The Physics Potential of a Future Linear e^+e^- Collider

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Outline

- Introduction
- Higgs boson
  - production cross section
  - decay branching fraction
  - potential(s)
- Supersymmetry
  - scalar muon mass and spin
  - scalar top mass and mixing angle
- Conclusions

Introduction

- e^+e^- **Linear Collider addresses fundamental questions:**
  How is the electroweak symmetry broken?
  How do particles obtain masses?

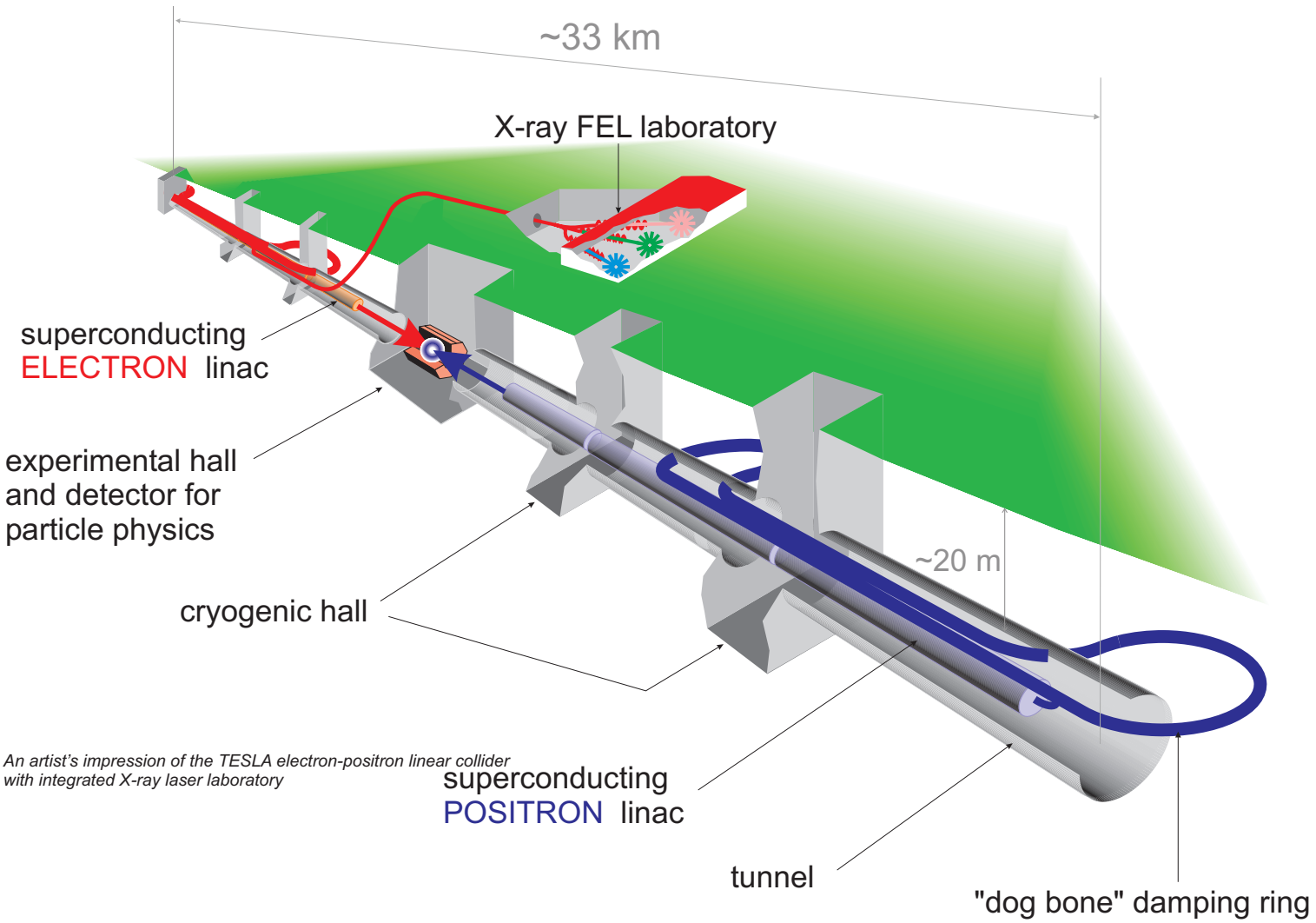
  If the the Higgs mechanism is the correct description, there must be a physical (observable) Higgs boson.

- **The Standard Model is unlikely the final theory:**
  If the world is Supersymmetric, new particles will be identified and their properties measured.

  Tevatron, LHC: likely first signals,
  LC: complementary information to understand the underlying theory.

- **Designs: TESLA (Europe), NLC (USA), JLC (Asia)**
  Technical challenges:
  Energy: 500 GeV, extensible to 1 TeV
  Luminosity: 500 fb^{-1} per year

