The ILC Physics Menu—500 GeV and 1TeV

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Some useful references

1. A. Djouadi *et al.*, "International Linear Collider Reference Design Report Volume 2: PHYSICS AT THE ILC," arXiv:0709.1893 [hep-ph].
2. G. Weiglein *et al.* [LHC/ILC Study Group], "Physics interplay of the LHC and the ILC," Phys. Rept. **426**, 47 (2006).
3. G.A. Moortgat-Pick *et al.*, "The role of polarized positrons and electrons in revealing fundamental interactions at the linear collider," arXiv:hep-ph/0507011.
4. K. Fujii, D.J. Miller and A. Soni, editors, "Linear collider physics in the new millennium," (World Scientific, Singapore, 2005).

Outline

- Setting the stage for phenomenology at the ILC
  - the known knowns, the known unknowns, and the unknown unknowns
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  - The precision Higgs program
  - Beyond the Standard Model Higgs boson
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- Additional benefits
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  - synergy and complementarity

Setting the stage for Phenomenology at the ILC

After a decade of LHC running, our knowledge of the Standard Model and what lies ahead at the Terascale will have been significantly enhanced. What will be the value added by the ILC to this enterprise?

1. The known knowns: precision studies of Standard Model (SM) physics
   - precision top studies (threshold top quark production, rare top decays)
   - precision electroweak observables—the next generation

2. The known unknowns: precision studies of electroweak symmetry breaking (EWSB) dynamics
   - precision Higgs studies (for $m_H \lesssim 150$ GeV)
   - phenomenology of alternative theories of EWSB dynamics
   - anomalous behavior of gauge boson interactions

3. The unknown unknowns: new physics beyond the SM at the Terascale

   - precision studies of the partial spectrum of the new physics
   - distinguishing among multiple interpretations of new physics
   - potential for novel discoveries of new phenomena
   - in the absence of new physics, hints for the next energy threshold?

No one can guarantee today the existence of new physics at the Terascale (hence, the epithet "unknown unknowns" above). Nevertheless, strong motivations exist for the expectation of new physics at the Terascale:

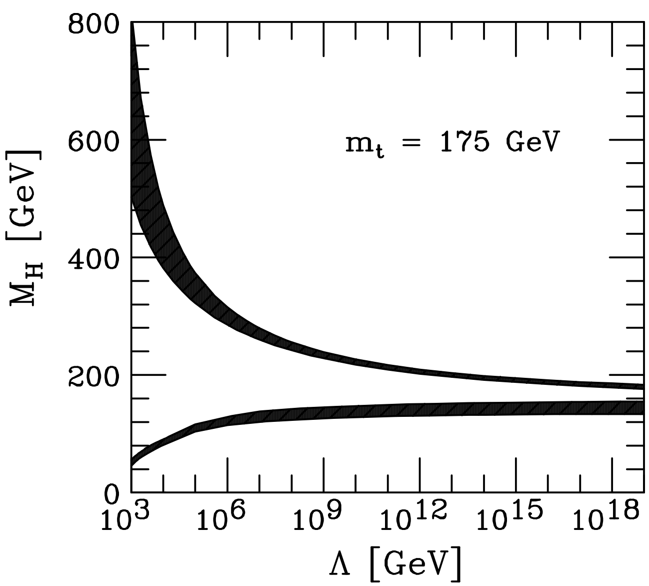
- Naturalness (accounting for the gauge hierarchy: $m_W/M_{\rm Pl} \sim 10^{-17}$)

- Dark matter (a thermal relic of the big bang with weak-scale interaction strength can explain the observed dark matter abundance)

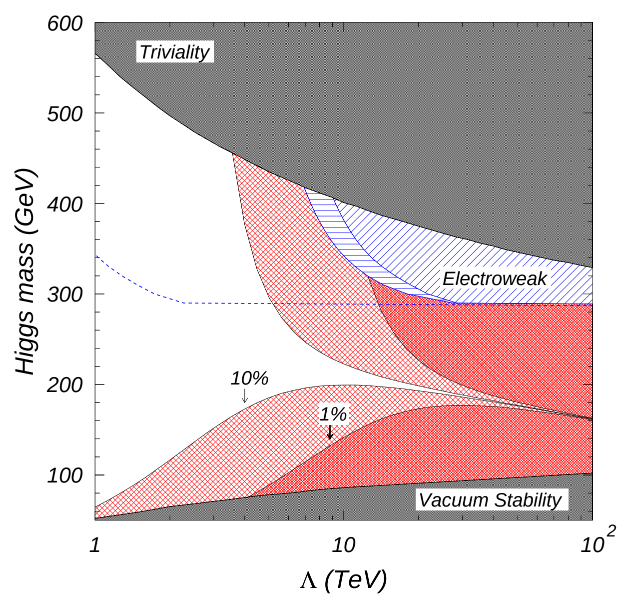
- Gauge coupling unification (this can be achieved in weak-scale supersymmetric extensions of the Standard Model)

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 $\Lambda \lesssim \mathcal{O}$(a few TeV).



