Opportunities for Discovery at the International Linear Collider (ILC)

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Outline

- **Anticipating the future of 21st century particle physics**

  – electroweak symmetry breaking, TeV-scale physics and beyond

- **A path to the ILC**

  – furthering the goals of the LHC

- **Complementarity and synergy**

  – New physics signals and precision measurements

- **A few case studies**
  – precision Higgs program
  – elucidation of TeV-scale supersymmetry
  – confusion scenarios
  – probing higher energies through virtual effects
  – connections with cosmology

Anticipating the future of 21st century particle physics

1. Completing the Standard Model (SM)—elucidating the dynamics of electroweak symmetry breaking (EWSB)

- elementary Higgs bosons (weakly-coupled scalar dynamics)

- strongly-coupled EWSB dynamics (with or without Higgs-like scalars)

- strongly-coupled EWSB dynamics masquerading as weakly-coupled EWSB dynamics (with a scalar state resembling the SM Higgs boson) *e.g.* little Higgs models

Precision electroweak physics provides strong hints for a SM-like Higgs boson. How devious is nature likely to be (are there new physics conspiracies?)
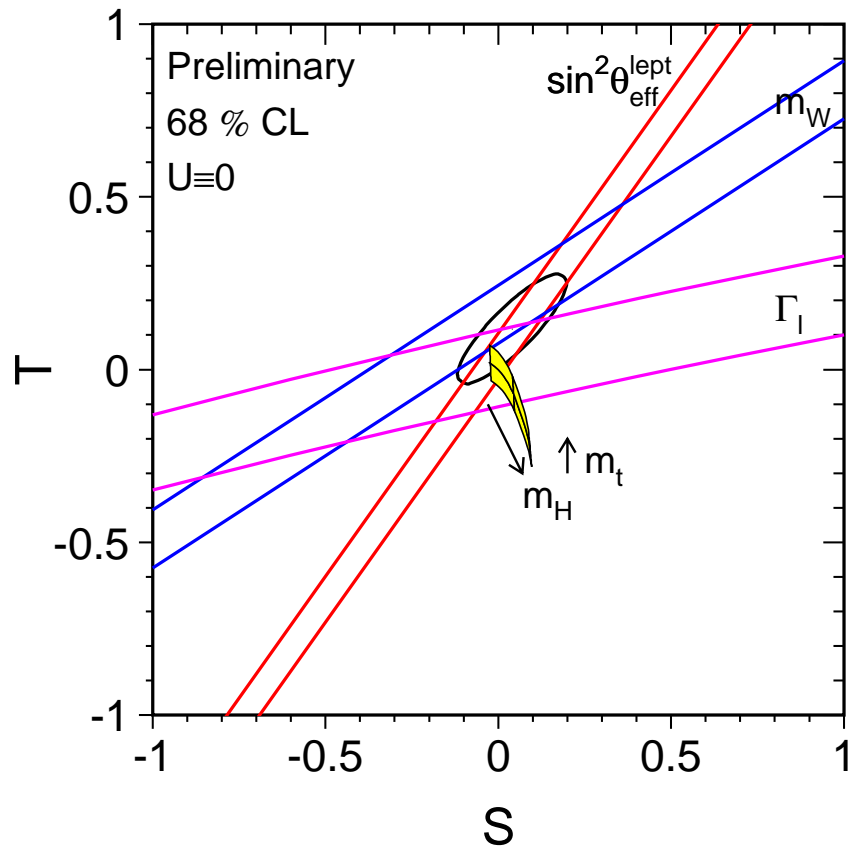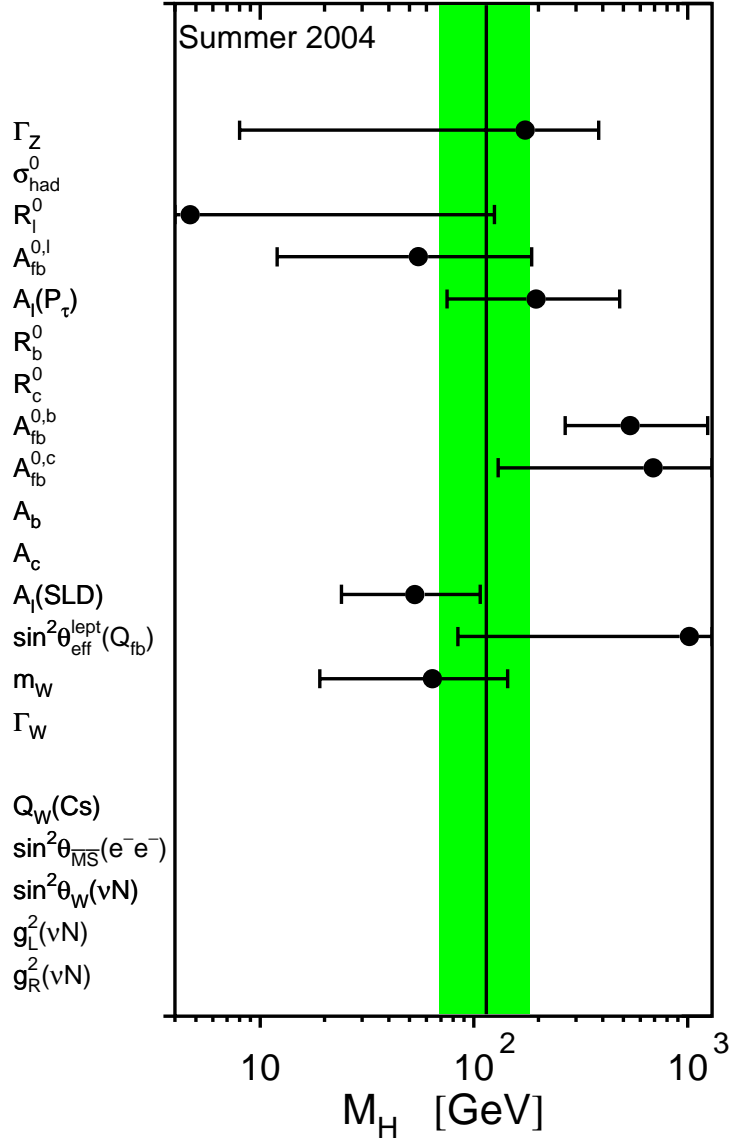
Summer 2004 results of the global electroweak fits taken from the LEP Electroweak Working Group web page.

