Physics Goals
of the
Linear Collider

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SLAC, Stanford U.

previous workshops of the LCWS series
have addressed the question:

Why do we need a linear collider?

they made clear that the LC has a
broad and rich physics program

Now we must turn to the next question:

How difficult are the measurements?
How well must they be done?

many issues arise in thinking about the
linear collider detector:

tracking, calorimetric resolutions

vertex detection:
how high efficiency is enough?

hermeticity

solenoidal field vs. machine backgrounds

These questions must be evaluated
in the context of physics measurements.

first, what is the role of the LC experiments?

If there are **new particles**
in the LC energy region,
the LC will discover them

New particles should also be discovered
earlier: at LEP2, Tevatron, LHC

The primary role of the LC experiments
will be to turn the signs and hints from
these experiments into the
textbook data on the next scale of physics.

for this, the LC detector must be
a **precision instrument.**

As I review the LC physics,
I will point out the **experiments** that
the LC detector **must be** able to do.

This is the next challenge in planning
the LC physics program

The success of the Standard Model brings into relief the question of its foundations,

in particular, the question:

What is the mechanism of electroweak symmetry breaking?

scale of electroweak symmetry breaking:

$$m_W = \frac{g}{2} v \quad \longrightarrow \quad v = 246 \text{ GeV}$$

so, a LC with $\sqrt{s} \sim 1$ TeV ought to be able to discover and prove the answer to this question

I will discuss three approaches to this problem:

1. $e^+e^- \to f\bar{f}$

   search for **contact interactions**

2. strong-coupling route to EWSB

   $e^+e^- \to W^+W^-, t\bar{t}$

3. weak-coupling route to EWSB

   $e^+e^- \to Z^0 h^0$, SUSY

$e^+e^- \to f\bar{f}$

the Standard Model gives simple, precise formulae:

$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to f_L \bar{f}_R)$$

$$= \frac{\pi\alpha^2}{2s}\left[\, Q_f + \frac{(\frac{1}{2} - s_W^2)(I^3 - Q_f s_W^2)}{c_W^2\, s_W^2}\,\frac{s}{s - m_Z^2}\,\right]^2$$

$$\cdot\,(1 + \cos\theta)^2$$

deviations from this formula signal

new Z0 bosons

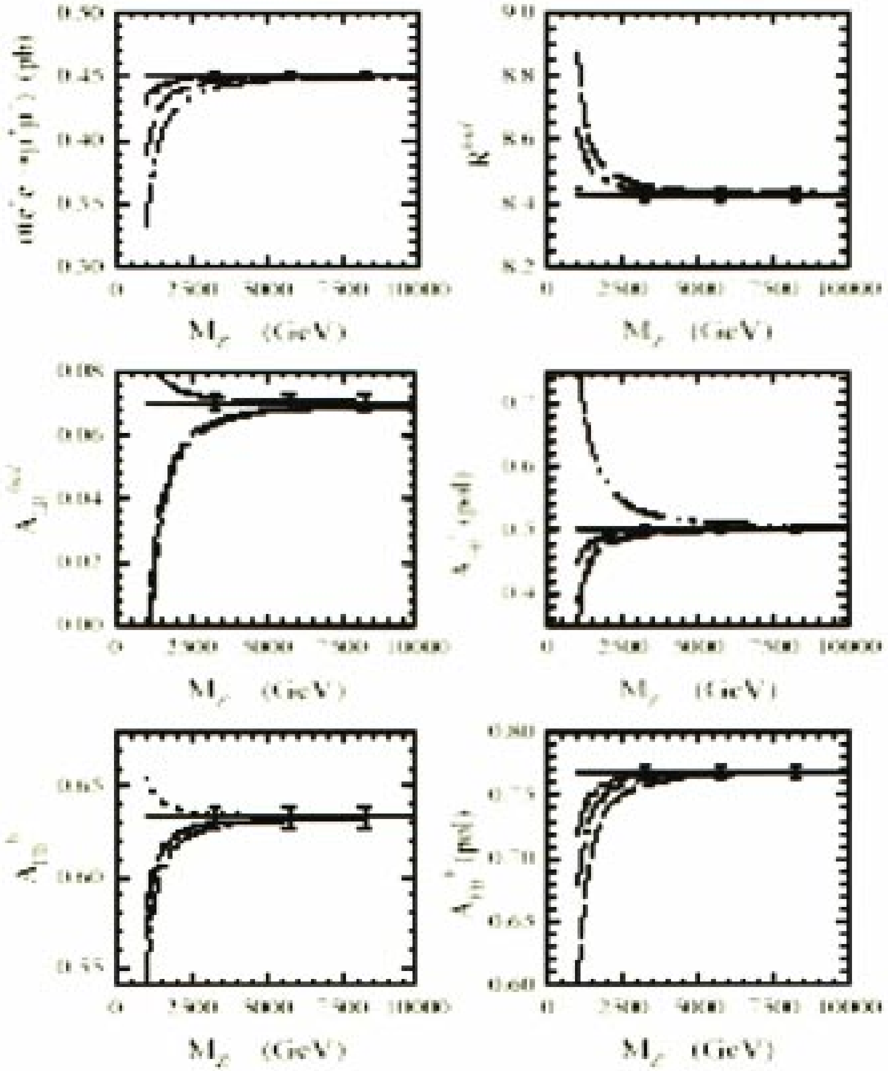
contact interactions, fermion compositeness

other exotic exchanges

e.g., spin 2 from higher dimensions

examples of Z0' effects

S. Godfrey



√s = 500 GeV

a linear collider with $\sqrt{s} \sim 1$ TeV

must be able to probe to

$m(Z^0) \sim 4$ TeV (match to LHC)