from Riesselmann



from Kolda and Murayama

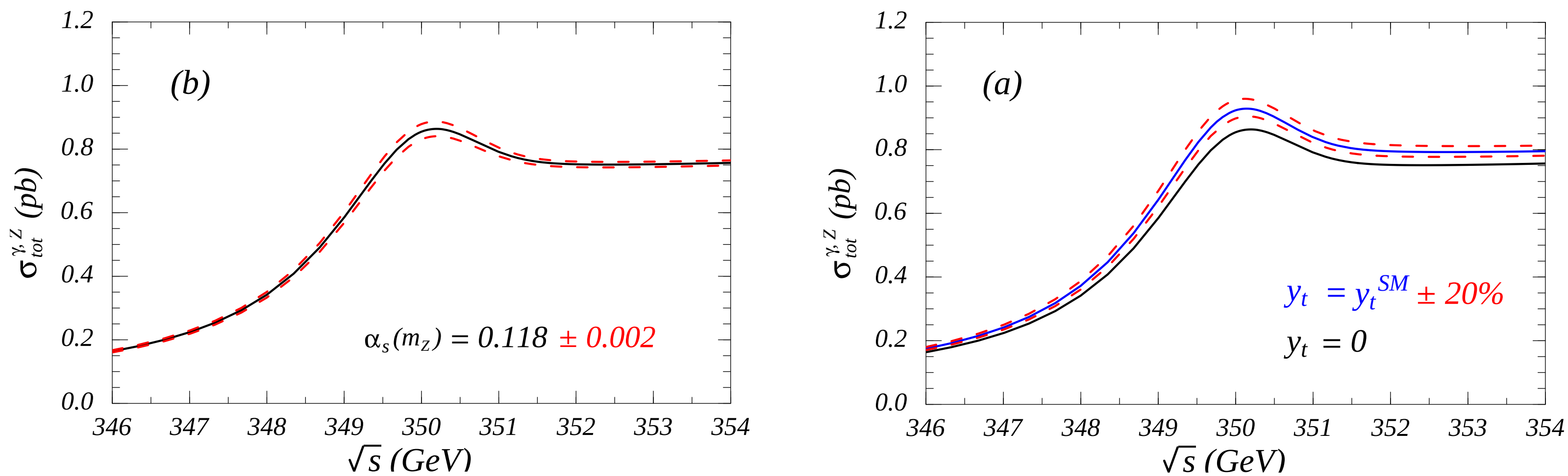
In the absence of naturalness, the Standard Model could persist all the way up to some very large energy scale (perhaps even the Planck scale), depending on the precise value of the Higgs boson mass.

Precision Top Physics

The ILC can measure the top quark production near threshold very precisely, which can yield top quark parameter uncertainties of:

$$\delta m_t \lesssim 200 \text{ MeV} \qquad \delta\Gamma_t/\Gamma_t \sim 5\%$$

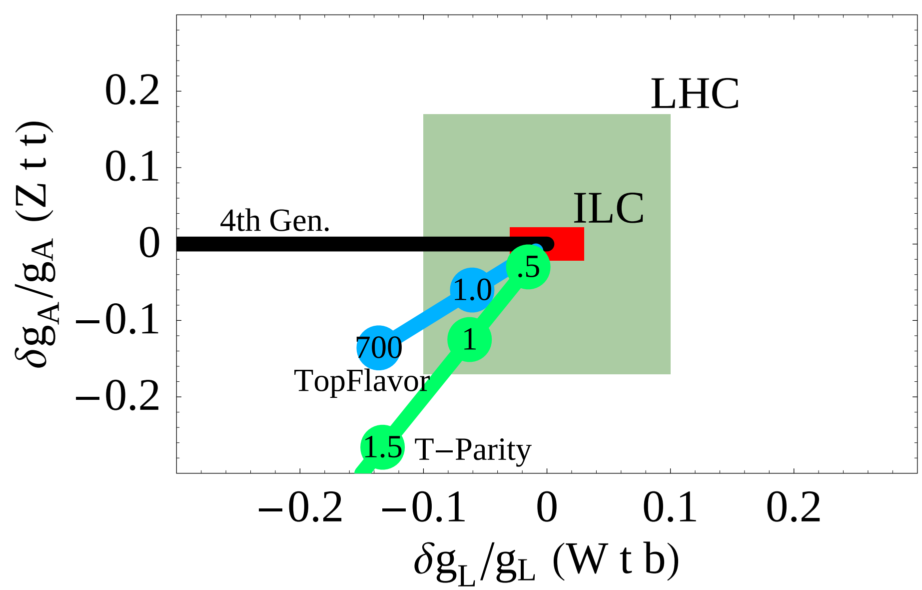
$$\delta\alpha_s(m_Z) \sim 0.002 \qquad \delta y_t/y_t \sim 0.2$$



In the right pane, the solid blue line corresponds to a SM Higgs mass of 115 GeV and y_t is the Higgs-top Yukawa coupling [A. Hoang, A. Manohar, I.W. Stewart and T. Teubner].

Such an accurate measurement of m_t (along with improved measurements of other precision electroweak observables) can significantly constrain or strengthen the need for new physics at a higher energy scale.

Deviations from SM predictions of the tbW and ttZ couplings can be measured quite precisely at the ILC. For example, assuming that the tbW coupling is purely left-handed, one can measure the deviation of the tbW coupling and the axial ttZ coupling from SM predictions [Batra and Tait]:



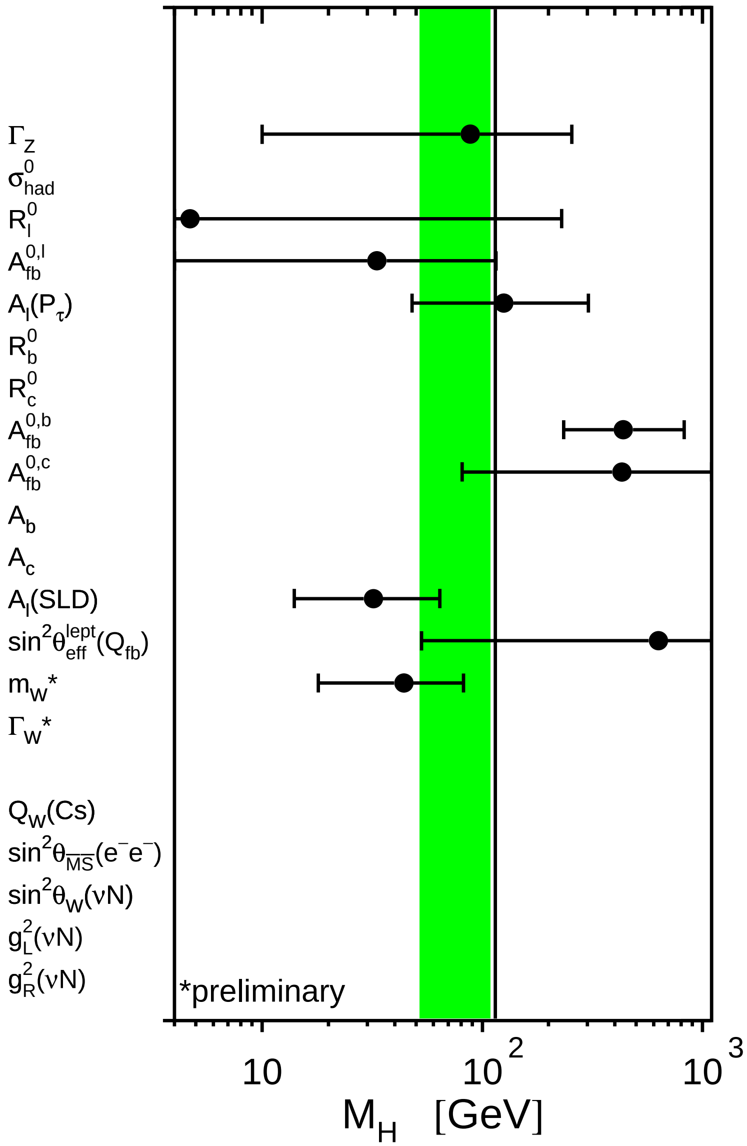
This can provide discrimination among theories of new Terascale physics.

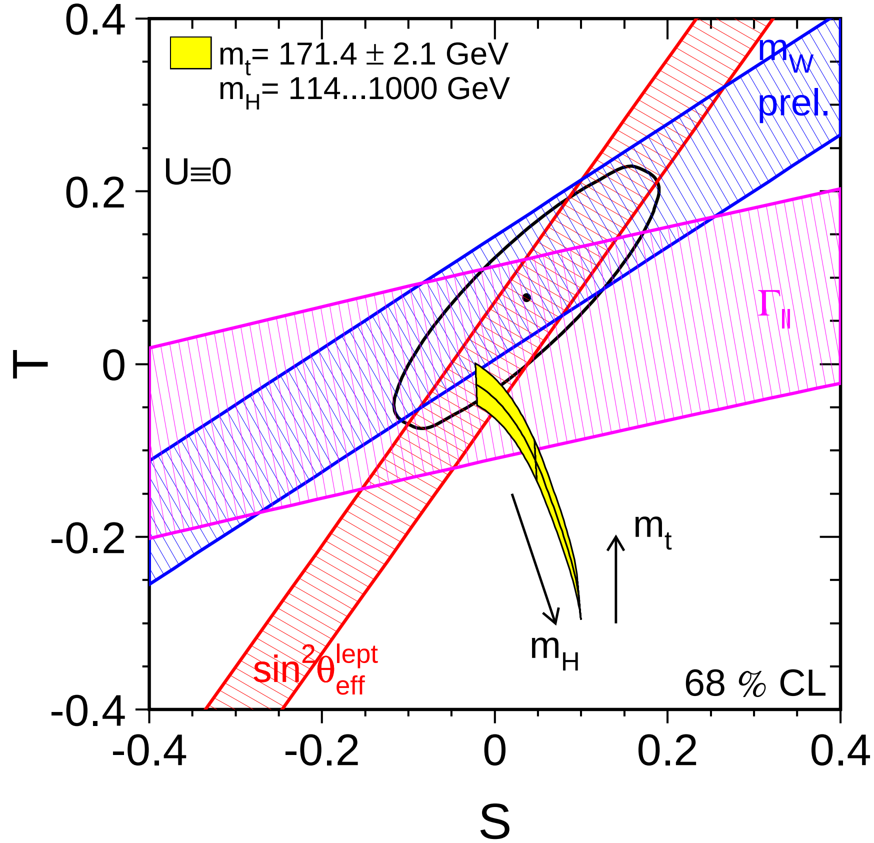
Discovering the dynamics of EWSB

The mechanism of electroweak symmetry breaking may be:

- 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)? Occam's razor suggests the first alternative, but nature is the ultimate decider.





Winter 2007 results of the global SM electroweak fits taken from the LEP Electroweak Working Group web page.

The precision Higgs program

Precision measurements of Higgs observables: mass, width, spin, C and P quantum numbers, partial widths and branching ratios, invisible decays, Higgs-top Yukawa coupling, Higgs trilinear self-coupling.

- If nothing is discovered beyond the SM Higgs boson at the LHC, the precision Higgs program may provide a significant clue for the energy scale of the new physics.
- Close to the decoupling limit, precision Higgs measurements can provide evidence for Higgs physics beyond the SM.
- The ILC can provide a substantive probe of the physics of EWSB dynamics, with some sensitivity to loop effects.
- For example, in weak-scale supersymmetry, precision Higgs physics can probe SUSY-breaking parameters and new sources of CP violation.