Schematic View of TESLA

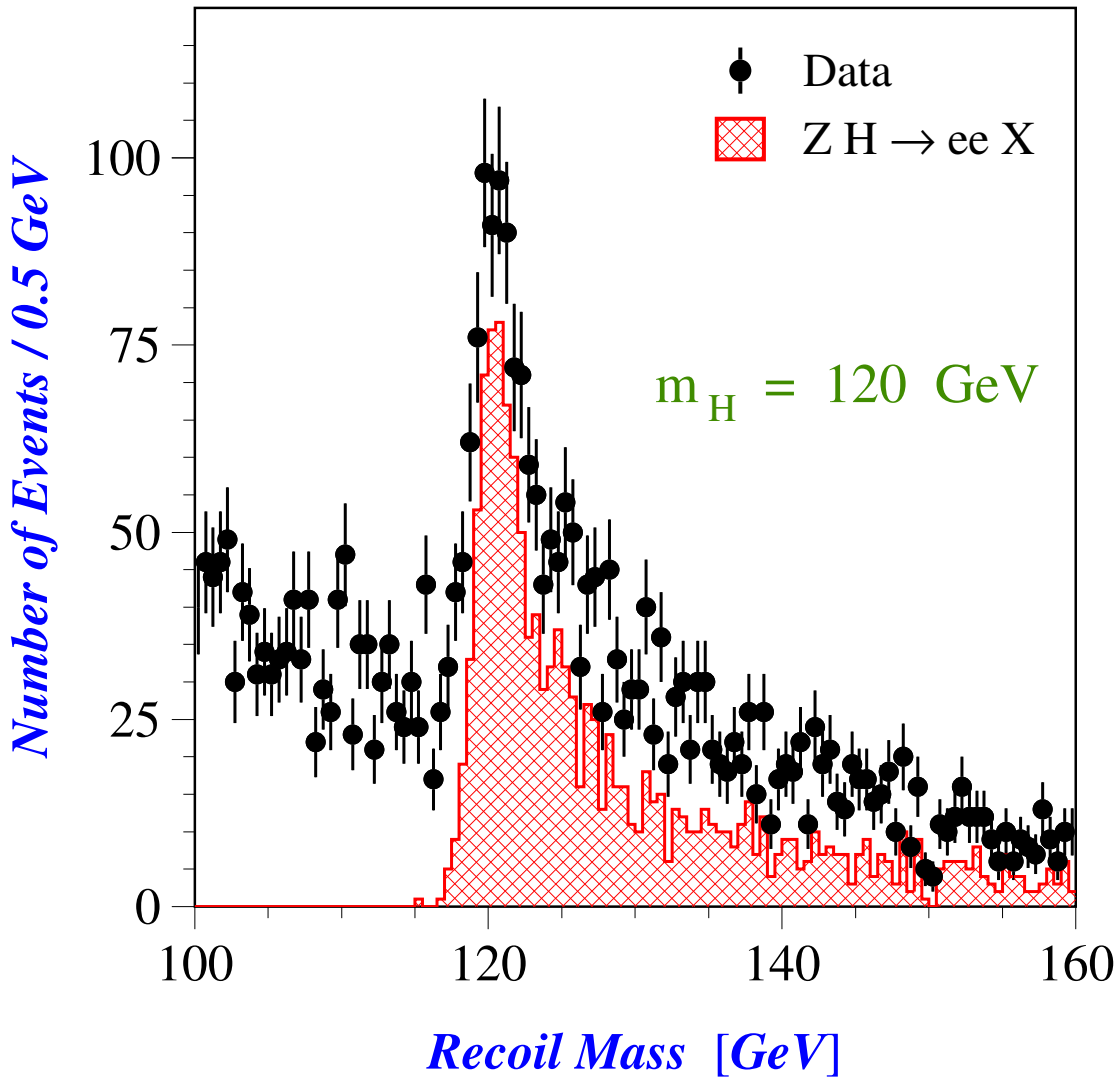


An artist's impression of the TESLA electron-positron linear collider with integrated X-ray laser laboratory

Total Cross Section

$e^+e^- \rightarrow HZ \rightarrow Hl^+l^-$

- **mass recoiling to lepton pair**
- **independent of branching ratio to measure total decay width Γ_H**
- **absolute normalization of branching ratios**

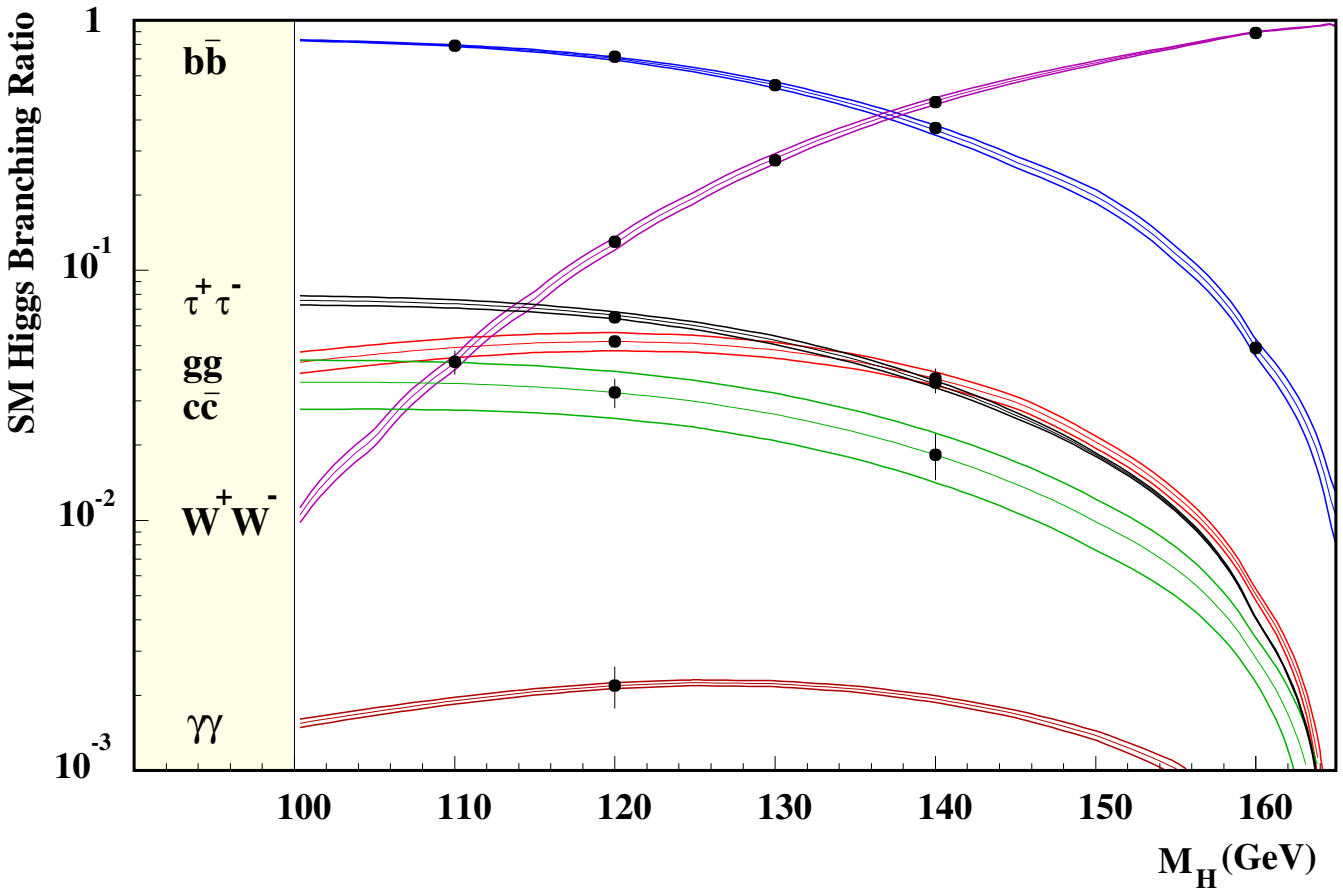


Precision: $\approx 2.5\%$

Decay Branching Ratio

$e^+e^- \to HZ$

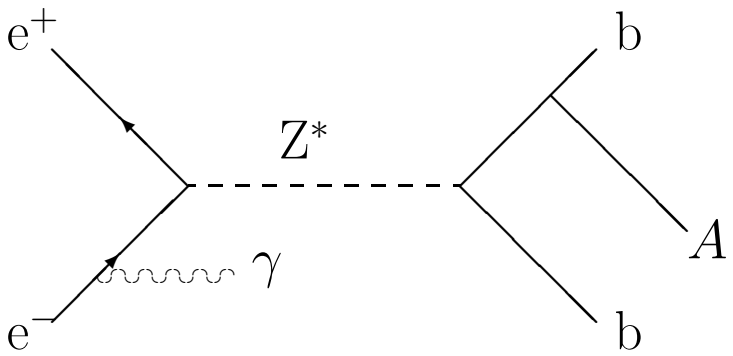
- $\mathrm{Br}(H \to b\bar{b}) = \Gamma(H \to b\bar{b})/\Gamma(H \to \text{anything})$
- **excellent b- and c-quark tagging needed:**
  UK LCFI collaboration.