2. Is there new TeV-scale physics?

- **Naturalness (in order to explain $m_W/M_{\rm Pl}$)**

  - Pro: successful explanation for the magnitude of $m_{\rm proton}/M_{\rm PL}$
  - Con: failure to understand the size of the cosmological constant

- **Unification of gauge couplings**

  - Pro: unsuccessful unification in the SM is repaired by introducing TeV-scale supersymmetry (which also provides a framework for explaining $m_W/M_{\rm Pl}$)
  - Con: unification could be repaired by adding new (non-SUSY) phenomena at scales significantly above 1 TeV. Alternatively, gauge coupling unification could just be a coincidence (it's just one data point)

- **Dark matter**

  - Pro: TeV-scale physics with a conserved multiplicative quantum number provides a candidate with the right annihilation cross section to yield a big bang relic with 25% critical density
  - Con: Models of dark matter exist that have no connection to the TeV scale (*e.g.* "invisible" axions)

Where must the Standard Model break down?

The Standard Model is a low-energy effective theory, valid only in a limited energy regime up to a scale Λ. "Naturalness" arguments suggest that $\Lambda \lesssim \mathcal{O}(\text{a few TeV})$.
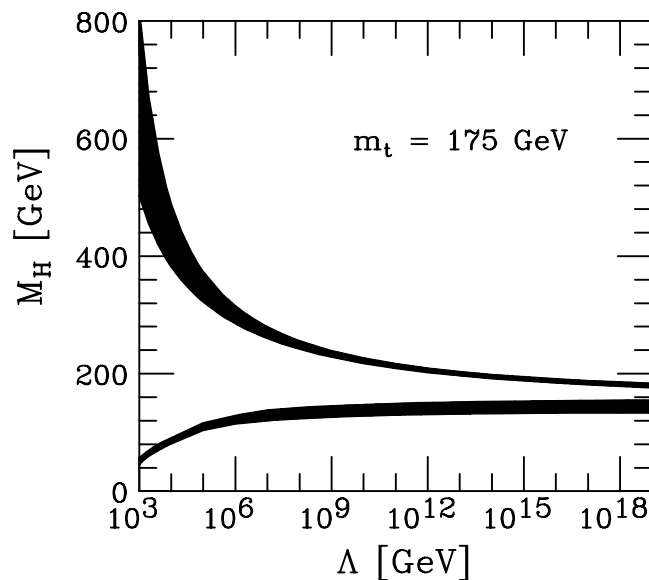
from Riesselmann
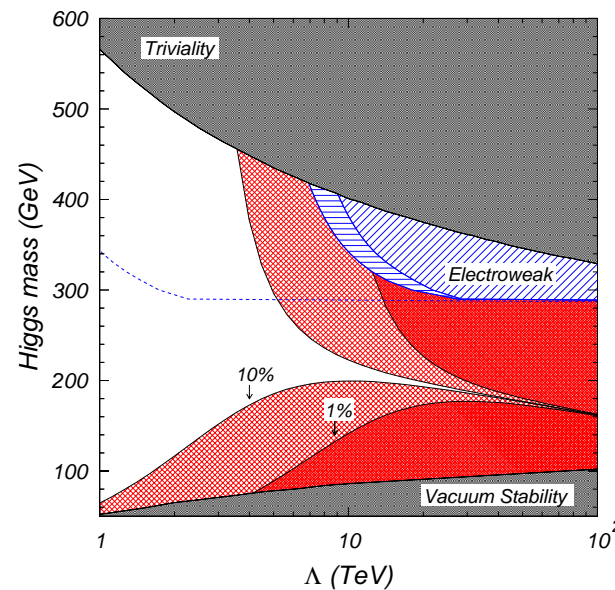
from Kolda and Murayama

In the absence of naturalness, the Standard Model could persist all the way up to some very large energy scale (perhaps even the Planck scale), depending on the precise value of the Higgs boson mass.

<u>Note</u>: the origin of flavor, CP violation and neutrino masses could in principle lie near the TeV-scale, but most likely are associated with much larger energy scales.

3. Scenarios for the future of particle physics

- After the SM Higgs boson, there is no TeV-scale physics. New physics is deferred to much higher energy scales.

- New TeV-scale physics reveals the existence of new 10 TeV-scale physics. Another layer of the onion is removed. . .

- New TeV-scale physics provides a window to GUT/Planck-scale physics.

A path to the ILC

The International Linear Collider (ILC), with $\sqrt{s} = 500$ GeV (with an upgrade path to 1 TeV) is proposed as the facility that will complement the LHC in the twin goals of deciphering EWSB dynamics and revealing new TeV-scale physics. Realizing the ILC is a technical and political challenge, so it is critical to provide:

- a convincing case for the technological and financial viability of the machine; and

- a scientific case that is strong enough to be appreciated by other scientists and the political establishments.

Much work has gone in to building the scientific case for the ILC (some of which I will describe below). It is now imperative to develop the detailed conceptual and technical designs of the machine and the detectors. In this way, the international particle physics community will be ready to press for the final approval of the ILC (and begin its construction) around the time of the first major discoveries of the LHC. Of course, the nature of the LHC discoveries could have a considerable impact on the final form of the ILC proposal and its ultimate chances for successfully going forward.

Complementarity and Synergy

The LHC and ILC provide complementary approaches to the TeV scale, in the same way that the CERN $S p\bar{p} S$/Tevatron and LEP/SLC provided complementary approaches to the 100 GeV scale. If the ILC is constructed to operate at some point during the LHC era, then there is potential for a synergetic interplay of the LHC and ILC physics programs:

- The combined interpretation of LHC and ILC data can yield a more unambiguous interpretation of the underlying physics than the results of both colliders taken separately.

- Combined analyses of data during concurrent LHC/ILC running implies that results obtained at one machine can influence the analysis techniques at the other machine, leading to optimized search strategies of new physics signals.