Anticipated precision Higgs measurements at the ILC

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

Higgs coupling	$\delta\mathrm{BR}/\mathrm{BR}$	$\delta g/g$
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%	—
hhh †	—	36%

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

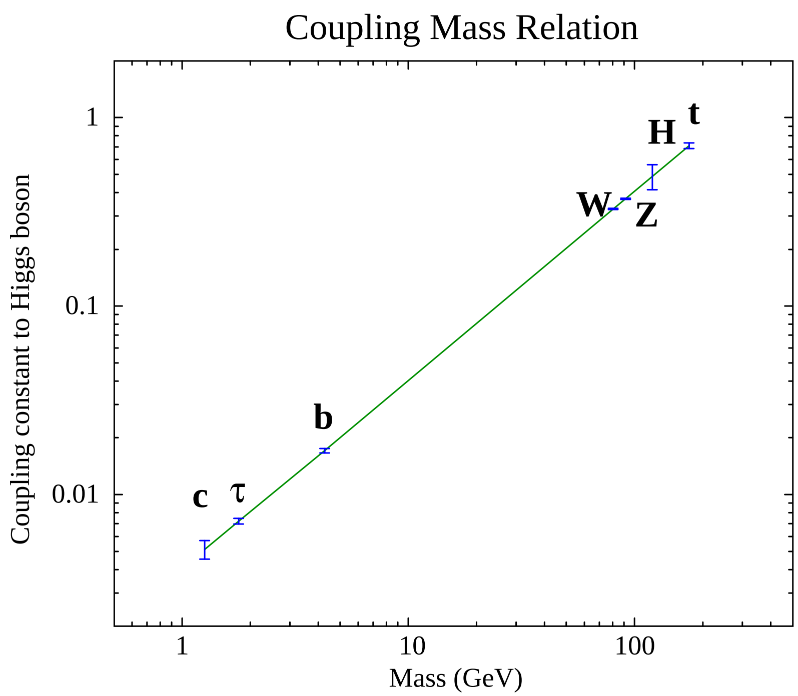
† In the hhh channel, error can be reduced to 23% [18%] for $\mathcal{L} = 1000$ [2000] fb^{-1} [Castanier *et al.*]

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

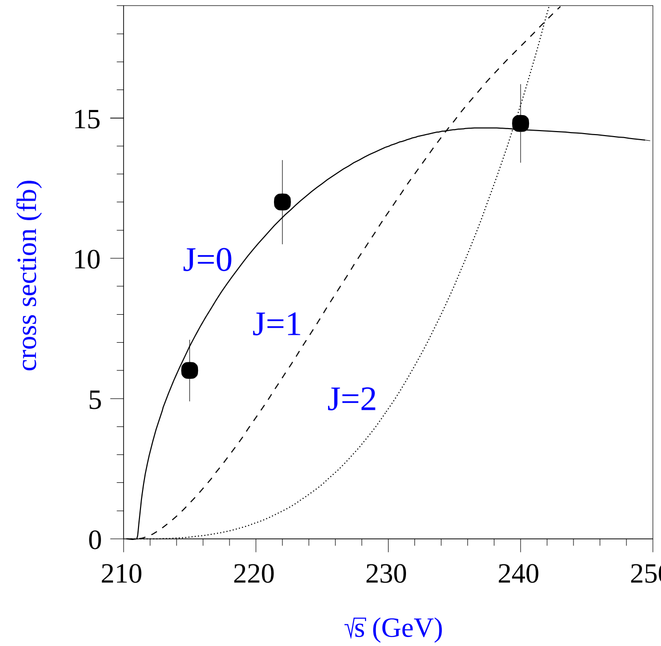
Higgs coupling	$\delta\mathrm{BR}/\mathrm{BR}$	$\delta g/g$
hWW	2.0%	—
$ht\bar{t}$	—	6.0%
$hb\bar{b}$	1.6%	—
$hc\bar{c}$	8.3%	—
$h\tau\tau$	5.0%	—
hgg	2.3%	—
$h\gamma\gamma$	5.4%	—
hhh	—	12%
total decay rate	—	3.4%

Expected fractional uncertainties for LC measurements of Higgs branching ratios [BR($h \to XX$)] 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 $\mathcal{L} = 1000\ \mathrm{fb}^{-1}$) can provide further improvements via the processes $e^+e^- \to \bar{\nu}_e\nu_e h$, $e^+e^- \to \bar{\nu}_e\nu_e hh$ and $e^+e^- \to t\bar{t}h$ [Barklow, Yamashita, Gay, Besson, Winter and others].

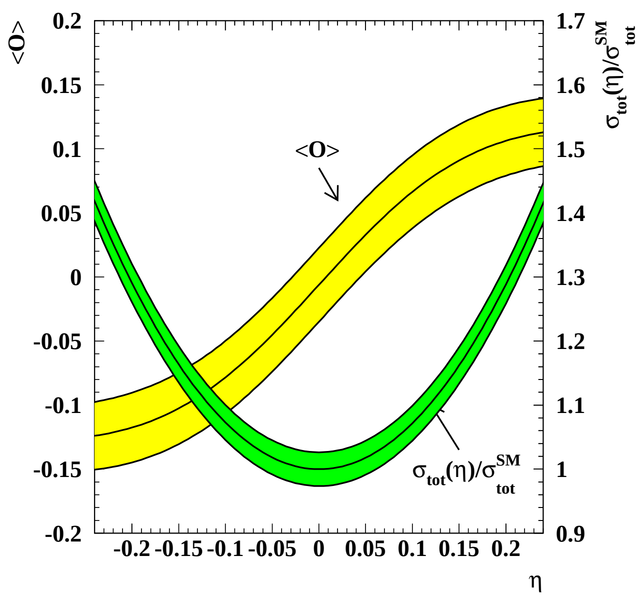
On the next slide, I exhibit the spin dependence [Dova *et al.*], and the CP determination at $\sqrt{s} = 350$ GeV (where η is the admixture of CP-odd scalar coupling to ZZ [Schumacher]) and at higher energies (where b is the admixture of P-odd coupling to $t\bar{t}$ [Dev *et al.*])