- **Similar theoretical and predicted experimental errors.**
- **Precision measurements for all decay modes.**

$b\bar{b}A$ Simulation

$e^+e^- \rightarrow b\bar{b} \rightarrow b\bar{b}A \rightarrow b\bar{b}b\bar{b}$



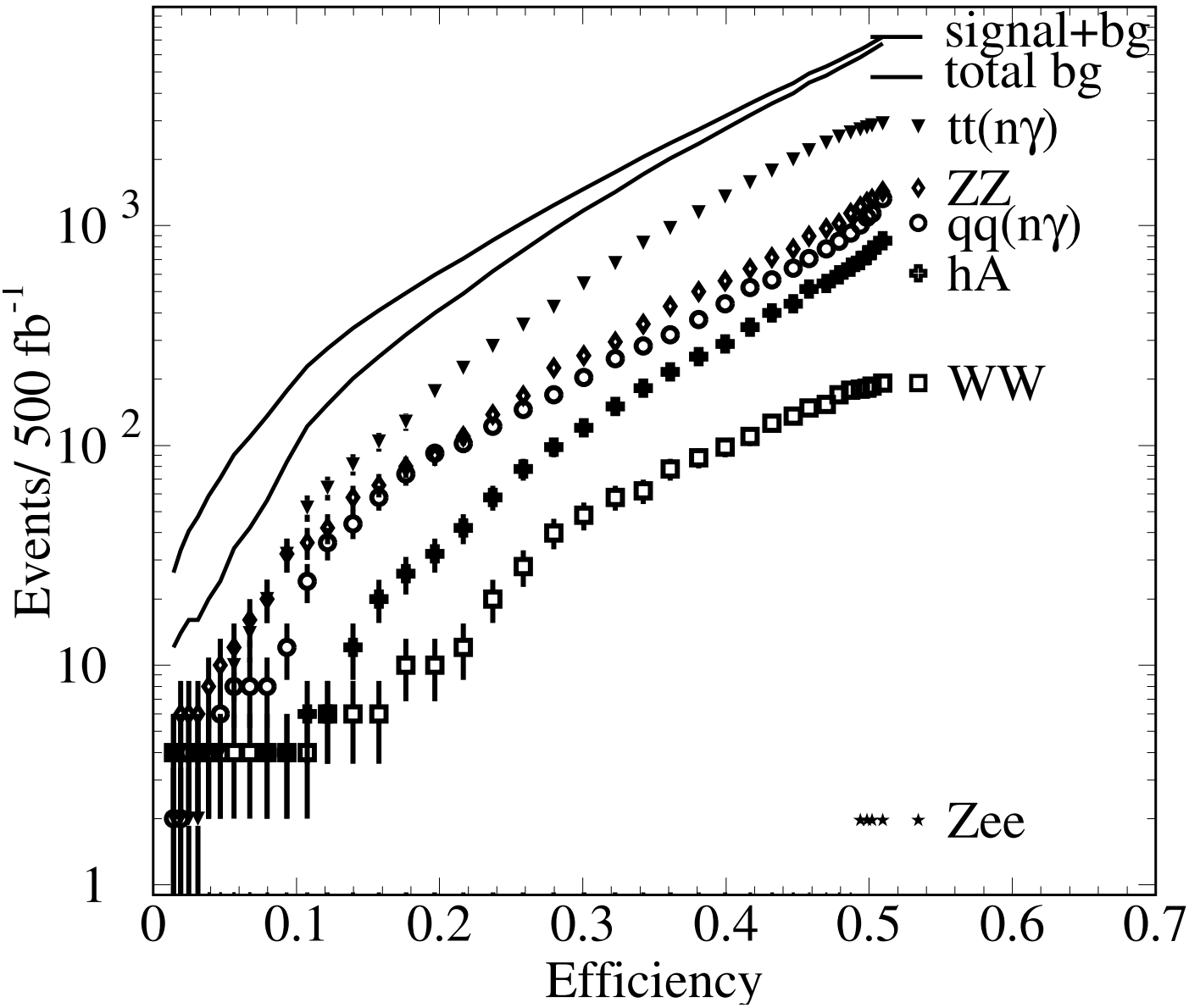
Higgs model with two Higgs Doublets

$\tan\beta = V_1/V_2$

$b\bar{b}A$ coupling $\propto \tan\beta$, thus rate $\propto \tan^2\beta$, and $b\bar{b}A$ rate determines $\tan\beta$.

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

Signal and Background



$b\bar{b}A$ Results for 500 fb^{-1}

For $\tan\beta = 50$ and $m_A = 100$ GeV:

$$\Delta \tan^2\beta / \tan^2\beta = \Delta N_{\text{signal}} / N_{\text{signal}}$$
$$= \sqrt{N_{\text{signal}} + N_{\text{background}}} / N_{\text{signal}} = 0.14.$$