The LHC/ILC Study Group has documented numerous examples of the complementarity and potential synergy of the LHC and ILC [see G. Weiglein *et al.*, hep-ph/0410364]. Two examples (of many) are:

- The precision Higgs program at the ILC and the search for heavy Higgs scalars at the LHC

Many models of weakly-coupled scalar EWSB dynamics predict the existence of a Higgs boson whose properties are nearly indistinguishable from the SM Higgs boson. This is called the *decoupling limit*. In multi-Higgs models, the approach to the decoupling limits scales as m_Z^2/m_A^2, where m_A is a typical mass of the heavier Higgs states. Deviations of the couplings of the lightest Higgs boson from the corresponding SM predictions at the ILC can provide an estimate of the mass scale associated with the heavier Higgs states and provide crucial information for LHC searches for the heavier Higgs bosons.

- Precision ILC measurements of the light neutralino/chargino states in TeV-scale supersymmetry models can help LHC disentangle complex decay chains of heavier decaying supersymmetric particles.
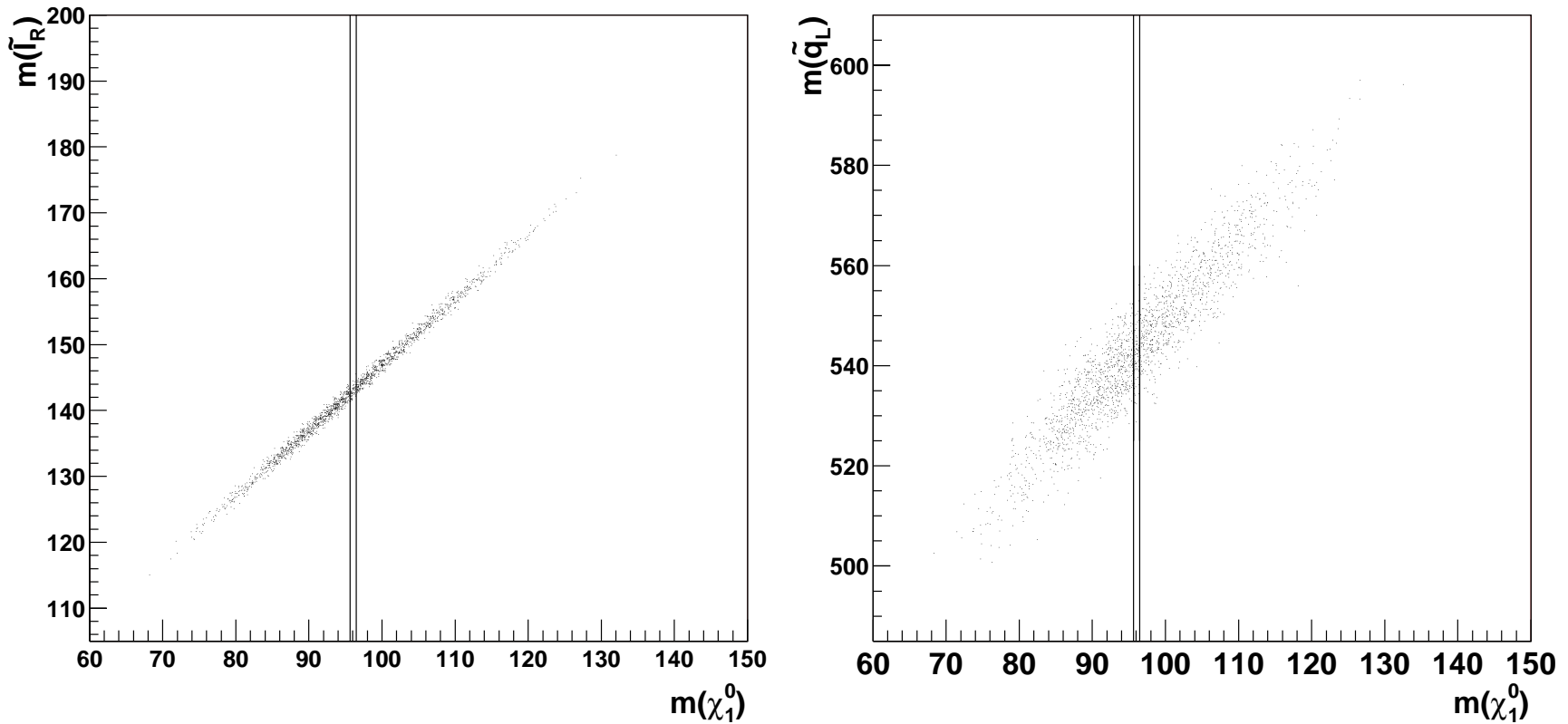
Dots: LHC alone. Vertical bands: fixing the mass of $\tilde{\chi}_1^0$ to within $\pm 2\sigma$ with ILC input ($\sigma = 0.2\%$) [M. Chiorboli *et al.*].

LHC

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SLAC Workshop
23 March 2005

LHC/ILC Synergies

ILC

Organizing Committee:
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Howard Haber
John Conway

http://www.ippp.dur.ac.uk/~georg/lhclc/

A few case studies

1. The precision Higgs program

- If nothing is discovered beyond the SM Higgs boson at the LHC, this may provide the only clue for the next energy scale of new physics.

- Close to the decoupling limit, this can provide evidence for Higgs physics beyond the SM.

- Provides strong tests of the physics of EWSB dynamics, with some sensitivity to loop effects.

- In TeV-scale supersymmetry, this can probe supersymmetry breaking parameters and new sources of CP violation.

Anticipated precision Higgs measurements at the ILC

$\sqrt{s} = 350—500$ GeV and $\mathcal{L} = 500$ fb^{-1}

Higgs coupling	δBR/BR	$\delta g/g$
hWW	5.1%	1.2%
hZZ	—	1.2%
$hb\bar{b}$	2.4%	2.1%
$hc\bar{c}$	12.0%	—
$h\tau\tau$	5.0%	3.2%
$h\mu\mu$*	$\sim 30\%$	$\sim 15\%$
hgg	8.2%	—
$h\gamma\gamma$	16%	—

*$\sqrt{s} = 800$ GeV assumed for the $\mu^+\mu^-$ channel

$\sqrt{s} = 800—1000$ GeV and $\mathcal{L} = 1000$ fb^{-1}

Higgs coupling	δBR/BR	$\delta g/g$
hWW	2.0%	—
$ht\bar{t}$	—	6.0%
$hb\bar{b}$	1.6%	—
$hc\bar{c}$	8.3%	—
$h\tau\tau$	5.0%	—
hgg	2.3%	—
$h\gamma\gamma$	5.4%	—
hhh	—	12%
total decay rate	—	3.4%

Expected fractional uncertainties for LC measurements of Higgs branching ratios [BR($h \rightarrow XX$)] and couplings [g_{hXX}], for various choices of final state XX, assuming $m_h = 120$ GeV [Battaglia, Boos, De Roeck, Desch, Kuhl, and others]. An upgraded ILC running at 1 TeV (with $\mathcal{L} = 1000$ fb^{-1}) can provide further improvements via the processes $e^+e^- \rightarrow \bar{\nu}_e\nu_e h$, $e^+e^- \rightarrow \bar{\nu}_e\nu_e hh$ and $e^+e^- \rightarrow t\bar{t}h$ [Barklow, Yamashita, Gay, Besson, Winter and others].