$\Lambda \sim 10$ TeV

independently, in couplings to

b , c , τ_L / τ_R , μ , e

Strong-Coupling Route to EWSB

$e^+e^- \to W^+W^-$

measure anomalous $WW\gamma$, WWZ couplings
to 10^{-3} level

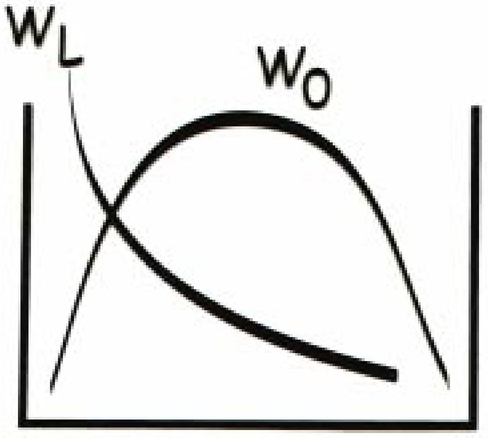
and

model for nonstandard reactions with
decay to W

most important Standard Model background
(control using e^-_R polarization)

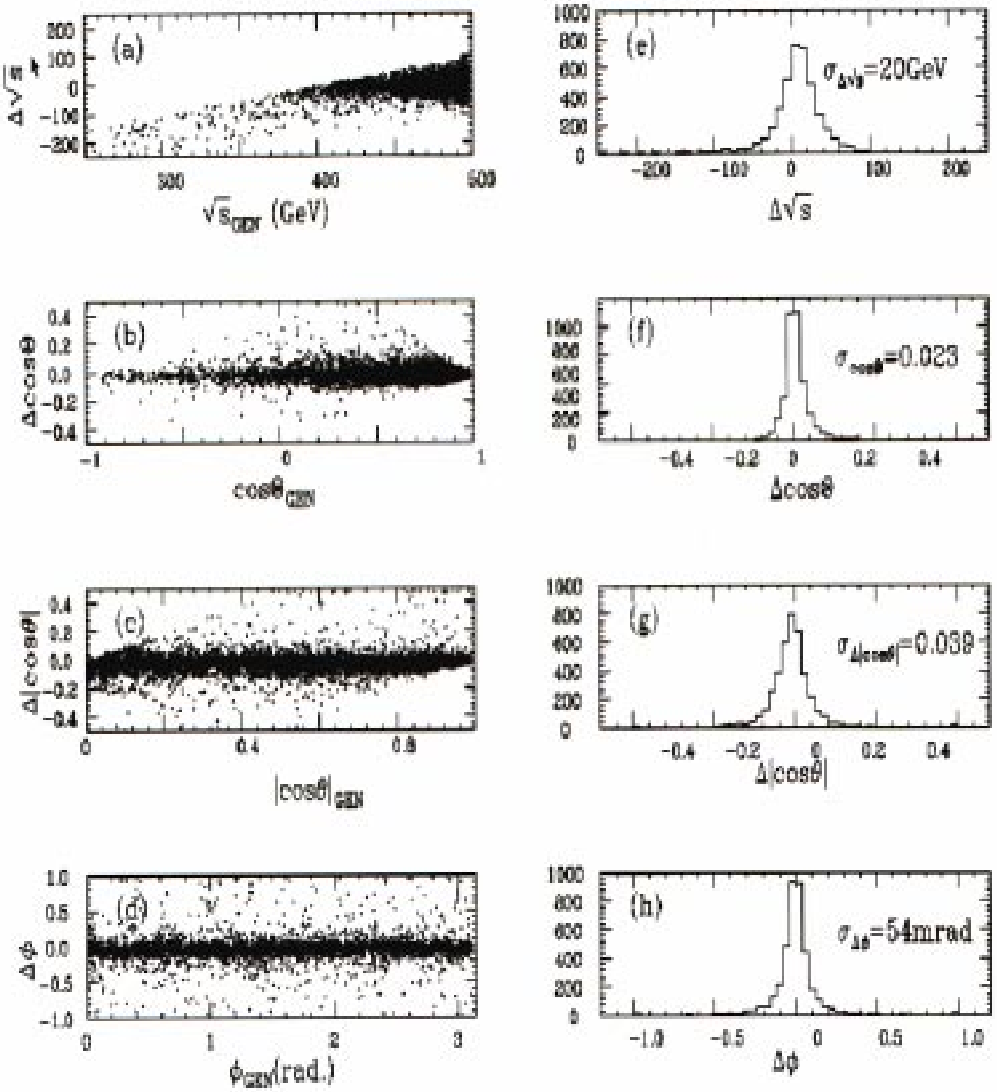
the key to understanding the W is to perform a polarization analysis:

W_0 -> π^0 of the spontaneously broken Higgs sector



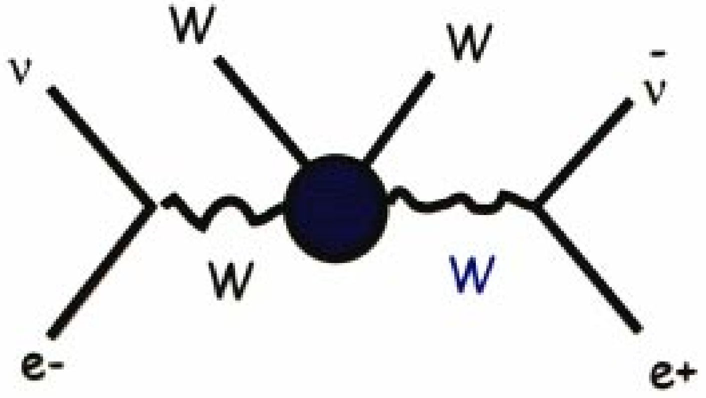
cos θ

A. Miyamoto



(a)
$\Delta\sqrt{s}$
200
100
0
-100
-200
300
400
500
$\sqrt{s}_{GEN}$ (GeV)
(e)
$\sigma_{\Delta\sqrt{s}}$=20GeV
1000
800
600
400
200
0
-200
-100
0
100
200
$\Delta\sqrt{s}$
(b)
$\Delta\cos\theta$
0.4
0.2
0.0
-0.2
-0.4
-1
0
1
$\cos\theta_{GEN}$
(f)
$\sigma_{\cos\theta}$=0.023
1000
800
600
400
200
0
-0.4
-0.2
0
0.2
0.4
$\Delta\cos\theta$
(c)
$\Delta|\cos\theta|$
0.4
0.2
0.0
-0.2
-0.4
0
0.4
0.8
$|\cos\theta|_{GEN}$
(g)
$\sigma_{\Delta|\cos\theta|}$=0.039
1000
800
600
400
200
0
-0.4
-0.2
0
0.2
0.4
$\Delta|\cos\theta|$
(d)
$\Delta\phi$
1.0
0.5
0.0
-0.5
-1.0
0
1
2
3
ϕ_{GEN}(rad.)
(h)
$\sigma_{\Delta\phi}$=54mrad
1000
800
600
400
200
0
-1.0
-0.5
0
0.5
1.0
$\Delta\phi$

direct studies of the strongly interacting
Higgs sector are possible through



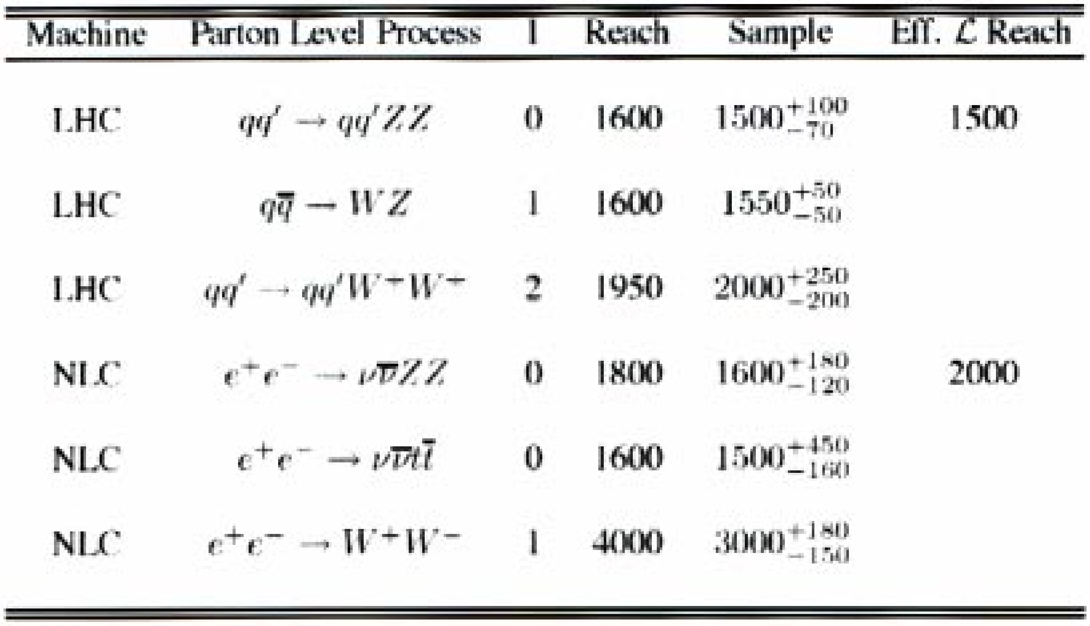
1.5 TeV, 100 fb-1 is comparable to LHC

low rate, background from $\gamma\gamma$

➤ detect W, Z in hadronic modes

e+e- -> $\nu\bar{\nu} t \bar{t}$ gives a direct probe of the new sector coupling to t

Snowmass '96



Machine	Parton Level Process	I	Reach	Sample	Eff. $\mathcal{L}$ Reach
LHC	$qq' \to qq'ZZ$	0	1600	1500^{+100}_{-70}	1500
LHC	$q\overline{q} \to WZ$	1	1600	1550^{+50}_{-50}	
LHC	$qq' \to qq'W^+W^+$	2	1950	2000^{+250}_{-200}	
NLC	$e^+e^- \to \nu\overline{\nu}ZZ$	0	1800	1600^{+180}_{-120}	2000
NLC	$e^+e^- \to \nu\overline{\nu}t\overline{t}$	0	1600	1500^{+450}_{-160}	
NLC	$e^+e^- \to W^+W^-$	1	4000	3000^{+180}_{-150}	

e^+e^- -> $t\,\bar{t}$

the Standard Model already predicts a rich structure:

- $e^-_L e^+$ -> $t\,\bar{t}$ is dominated by forward t_L
- short t lifetime → t retains its polarization
- t -> b W^+ is an effective polarization analyzer