$\Delta \tan\beta / \tan\beta = 7\%.$

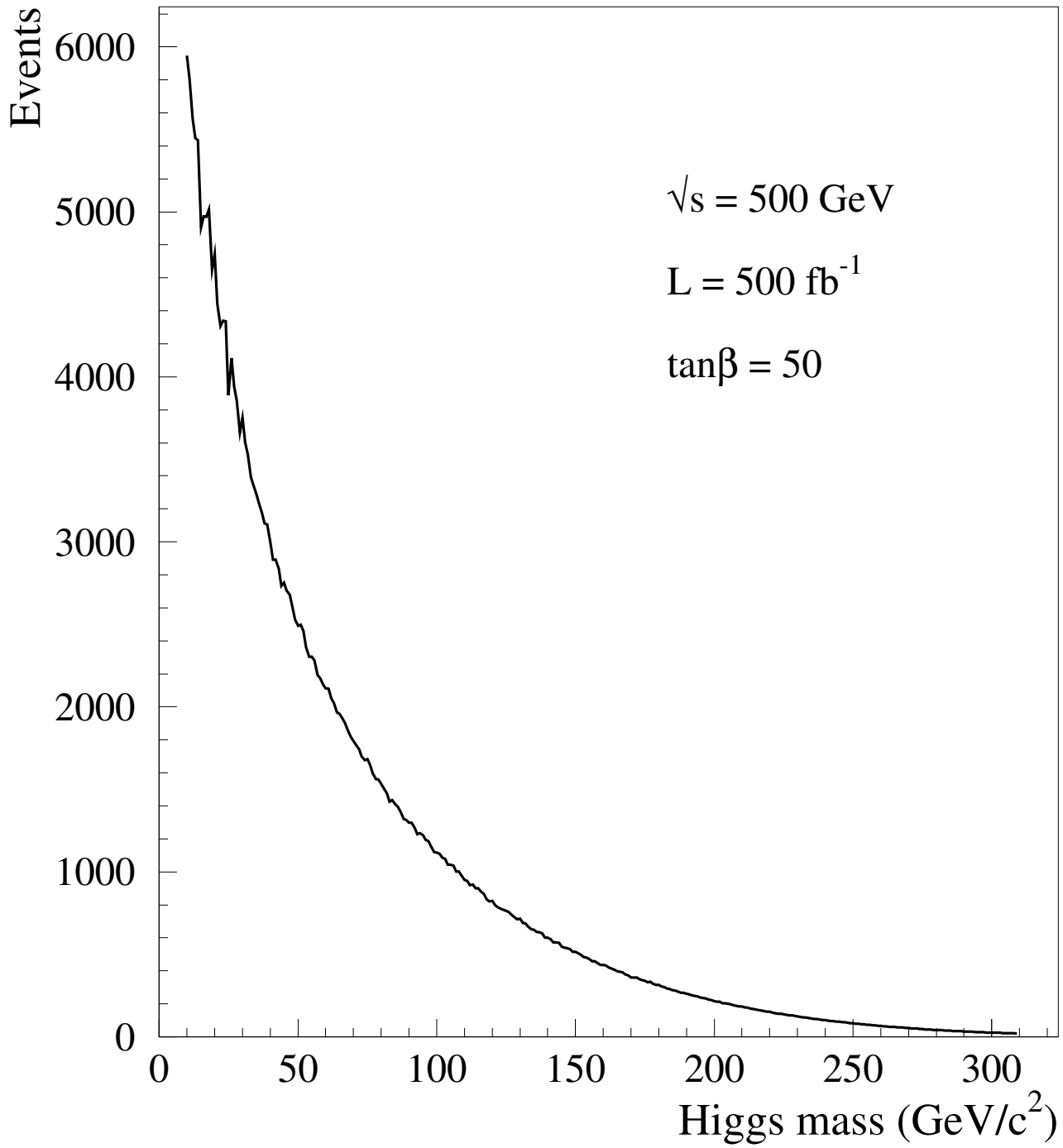
$b\bar{b}h$ or $b\bar{b}H$ could double the number of signal events and have the same $\tan\beta$ dependence:

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

$\Delta \tan\beta / \tan\beta = 4\%.$

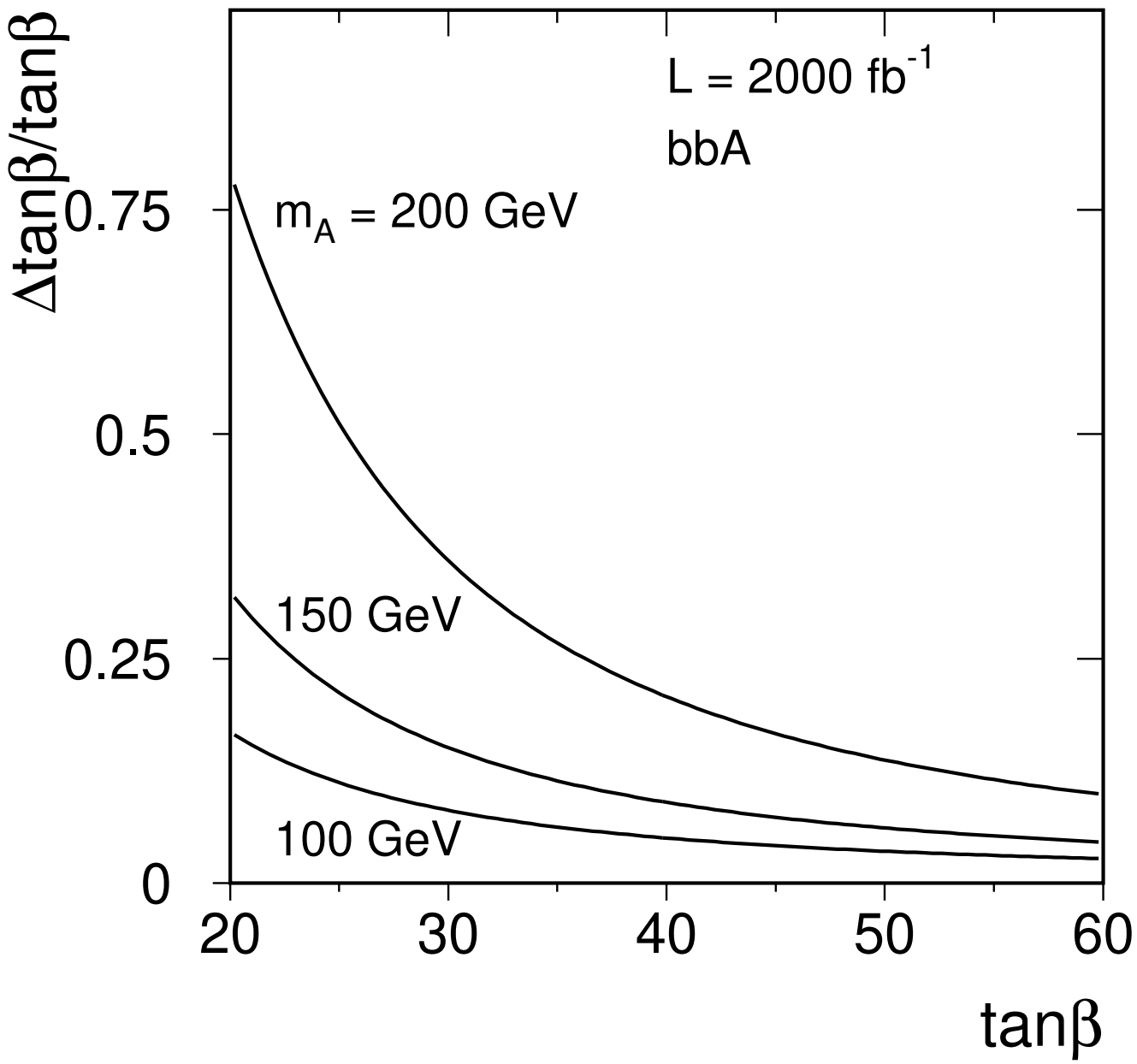
Experimental challenge:
at 10% efficiency, $\Delta \tan\beta / \tan\beta < 5\%$ requires
$\Delta\epsilon/\epsilon < 0.1$, thus $\Delta\epsilon < 1\%$.