As an example, consider the MSSM Higgs sector. If we only keep the leading $\tan\beta$-enhanced radiative corrections, then for $m_A \gg m_Z$ (approaching the decoupling limit),

$$\frac{g_{hVV}^2}{g_{h_{\mathrm{SM}}VV}^2} \simeq 1 - \frac{c^2 m_Z^4 \sin^2 4\beta}{4 m_A^4} \,,$$

$$\frac{g_{htt}^2}{g_{h_{\mathrm{SM}}tt}^2} \simeq 1 + \frac{c m_Z^2 \sin 4\beta \cot \beta}{m_A^2} \,,$$

$$\frac{g_{hbb}^2}{g_{h_{\mathrm{SM}}bb}^2} \simeq 1 - \frac{4 c m_Z^2 \cos 2\beta}{m_A^2} \left[\sin^2 \beta - \frac{\Delta_b}{1 + \Delta_b} \right] \,,$$

where $c \equiv 1 + \mathcal{O}(g^2)$ and $\Delta_b \equiv \tan\beta \times \mathcal{O}(g^2)$ [g is a generic gauge or Yukawa coupling]. The quantities c and Δ_b depend on the MSSM spectrum. The approach to decoupling is fastest for the h couplings to vector boson pairs and slowest for the couplings to down-type quarks.
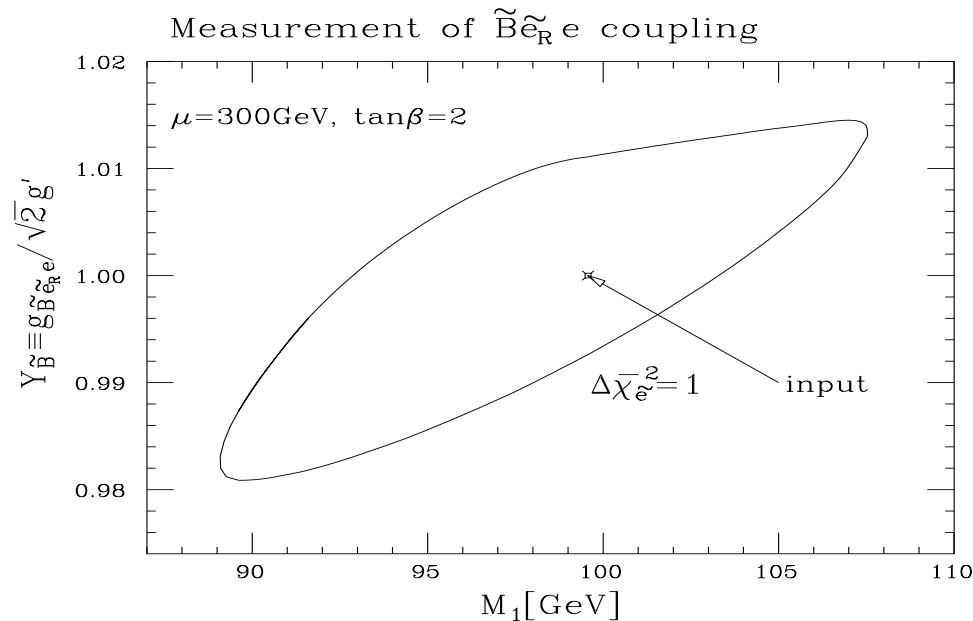
Thus, deviations from the decoupling limit implicitly contain information about the EWSB sector and the associated TeV-scale dynamics.
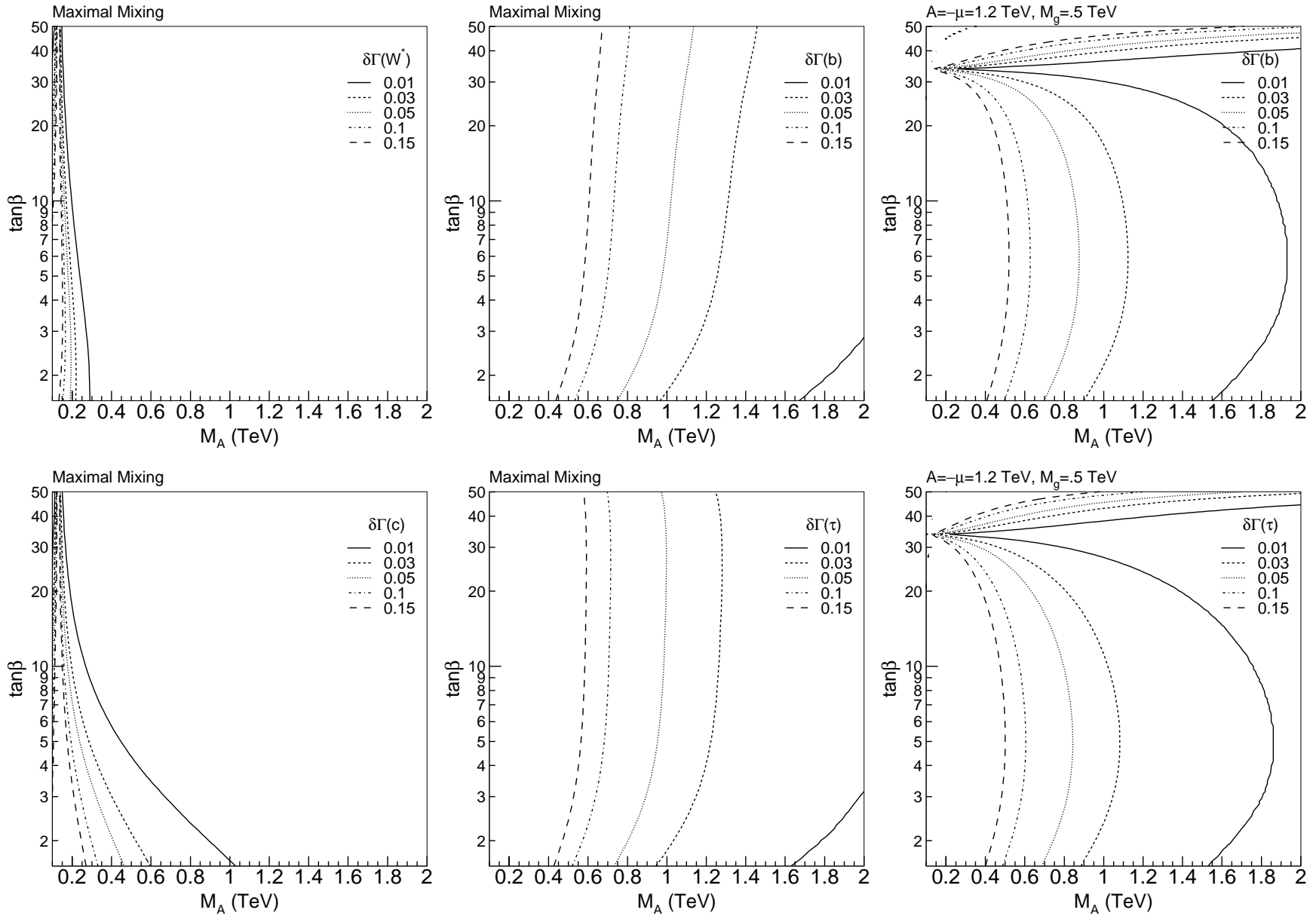
Deviations of Higgs partial widths from their SM values in two different MSSM scenarios (Carena, Haber, Logan and Mrenna).

