mathrm{b\bar{b}}\tau^+\tau^-$ rates can be used: $\tan\beta$ accuracy ± 0.15 at $\tan\beta = 5$, improving to ± 0.06 at $\tan\beta = 40$. The corresponding rates with $H, A \to \mu^+\mu^-$ yield a somewhat better determination at higher $\tan\beta$: ± 0.12 at $\tan\beta = 10$ and ± 0.05 at $\tan\beta = 40$.

Interpolating, we estimate that at $(m_{\mathrm{h}}, m_{\mathrm{A}}) \sim 200$ GeV the error on $\tan\beta$ based on these rates would be smaller than ± 0.1 for $\tan\beta \gtrsim 13$, asymptoting to ± 0.05 at large $\tan\beta$.

$\tan\beta$ sensitivity for $\tan\beta < 20-30$ is largely due to loop-induced $gg \to A$ and $gg \to H$ production processes. Thus, significant knowledge of the particles, including SUSY particles, that go into the loops responsible for the $gg \to H$ and $gg \to A$ couplings.

3. $gg \to t\bar{b}H^- + \bar{t}bH^+$ with $H^\pm \to \tau^\pm \nu$

   The $tbH^\pm \to tb\tau\nu$ rate gives a fractional $\tan\beta$ uncertainty, $\Delta\tan\beta/\tan\beta$, ranging from ± 0.074 at $\tan\beta = 20$ to ± 0.054 at $\tan\beta = 50$. Clearer signal to interpret for $\tan\beta$.

Sensitivity to $\tan\beta$ deriving from direct measurements of the decay widths has not been studied by the LHC experiments. One can expect excellent $\tan\beta$ accuracy at the higher $\tan\beta$ values for which the $gg \to b\bar{b}\mu^+\mu^-$ signal for the H and A is detectable.

Relation to LHC $\tan\beta$ Determination

MSSM: (m_h,m_A) = 200 GeV. $\Delta\tan\beta/\tan\beta$, $\mathcal{L} = 2000$ fb^{-1} LC, cf. $\mathcal{L} = 300$ fb^{-1} LHC

LHC maximal mixing results from combining the determinations H, A production from ATLAS, TDR, CERN/LHCC/99–14/15 and $H^\pm$ production from K.A. Assamagan, etal, EPJdirect C **4**, 9 (2002).

$\tan\beta$ range	LHC	LC (case I)	LC (case II)
1	0.12	0.15	0.1
1.5–5	very large	0.03–0.05	0.03–0.05
10	0.12	0.1	0.05
13–30	0.05	0.6–0.1	0.05–0.1
40–60	0.05–0.03	0.05–0.025	0.05–0.025

Conclusions

- Korea LCWS proceedings: hep-ph/0211123.
- LC Neutral and charged Higgs boson channels lead to high $\tan\beta$ precision over a large parameter range.
- Preprint: hep-ph/0212151.
- LC-LHC : Regardless of relative LHC vs LC errors, clean LC environment will provide an important and independent measurement.
- Different uncertainties associated with $\tan\beta$ determination at hadron and e^+e^- collider because of the different backgrounds.
- LHC and LC measurements of $\tan\beta$ will be highly complementary in that systematic errors involved will be very different.