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



At 100 GeV: 1000 events.
At 200 GeV: 200 events.

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



How to prove Supersymmetry ?

- **Every Standard Model particle has a superpartner.**

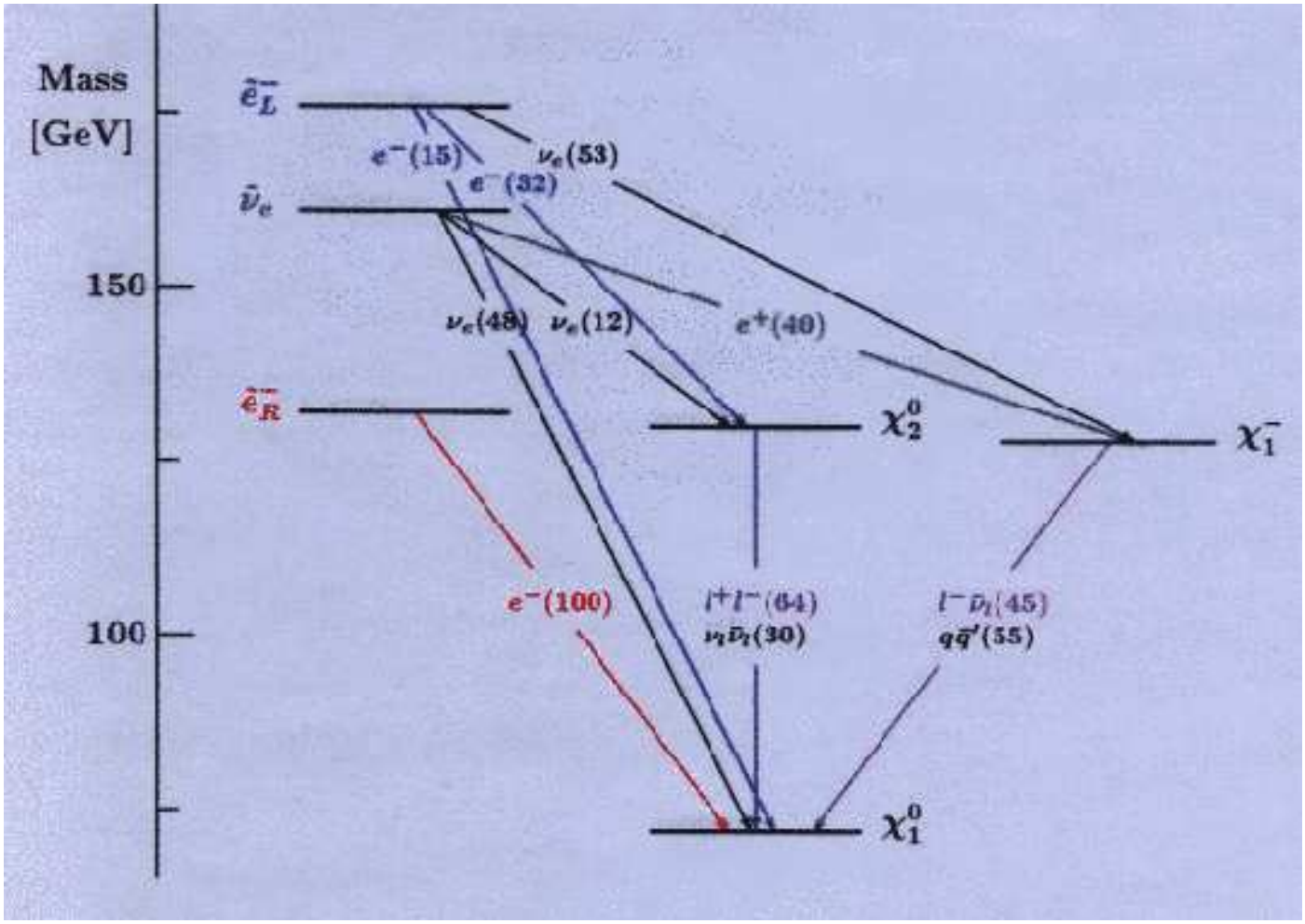
- **Need to find evidence that observations which are consistent with Supersymmetry are not due to other reactions.**

- **Criteria:**
  - **superpartners differ by spin 1/2**
  - **their gauge quantum numbers are identical**
  - **their couplings are identical**

- **Precision measurements:**
  - **branching ratios**
  - **mass**
  - **cross-sections**
  - **angular distribution**