2. Confirming and elucidating TeV-scale supersymmetry

• If new physics signals are observed at the Tevatron and/or LHC, how can we be sure that it is supersymmetry?

 – Measure the spins of the new particles, and exhibit the superpartners of SM particles with spins differing by half a unit.
 – Verify that particle/sparticle interaction vertices are related to the corresponding SM vertices by the expected supersymmetric relations.

Measurement of $\widetilde{B}\widetilde{e}_R\,e$ coupling

$Y_{\widetilde{B}} \equiv g_{\widetilde{B}\widetilde{e}_R e}/\sqrt{2}\,g'$

$\mu{=}300\mathrm{GeV},\ \tan\beta{=}2$

$\Delta\bar{\chi}_{\widetilde{e}}^2{=}1$ input

$M_1\,[\mathrm{GeV}]$

[Nojiri, Fujii and Tsukamoto]

– Confirm supersymmetric expectations for the Higgs sector [more model dependent]

• Do supersymmetric breaking parameters exhibit any definite organizing principle?

– Are there simplifications when low-energy parameters are extrapolated to the GUT/Planck scale?
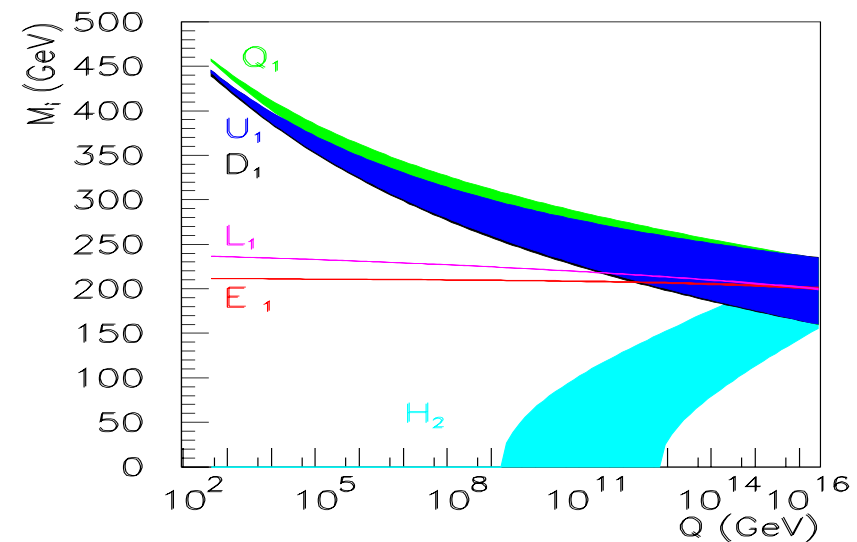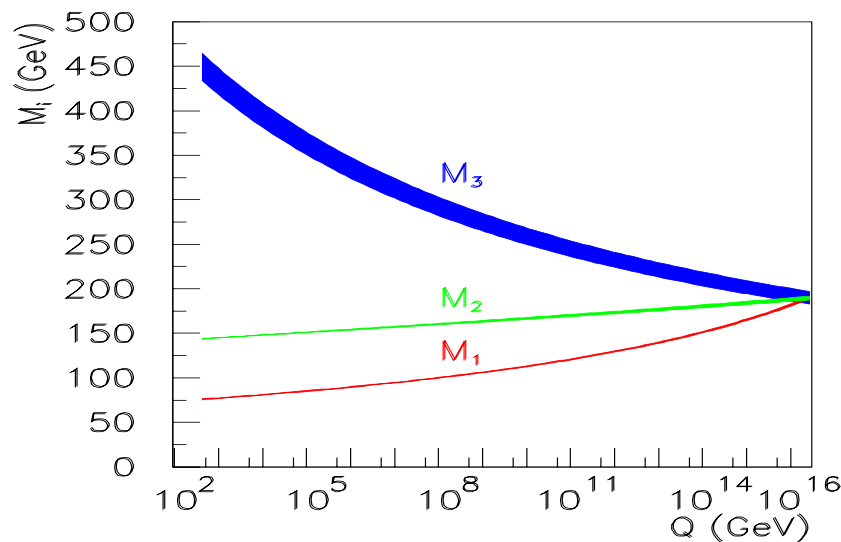

RGE evolution of gaugino (left) and scalar quark and lepton (right) mass parameters from the electroweak scale to the GUT scale in an mSUGRA model with $m_0 = 200$ GeV, $m_{1/2} = 190$ GeV, $A_0 = 500$ GeV, $\tan \beta = 30$ and $\mu < 0$. The bands indicate 95% CL contours. [Blair, Porod and Zerwas].