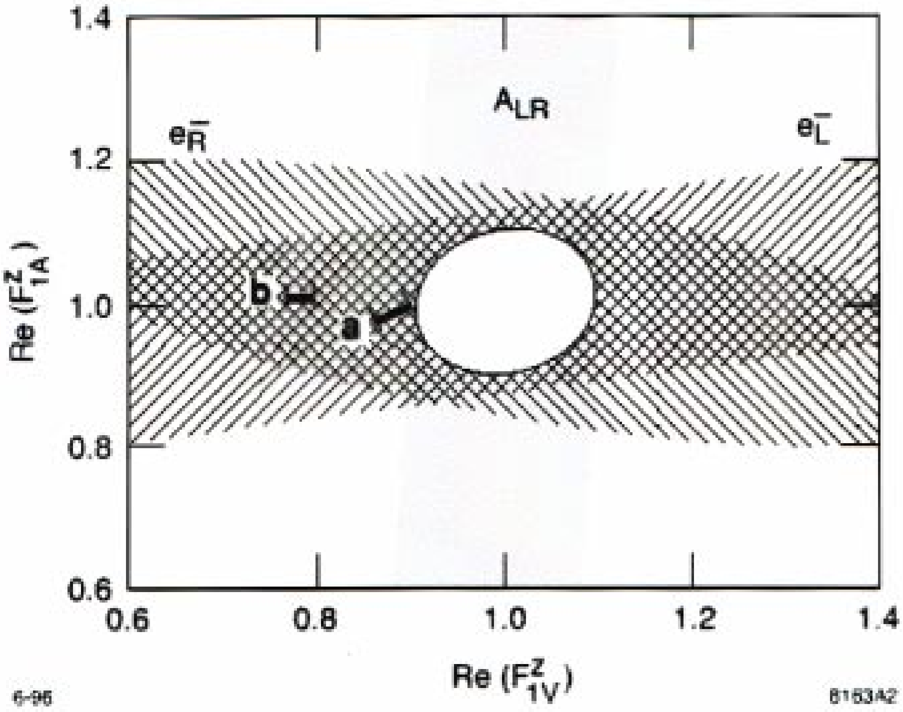
physics issues:

t anomalous couplings,
especially to Z^0

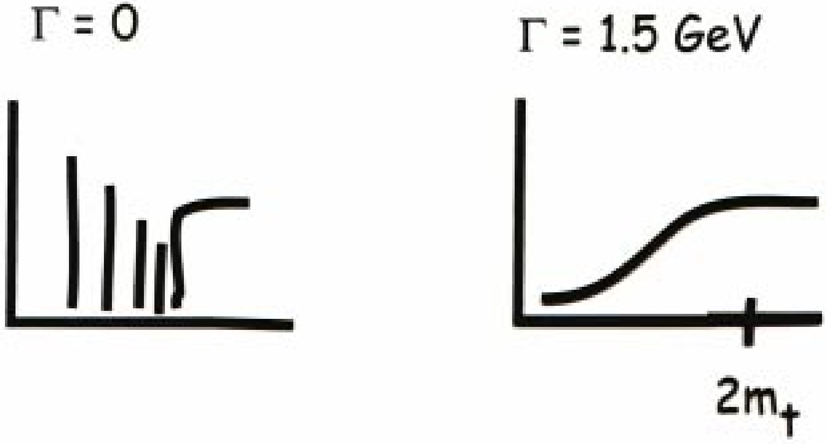
t -> b W^+_0 , t decay coupling to π^0

experimental challenge: polarization analysis for a **6-jet** final state

H. Murayama


A_{LR}
e_R^-
e_L^-
b
a
Re (F_{1A}^Z)
Re (F_{1V}^Z)
1.4
1.2
1.0
0.8
0.6
0.6
0.8
1.0
1.2
1.4
6-96
8163A2

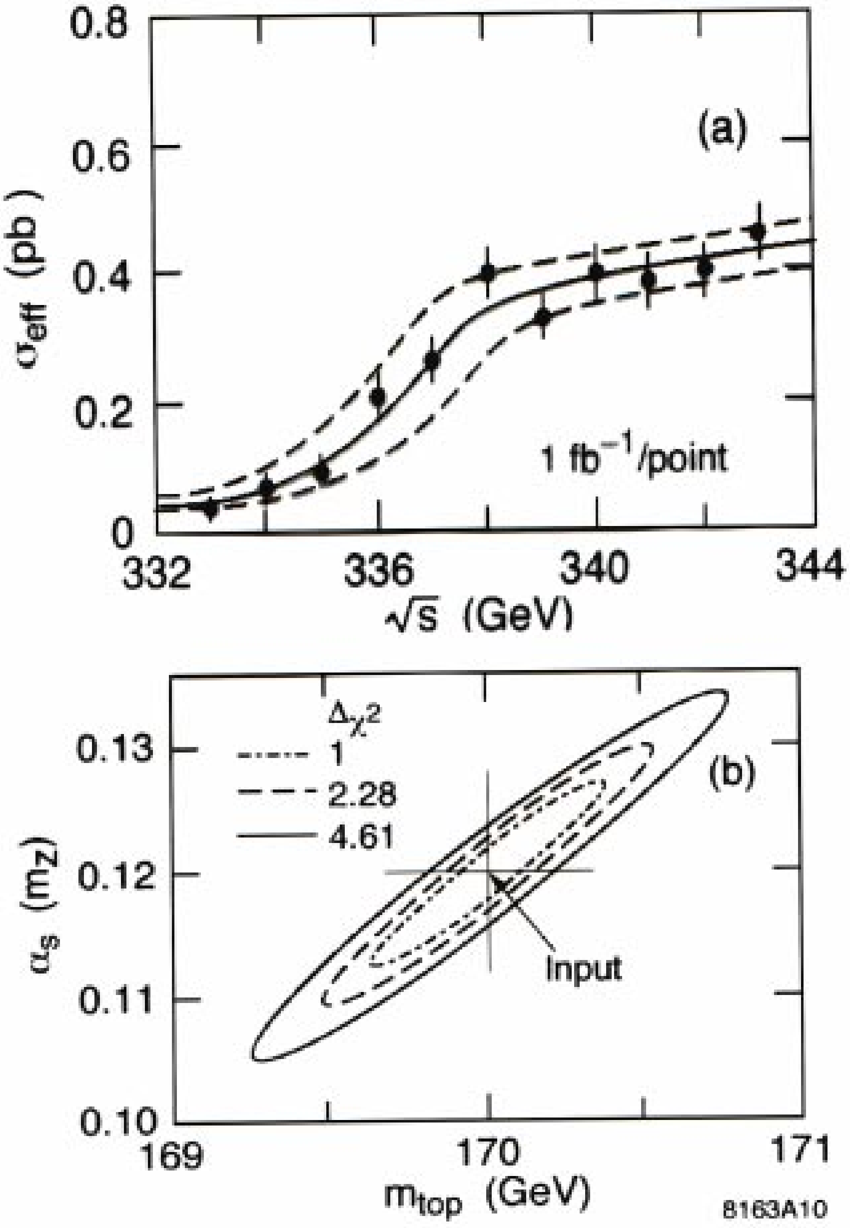
$e^+e^- \to t\,\bar{t}$ threshold region