Possible Decay Spectrum

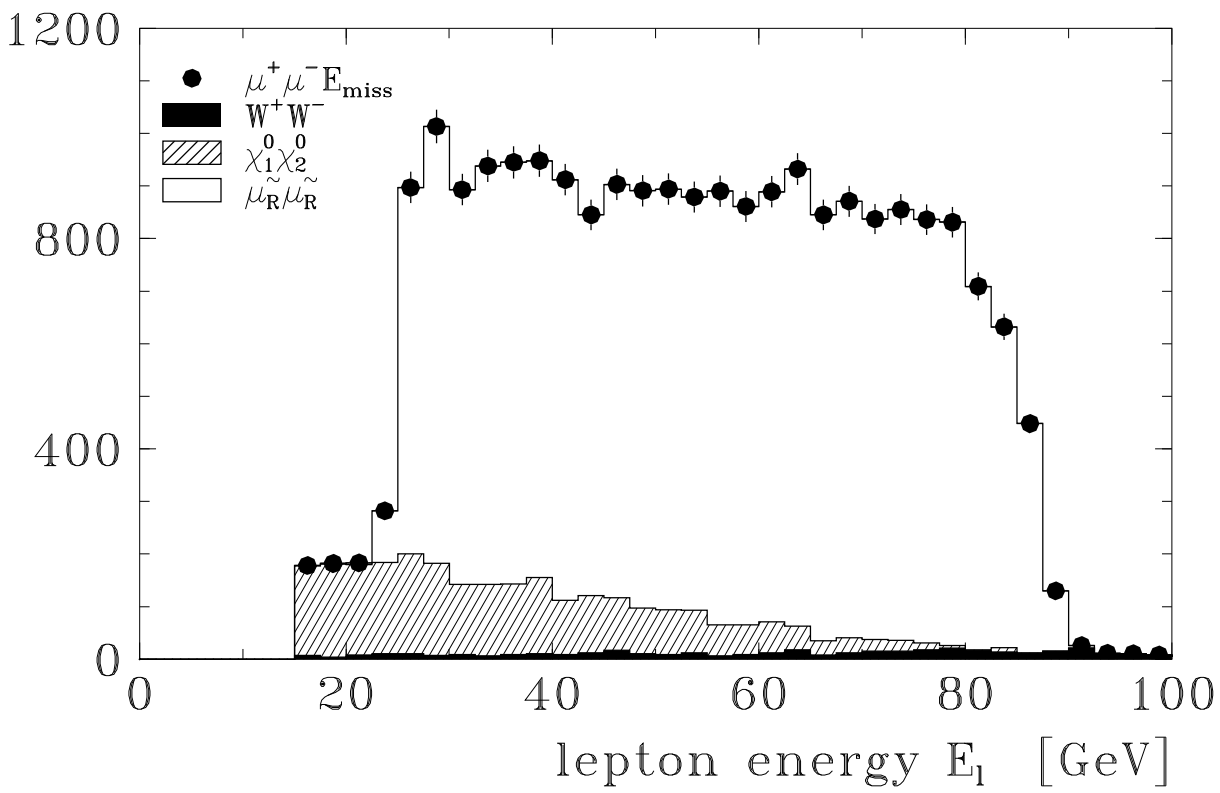
Measurements of branching fractions



Scalar Muons

$e^+e^- \rightarrow \tilde{\mu}_R^+ \tilde{\mu}_R^+ \rightarrow \mu^+ \tilde{\chi}^0 \mu^- \tilde{\chi}^0$

Flat spectrum of two-body decays:

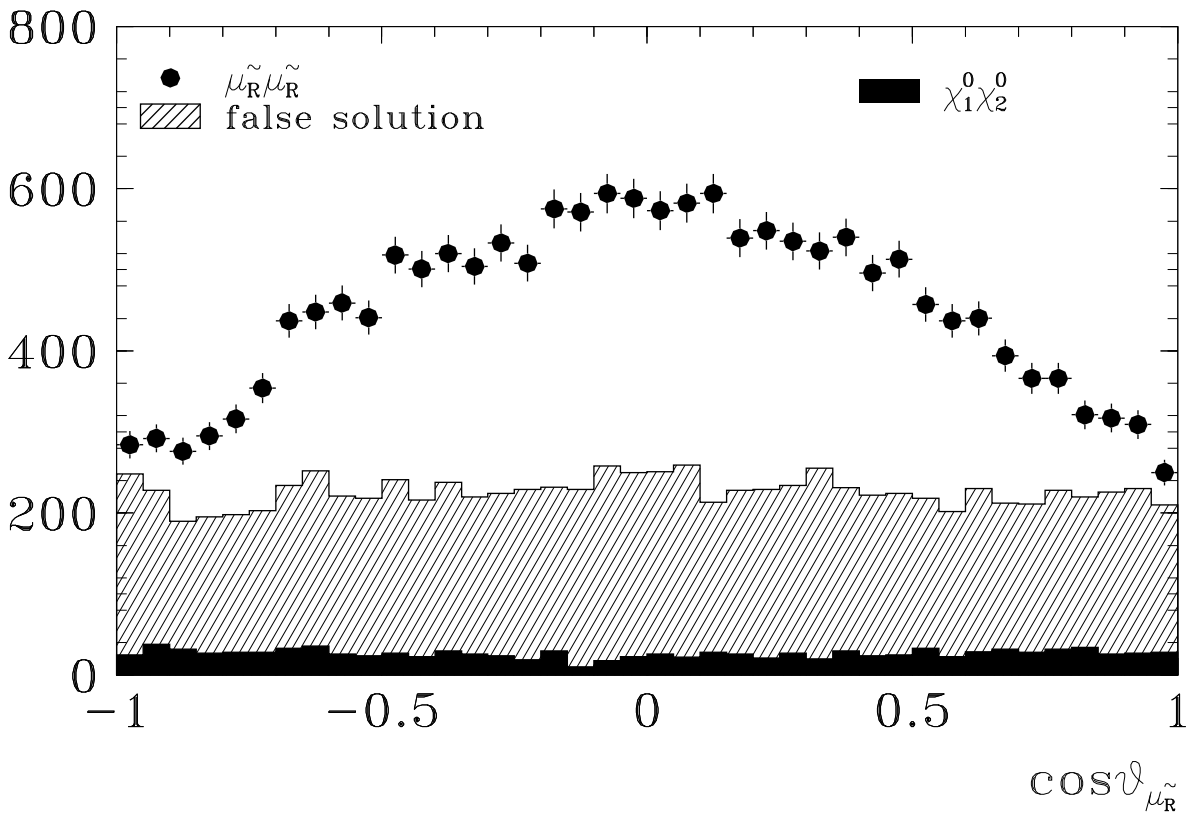


$m_{\tilde{\mu_R}} = 132.0 \pm 0.3$ GeV and $m_{\tilde{\chi^0}} = 71.9 \pm 0.2$ GeV

Angular Distribution

Reconstruction from μ direction

Expect $\sin^2\Theta$ production distribution for Spin 0.



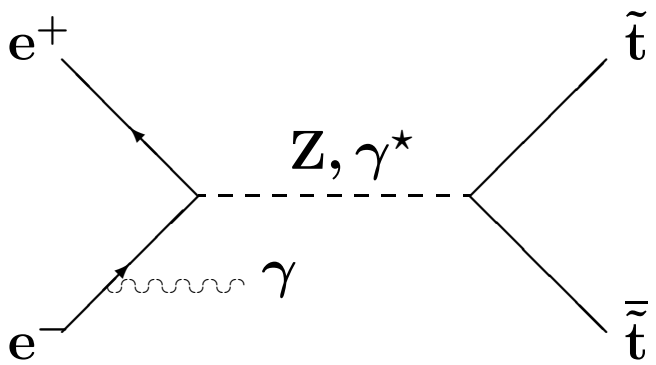
Scalar Top Quarks

- **SUSY partners of the quark helicity states.**
- **mixing proportional to the quark mass, large mixing, large mass splitting for the third generation.**

$$\tilde{t}_1 = \tilde{t}_L \cos\theta_{LR} + \tilde{t}_R \sin\theta_{LR}$$

Goal :
How well can we determine
$m_{\tilde{t}_1}$ **and** $\cos\theta_{LR}$ **?**