3. Confusion scenarios

An example: models of TeV-scale supersymmetry and universal extra dimensions (UED) with $R^{-1} \sim 1$ TeV both possess a spectrum of new particles (both colored and uncolored) that are accessible to the LHC.
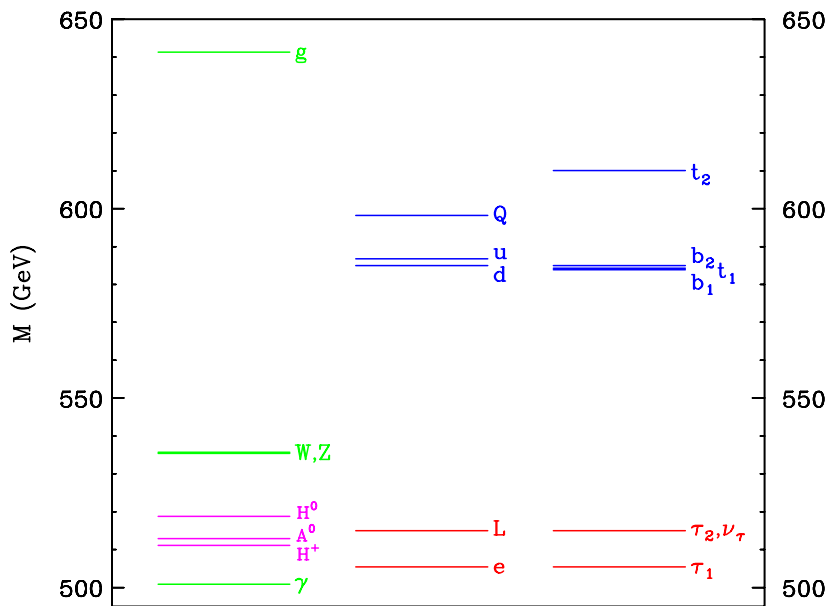

first KK level in minimal UED
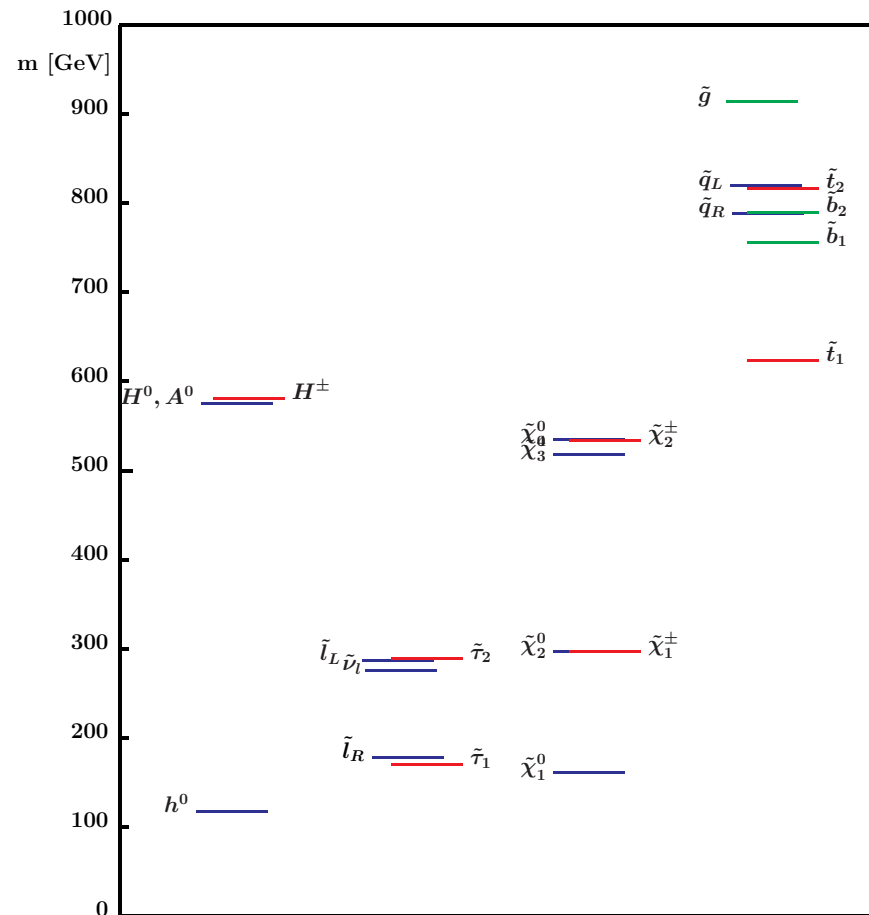
mSUGRA benchmark "SPS 3"