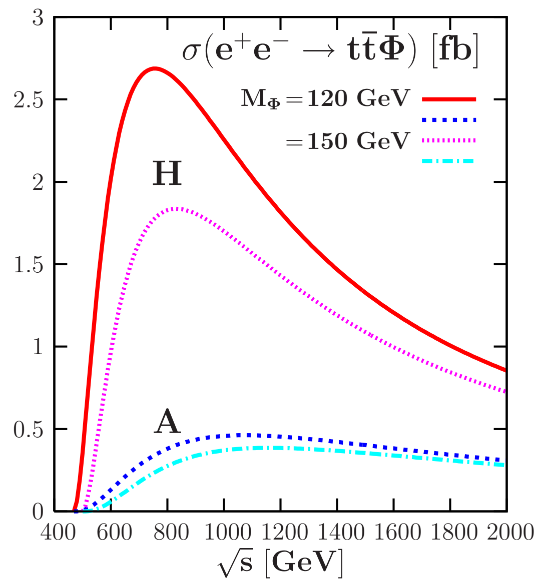
Coupling Mass Relation
Coupling constant to Higgs boson
Mass (GeV)
1
0.1
0.01
1
10
100
c
τ
b
W
Z
H
t



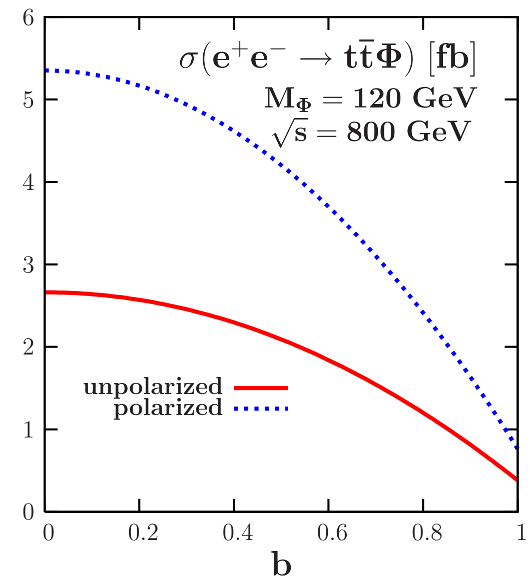
cross section (fb)
√s (GeV)
0
5
10
15
210
220
230
240
250
J=0
J=1
J=2



<O>
σ_tot(η)/σ^SM_tot
η
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
-0.2 -0.15 -0.1 -0.05 0 0.05 0.1 0.15 0.2
<O>
σ_tot(η)/σ^SM_tot



σ(e+e− → tt̄Φ) [fb]
M_Φ = 120 GeV
= 150 GeV
H
A
3
2.5
2
1.5
1
0.5
0
400 600 800 1000 1200 1400 1600 1800 2000
√s [GeV]



σ(e+e− → tt̄Φ) [fb]
M_Φ = 120 GeV
√s = 800 GeV
unpolarized
polarized
6
5
4
3
2
1
0
0 0.2 0.4 0.6 0.8 1
b