physics goal: most accurate
t mass measurement
(to 200 MeV)
measurement of t t h coupling

direct measurement of the effective
luminosity spectrum is crucial

Y. Sumino


0.8
0.6
0.4
0.2
0
$\sigma_{\rm eff}$ (pb)
(a)
1 fb^{-1}/point
332
336
340
344
$\sqrt{s}$ (GeV)
$\Delta\chi^2$
1
2.28
4.61
(b)
0.13
0.12
0.11
0.10
α_s (m_Z)
Input
169
170
171
$m_{\rm top}$ (GeV)
8163A10

Weak-coupling route to EWSB

Higgs boson

produce through $e^+e^- \to Z^0 h^0$

(rate ~ few tenths R)

h0 appears at a definite recoil energy

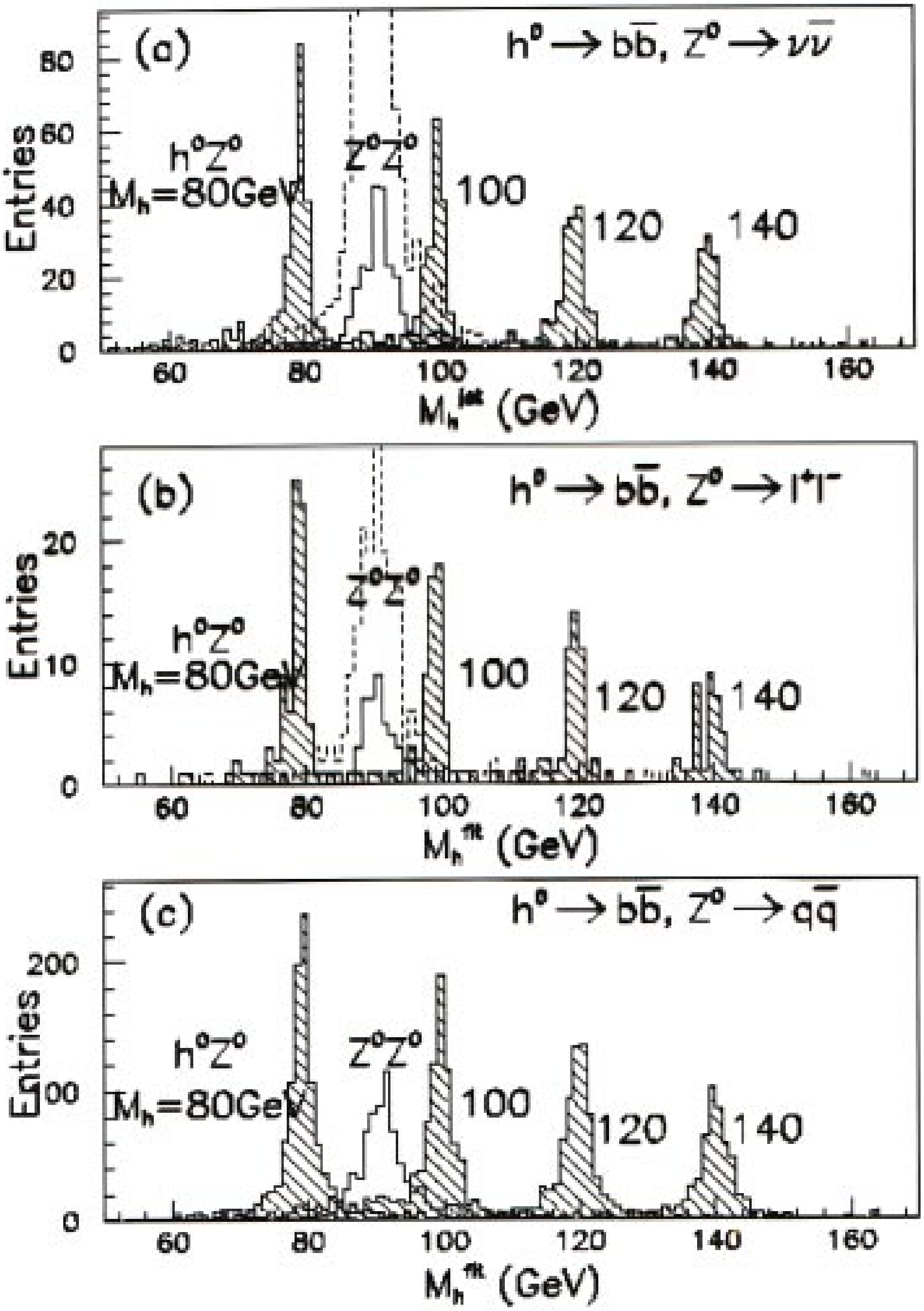
all Z0 decay modes are available

Higgs BR's in Minimal Standard Model

(m_h = 120 GeV)

$b\bar{b}$	dominant
$c\bar{c}$	6%
gg	6%
$\tau^+\tau^-$	8 %
WW^*	13%
$\gamma\gamma$	10^{-3}