Models of TeV-scale supersymmetry (with R-parity), UED with KK-parity and little Higgs models with T-parity all possess a parity-odd lightest particle. These models therefore possess a dark matter candidate (LSP, LKP and LTP) and yield missing energy signals at colliders. A definitive interpretation may not be possible after an LHC discovery. Precision measurements at an e^+e^- collider can provide the critical evidence to distinguish among different approaches [Battaglia, Datta, De Roeck, Kong and Matchev].
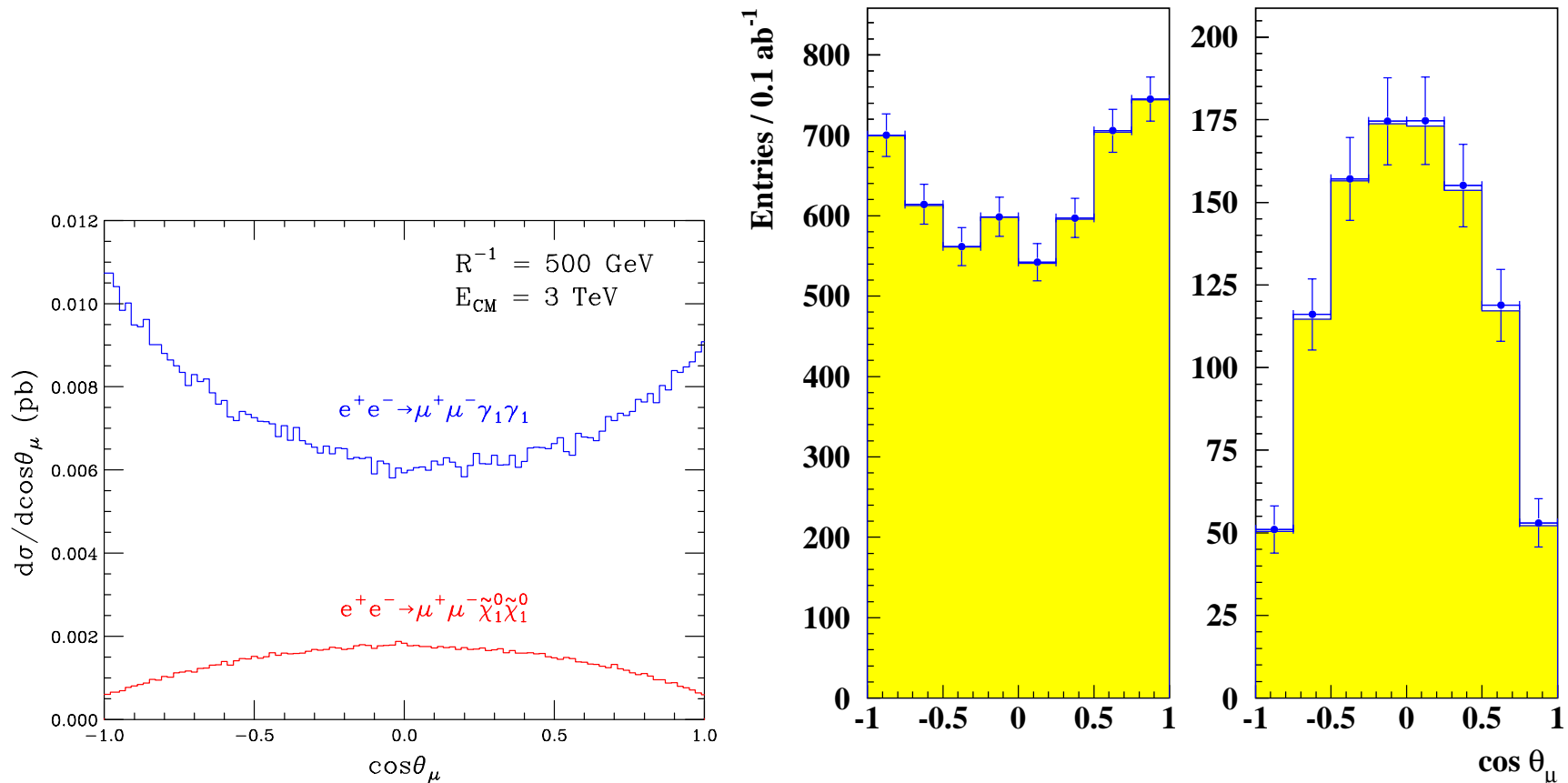
# 4. Probing higher energies through virtual effects

Precision measurements at the ILC (from Giga-Z to the highest center-of-mass energy) provide another means for distinguishing among different interpretations of new physics at the LHC.
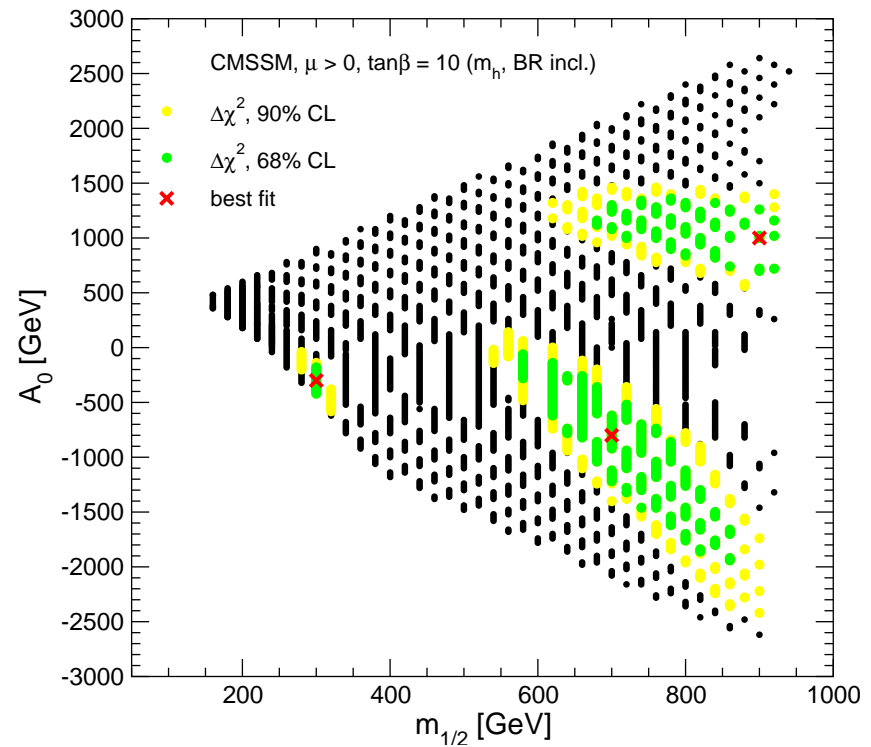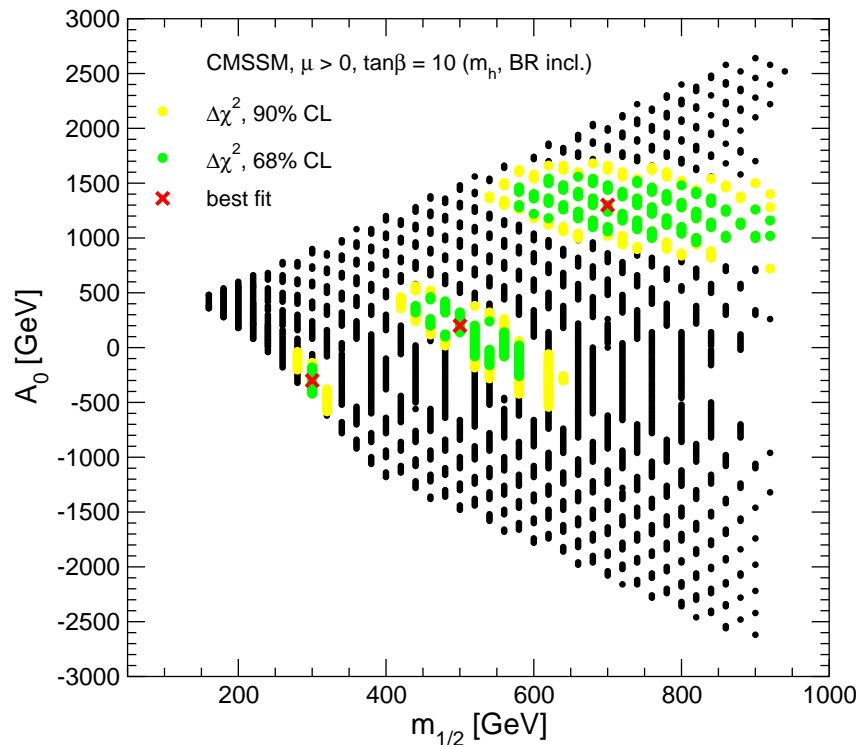
Precision ILC measurements of m_W, $\sin^2\theta_{\text{eff}}$, m_h, BR($h \to b\bar{b}$) and BR($h \to WW^*$) can provide strong constraints and test the consistency of mSUGRA parameter assumptions [Ellis, Heinemeyer, Olive, Weiglein].