Interpretations of deviations from SM Higgs branching ratios

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),

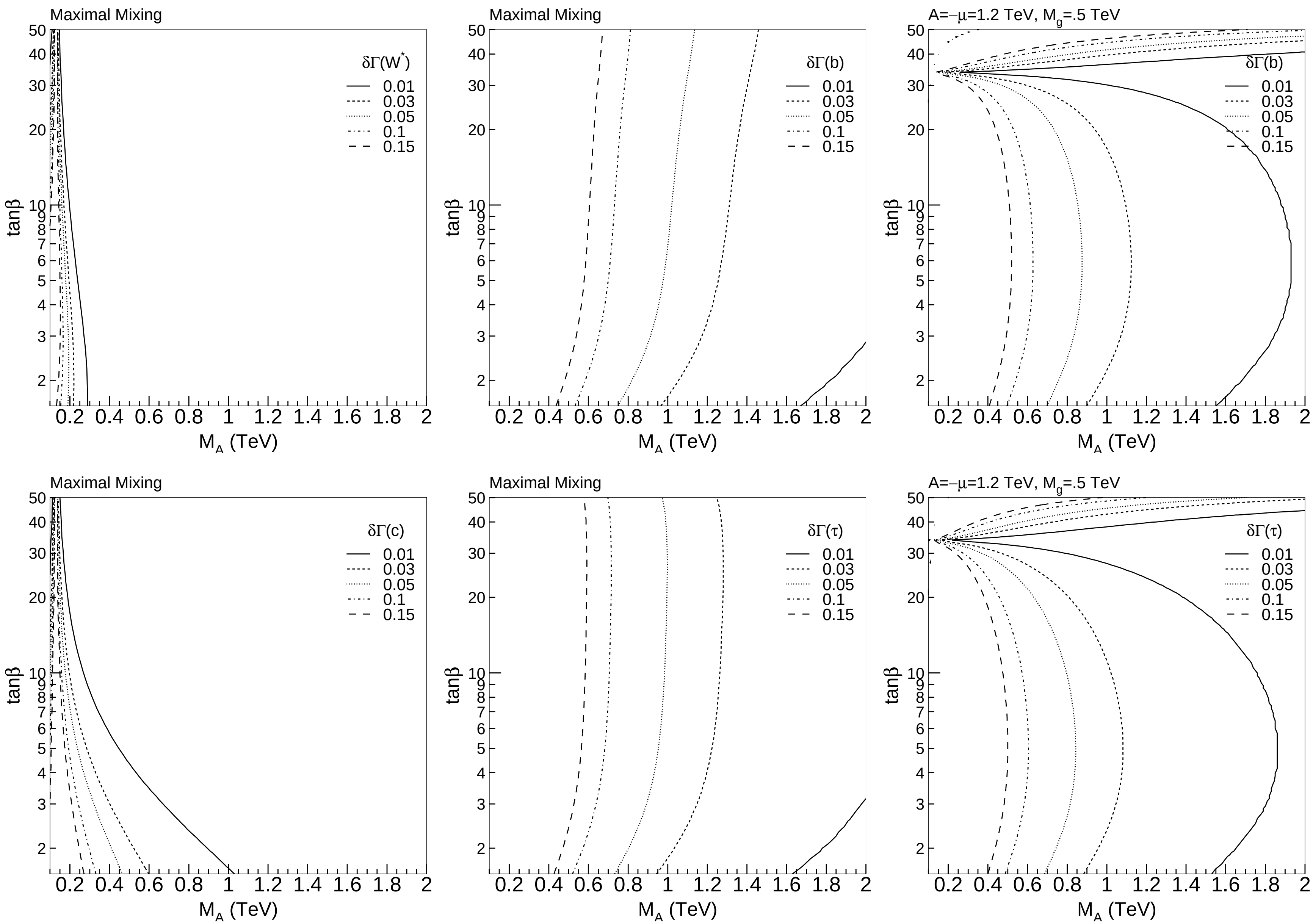
$$\frac{g^2_{hVV}}{g^2_{h_{\rm SM}VV}} \simeq 1 - \frac{c^2 m_Z^4 \sin^2 4\beta}{4m_A^4}\,,$$

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

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

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 Terascale dynamics.



Deviations of Higgs partial widths from their SM values in two different MSSM scenarios (Carena, Haber, Logan and Mrenna).

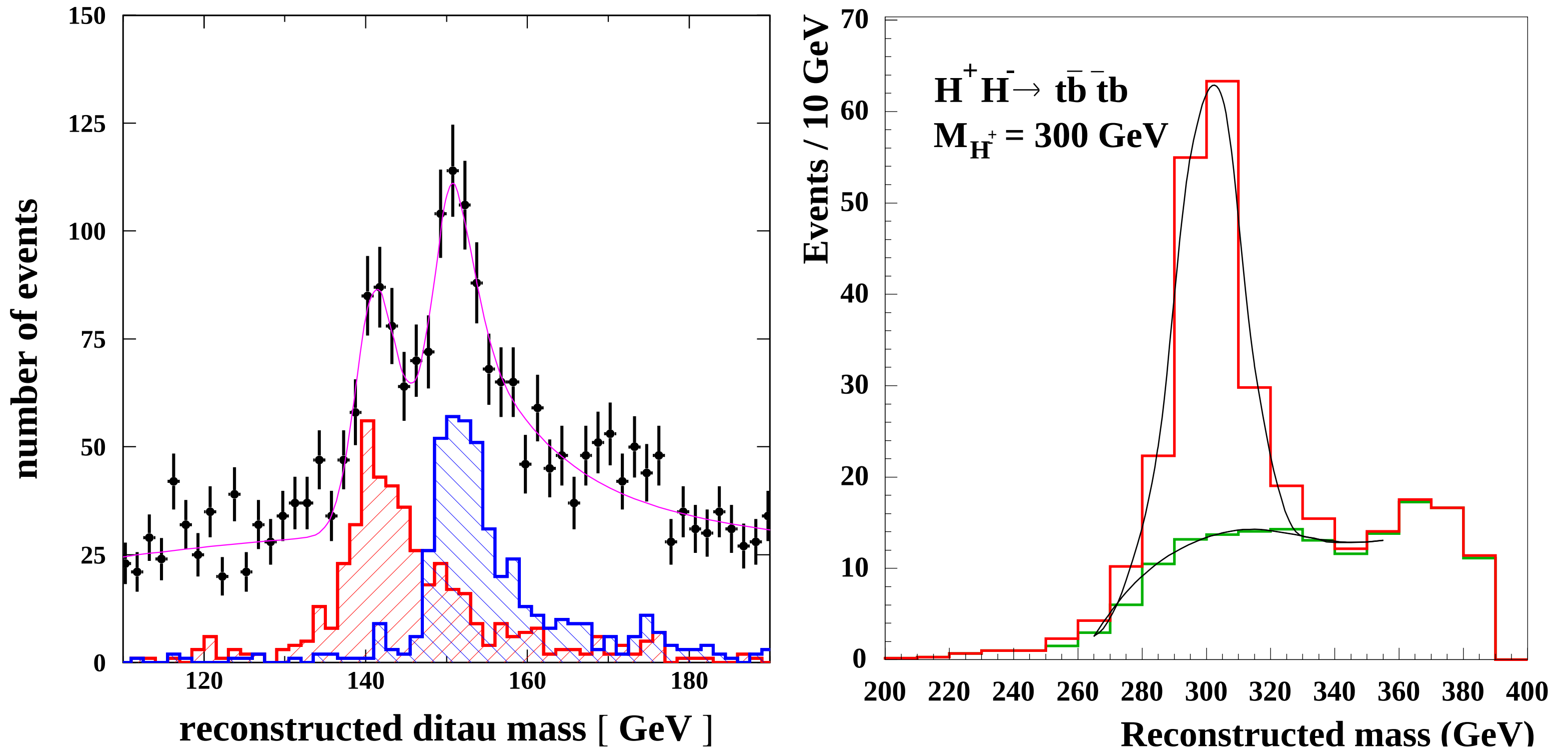
Beyond the SM Higgs boson

A plethora of possibilities:

- Non-minimal weakly-coupled Higgs sector (two-Higgs doublet models and beyond, additional singlets, ...)
- extra-dimensionally motivated scalars (radion, graviscalars, ...); gauge-Higgs unification
- pseudo-Goldstone bosons and their friends; little Higgs models and associated new dynamics
- strongly-interacting EWSB dynamics: heavy Higgs scalars; composite scalar bound states; Higgsless models
- unitarization of WW scattering

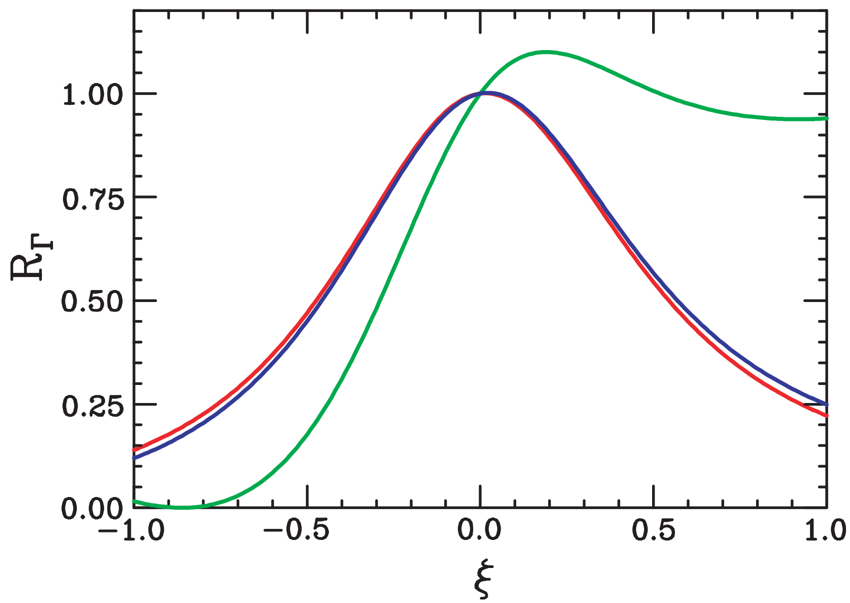
There are many model-building challenges—surviving precision electroweak constraints, avoiding little hierarchies, respecting unitarity, ...

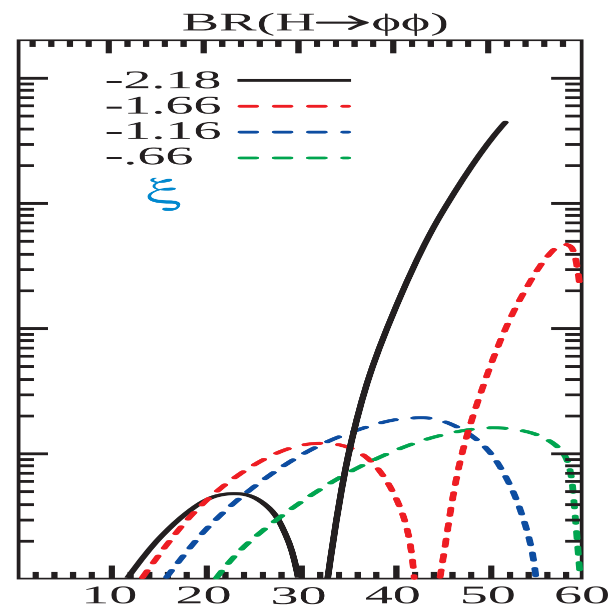
In the two-Higgs doublet model, the heavier CP-even, CP-odd and charged scalars are difficult to observe at the LHC in the parameter regime of moderate $\tan\beta$. At the ILC, detection of the associated production of H^+H^- and H^0A^0 is relatively straightforward assuming these final states are kinematically allowed.



Left pane: the reconstructed $\tau^+\tau^-$ invariant mass from a kinematic fit in $e^+e^- \to HA \to b\bar{b}\tau^+\tau^-$ for $M_A = 140$ GeV and $M_H = 150$ GeV at $\sqrt{s} = 500$ GeV with 500 fb^{-1} of data [K. Desch *et al.*]. Right pane: the dijet invariant mass distribution for $e^+e^- \to H^+H^- \to t\bar{b}\bar{t}b$ for $M_{H^\pm} = 300$ GeV after applying the intermediate W, t and equal mass final state constraints for 500 fb^{-1} of data at $\sqrt{s} = 800$ GeV [J.A. Aguilar-Saavedra *et al.*].