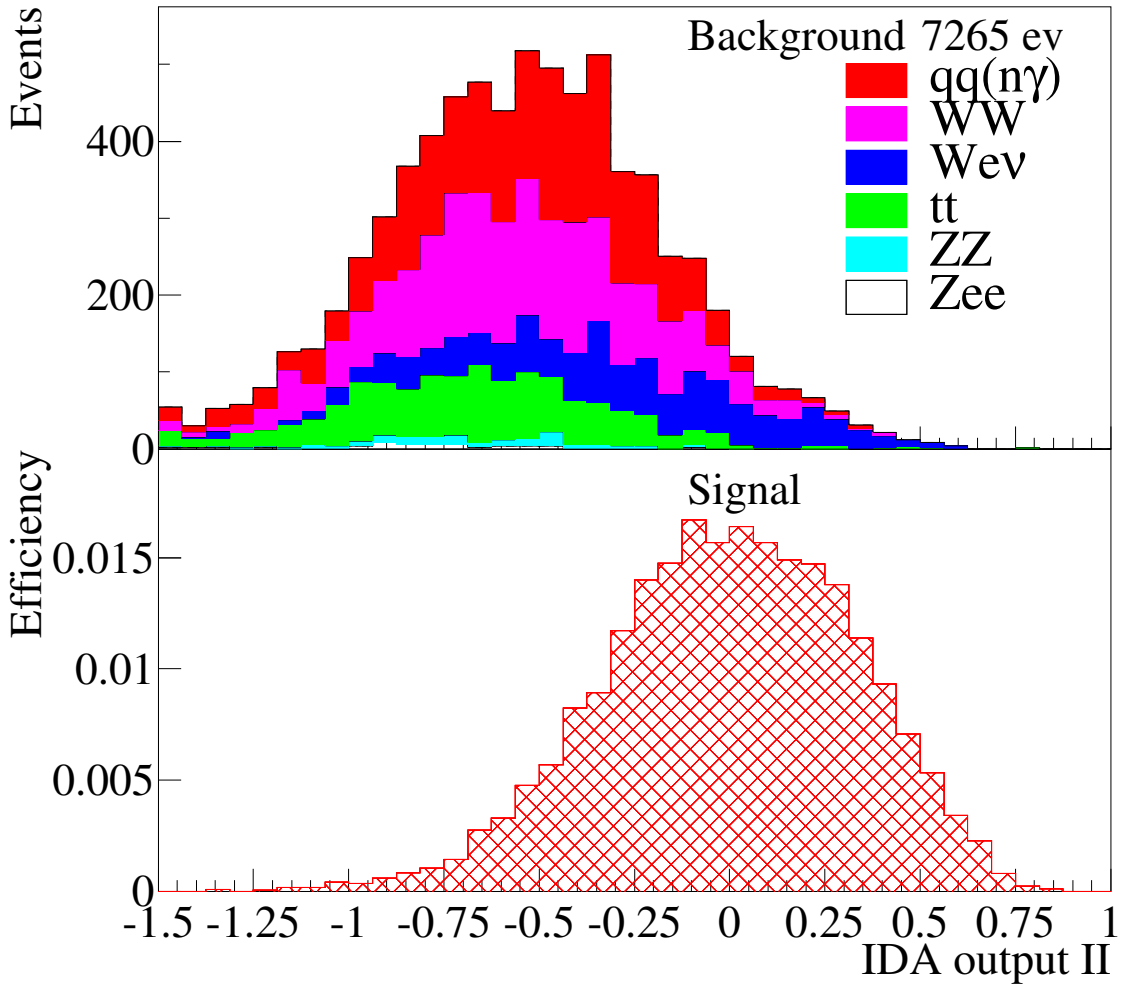
Production:



Decay:

- **two-body decays :** $\tilde{t}_1 \to c\tilde{\chi}_1^0$, $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$
- **three-body decays:** $\tilde{t}_1 \to bl\tilde{\nu}_l$

Signal and Background



Importance of Beam-Polarization

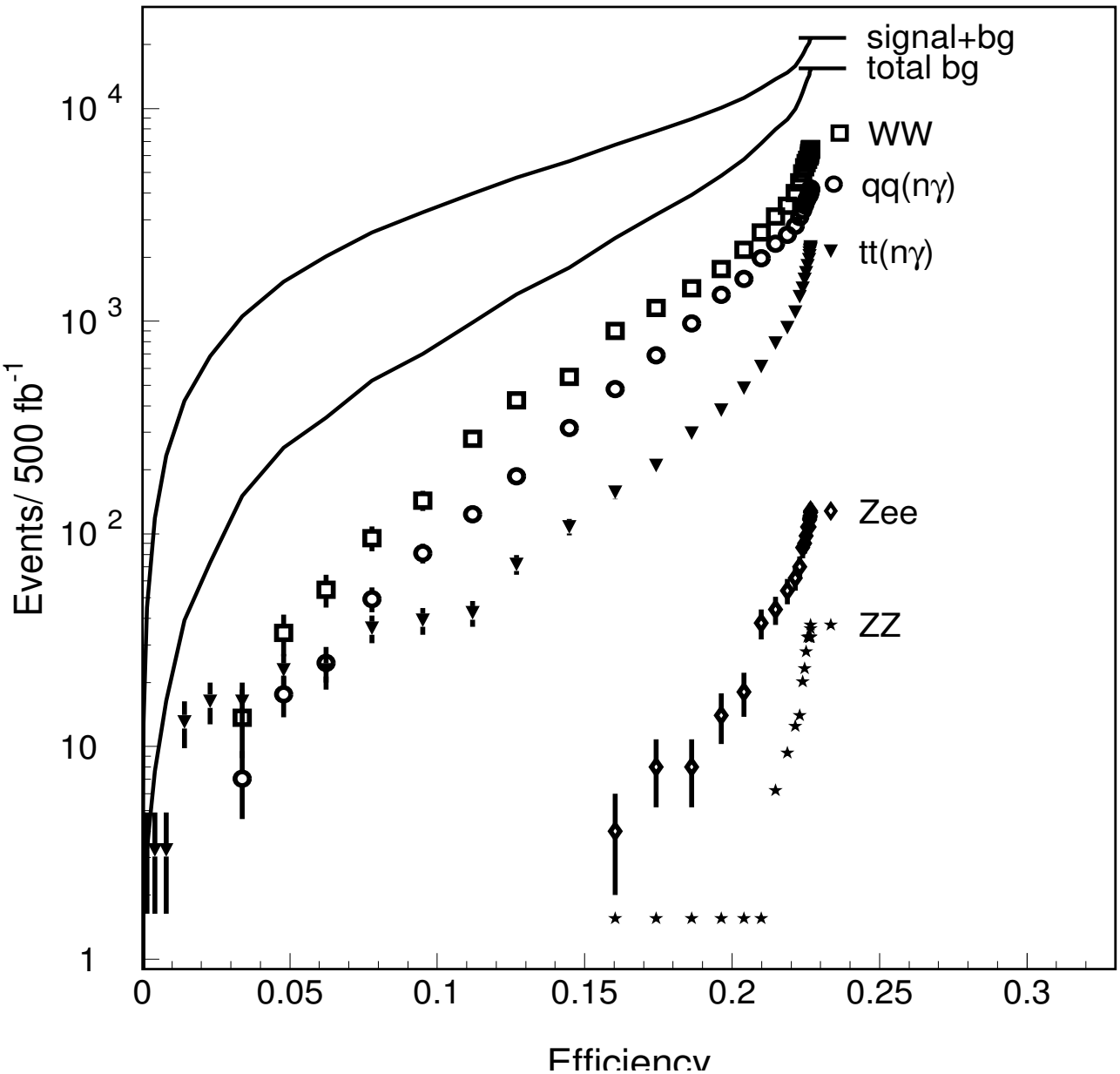
Polarization states : e^-/e^+ $-0.8/0.6$ versus $0.8/-0.6$