The direct detection of signals associated with strong EWSB dynamics lies beyond the kinematic reach of the ILC. Nevertheless, precision measurements of gauge boson pair production processes are sensitive to virtual effects that provide a significant window to new physics beyond 1 TeV.
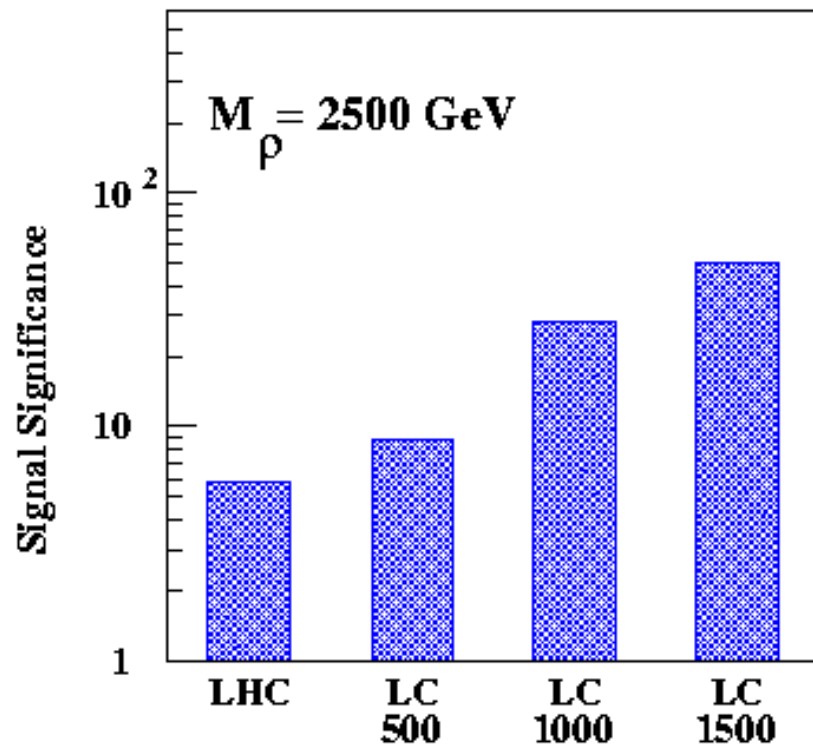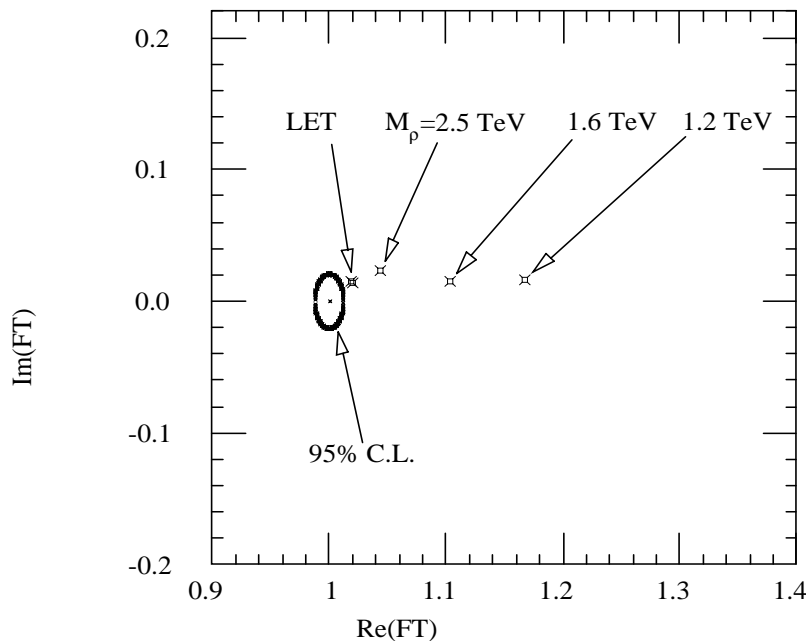
ILC sensitivity at $\sqrt{s} = 500$ GeV and $\mathcal{L} = 500$ fb^{-1} to strong EWSB dynamics. Data from $e^+e^- \rightarrow W^+W^-$ is combined with results for $e^+e^- \rightarrow \nu\bar{\nu}W^+W^-$, $\nu\bar{\nu}ZZ$ to produce the statistical significances shown here [Barklow, hep-ph/0112286].

5. Connections with cosmology

The physics of the very early universe depends critically on the our understanding of the fundamental laws of nature at the highest energy scales. For this reason alone, a thorough understanding of the physics of electroweak symmetry breaking and a comprehensive exploration of TeV-scale physics will have a profound impact on cosmology. Possible contributions of the ILC include [see J. Feng and M. Trodden]:

- A precision study of the particle that makes up the dark matter.

- Evidence for or against baryogenesis controlled by physics at the electroweak scale.

- New insights into the nature of the vacuum (through detailed studies of the Higgs boson), with implications for naturalness and vacuum energy.

- If supersymmetry and/or extra dimensions are confirmed, the implications for cosmology will be fantastic!