Orito and Kawagoe



Higgs mass measurement:

kinematic fitting of h-> bb and Z decay

$\Delta m \sim 300$ MeV

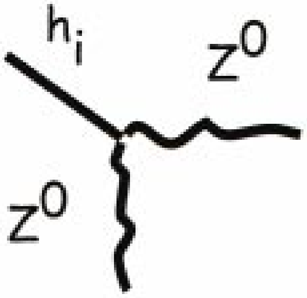
Higgs BR measurements:

$c\bar{c} / b\bar{b}$, $WW^*/b\bar{b}$, $\tau^+\tau^- / b\bar{b}$

directly test the Higgs coupling to mass

gg , $\gamma\gamma$ decay amplitudes sum over the whole spectrum

h0 –> $\gamma\gamma$ measurement motivates the $\gamma\gamma$ collider option for more general, multi-Higgs models



$$= \frac{m_Z^2}{v^2} W_i \qquad v = 246 \text{ GeV}$$

sum rule: $\Sigma \ W_i^2 = v^2$

thus, the LC can prove that the Higgs bosons
it finds fully generate the mass
of the the Z

recoil against the Z^0 →
search independently of Higgs decay mode

heavy Higgs states: H^0, A^0, H^+

in SUSY, typically at masses 300 - 600 GeV

Supersymmetry

if supersymmetry explains the electroweak scale, it will be discovered by the time of the LC experiments

but, this will be only the beginning of the story.

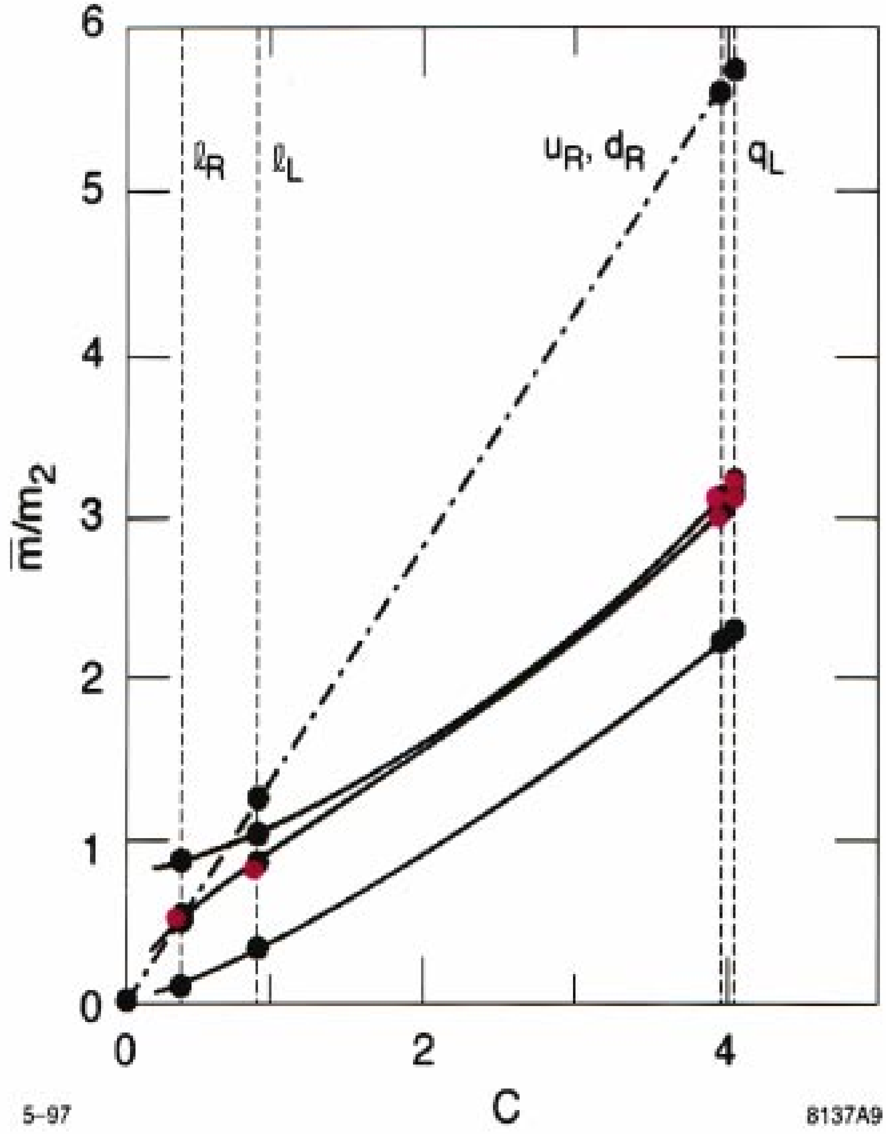
Supersymmetric models typically arise from new physics at very small distances