Polarization e^-/e^+	$\tilde{t}_1\bar{\tilde{t}}_1$ fb	$We\nu$ pb	WW pb	$q\bar{q}$ pb	$t\bar{t}$ pb	ZZ pb
-0.8/0.6	81.81	10.72	22.64	21.49	1.113	0.909
0/0	53.46	5.59	7.86	12.1	0.574	0.864
0.8/-0.6	76.41	1.780	0.786	13.99	0.542	0.464

better signal/background ratio for $0.8/-0.6$;
use this machine operation for discoveries.

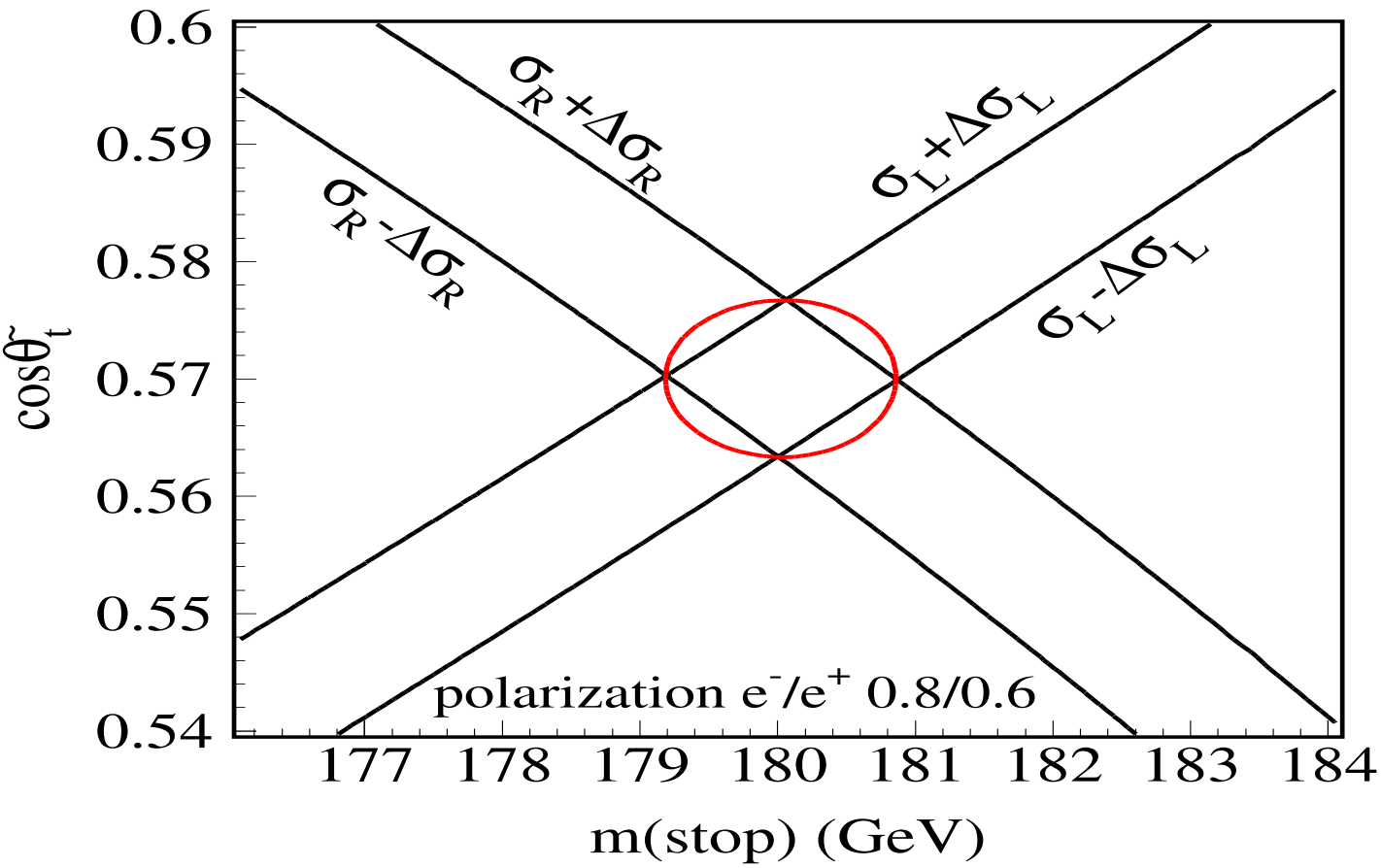
Scalar Top Signal and Background

$-0.8/0.6$ polariation



Scalar Top Results

Cross section measurement for
Left $(-0.8/0.6)$ and
Right $(0.8/-0.6)$ beam polarization.



$\Delta m_{\tilde{t}_1} = 0.8$ **GeV and** $\cos\theta_{LR} = 0.008$

Conclusions

- **After a first discovery at the Tevatron or the LHC, a detailed understanding of the new processes is difficult.**

- **Identification of Higgs boson properties.**

- **Unique precision in the Higgs boson sector to understand electroweak-symmetry breaking.**

- **Essential precision measurements establish Supersymmetry**
  as they were crucial at LEP for the Standard Model.

- **Precise determination of spin, mass and mixing angles.**

- **Milestones:**
  March 2001: TESLA TDR,
  summer 2001: Snowmass meeting

Conclusions

Report by the ECFA (European Committee for Future Accelerators) Working Group on "The future of accelerator-based particle physics in Europe":

"*The realisation, in as timely a fashion as possible, of a world-wide collaboration to construct a high luminosity e^+e^- linear collider with an energy range up to at least 400 GeV as the next accelerator project in particle physics; decisions concerning the chosen technology and the construction site for such a machine should be made soon*".

Approved in Budapest in July 2001

DOE/NSF High-Energy Physics, Advisory Panel, Planning for U.S. High-Energy Physics (submitted and approved by HEPAP- January 28, 2002)

We recommend that the highest priority of the U.S.program be a high-energy, high-luminosity, electron-positron linear collider, wherever it is built in the world. This facility is the next major step in the field and should be designed, built and operated as a fully international effort.