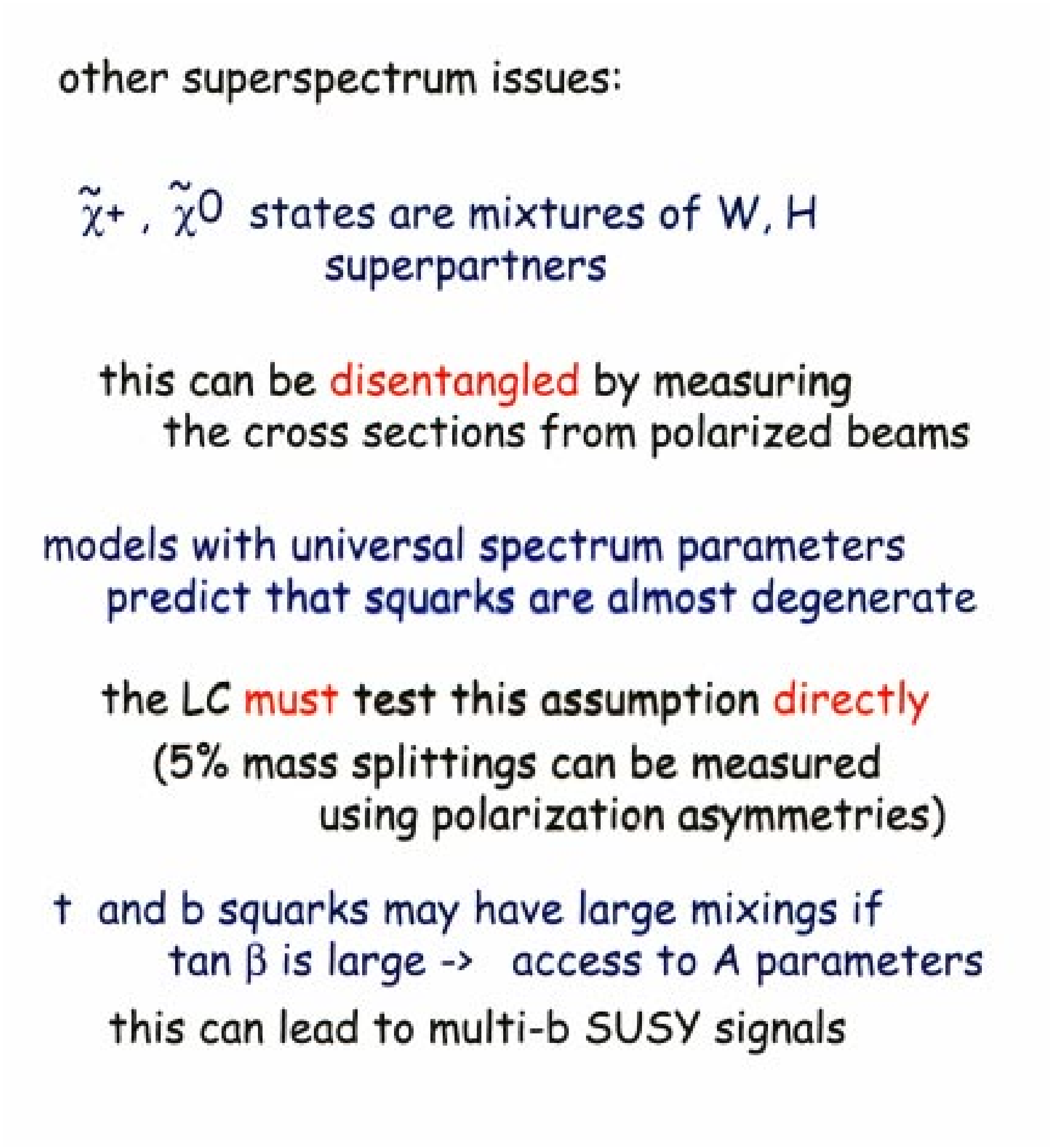
(e.g., GUT or string physics)

Clues to this new physics are encoded in the SUSY mass spectrum

The LC must be able to measure this spectrum systematically, and with precision

comparison of sfermion spectrum to models:





other superspectrum issues:

$\tilde{\chi}^+$, $\tilde{\chi}^0$ states are mixtures of W, H superpartners

this can be disentangled by measuring the cross sections from polarized beams

models with universal spectrum parameters predict that squarks are almost degenerate

the LC must test this assumption directly (5% mass splittings can be measured using polarization asymmetries)

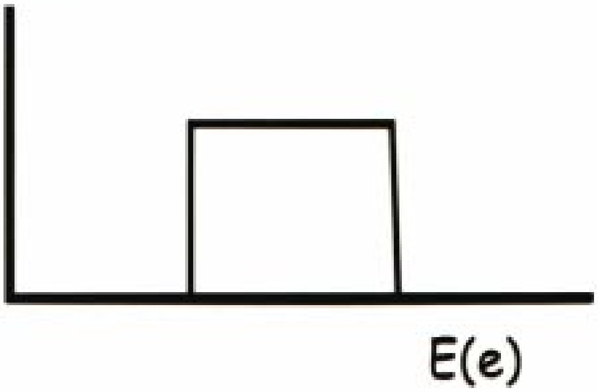
t and b squarks may have large mixings if $\tan\beta$ is large -> access to A parameters

this can lead to multi-b SUSY signals

example: $\tilde{e}^-$ mass measurement

$$e^+e^- \to \tilde{e}^+\tilde{e}^- \to e^+ e^- \tilde{\chi}^0 \tilde{\chi}^0$$

e energy spectrum:



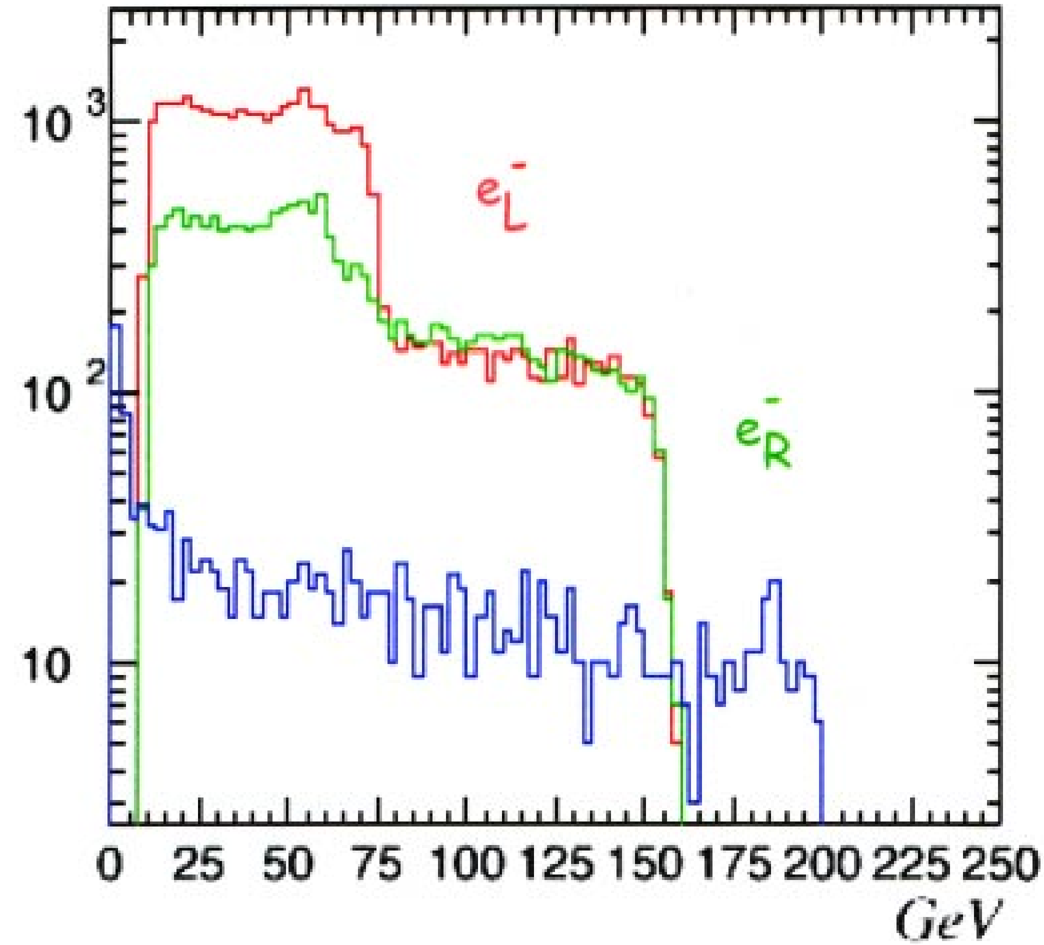
kinematic endpoints determine $m(\tilde{e})$, $m(\tilde{\chi})$;

1% accuracy is achievable

detector smearing of endpoints,
ISR, beamstrahlung smearing,
isolation from $\gamma\gamma$ background,
need to be considered carefully

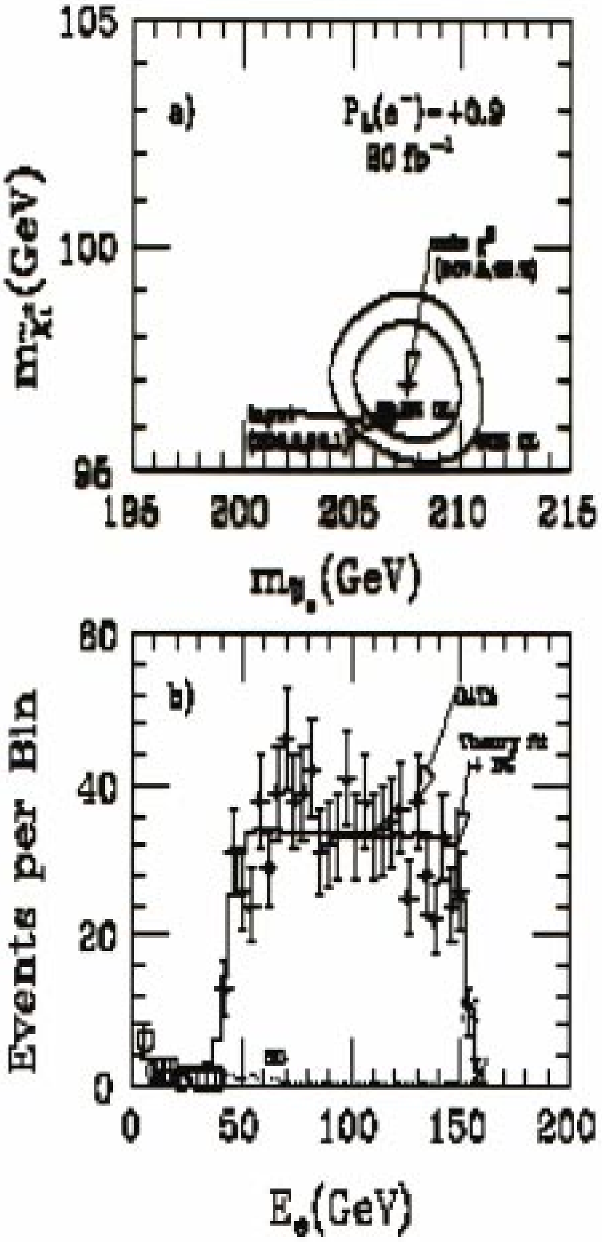
$e^+e^- \rightarrow \tilde{e}^+\tilde{e}^-$

L. Goodman



mass measurement in $\tilde{\nu} \to e^- \tilde{\chi}^+$

D. Wagner et al.



Supersymmetry connects naturally to the idea that Nature has more than 4 dimensions

It is possible that these new dimensions could be large and have effects visible at the LC.

$e^+e^- \to \gamma$ + (Graviton)

$e^+e^- \to f\bar{f}$ spin 2 contact terms
$\gamma\gamma \to \gamma\gamma$

Kaluza-Klein recurrences of γ, Z

The precise control of Standard Model reactions available at the LC makes these measurements possible.

Summary

The LC has a rich physics program which allows it to study the physics of the electroweak scale in any manifestation.

Using

precision understanding of Standard Model process
effect of polarized initial states
excellent b (and c) tagging
reconstruction of W and t in hadronic modes; polarization analysis

the LC can precisely characterize new interactions discovered at the TeV scale.

It is our job to insure that the LC detector is the precision instrument that can fulfill this promise.