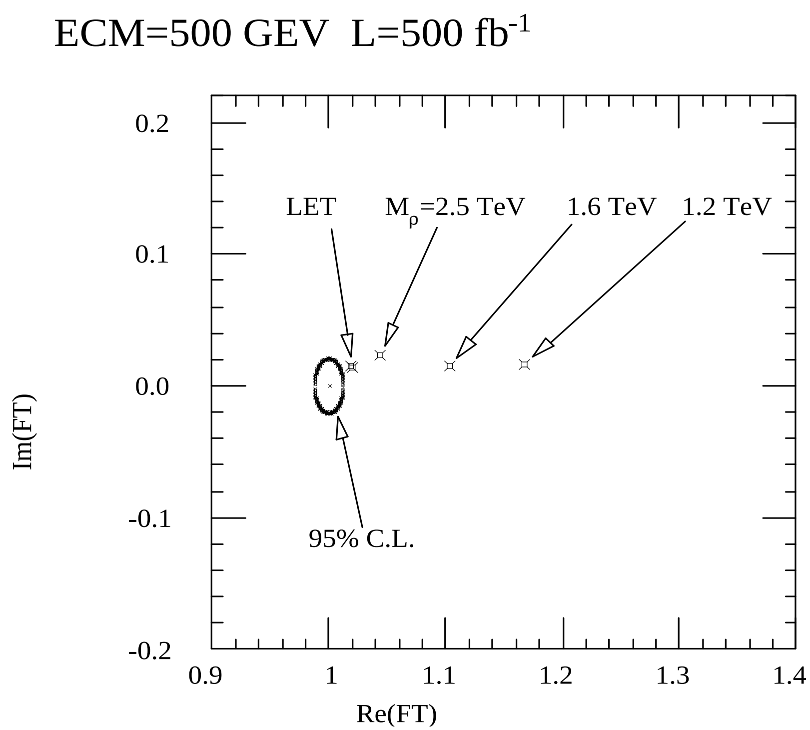
If the Higgs boson mixes with another scalar, then branching ratios can be altered. Below, we show the effect of Higgs-radion (H—ϕ) mixing in a warped extra-dimensional theory, where ξ is the mixing parameter and Λ is an energy scale, below which the theory effectively lives in three spatial dimensions. A new decay mode in which the Higgs boson decays into a pair of radions is also present.

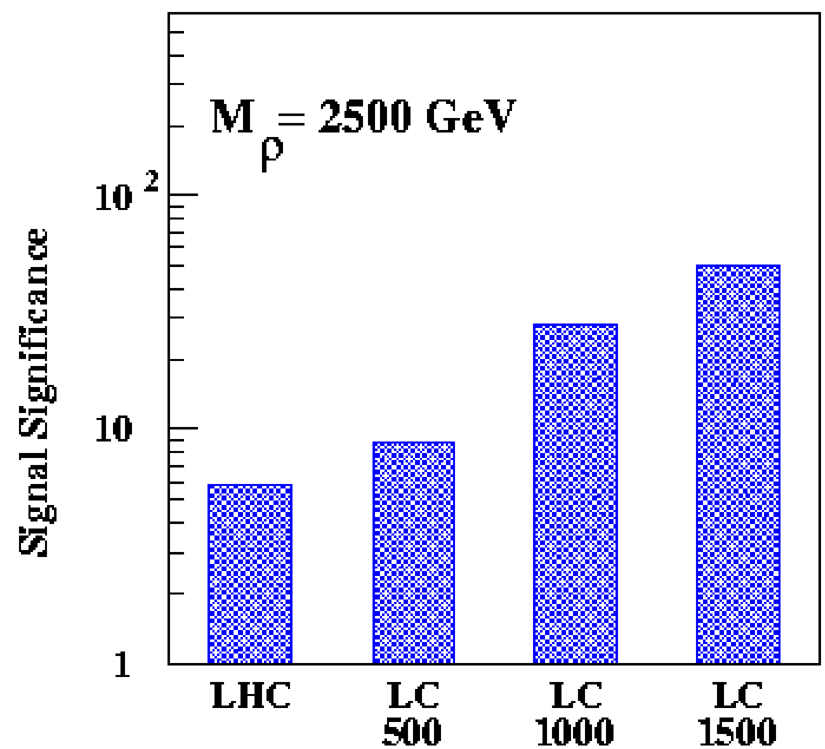




Left pane: the ratio R_Γ of the partial widths of the Higgs boson into ff/VV (red curve), $\gamma\gamma$ (blue curve) and gg (green curve) relative to their SM values, as a function of the mixing parameter ξ with $M_H = 125$ GeV, $M_\phi = 300$ GeV and $\Lambda = 1.2$ TeV [Hewett and Rizzo]. Right pane: the branching fractions for Higgs decay to a pair of radions for different ξ values and $M_H = 120$ GeV, with $\Lambda = 5$ TeV.

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 $\mathcal{L} = 500\ \mathrm{fb}^{-1}$ to strong EWSB dynamics. Data from $e^+e^- \to W^+W^-$ is combined with results for $e^+e^- \to \nu\bar{\nu}W^+W^-$, $\nu\bar{\nu}ZZ$ to produce the statistical significances shown here [Barklow, hep-ph/0112286].

Probing new physics at the Terascale

We expect a rich spectrum of particle masses associated with new physics at the Terascale. Many proposals for new physics have been considered:

- Weak-scale supersymmetry, and a spectrum of super-partners
- strong EWSB dynamics, and a spectrum of composite bound states
- little Higgs models, and a spectrum of new fermions (top partners), new gauge bosons and scalars
- extra-dimensional models, and a spectrum of Kaluza-Klein excitations
- generic new particles: vector-like fermions, new Ws and Zs, leptoquarks, diquarks, singlet fields, exotic quantum numbers, . . .

Most new phenomena (if present in nature) will first register their existence at the Tevatron and/or the LHC. Initially, the interpretation will be ambiguous. Precision studies at the ILC have the potential for employing critical measurements that can distinguish among models.

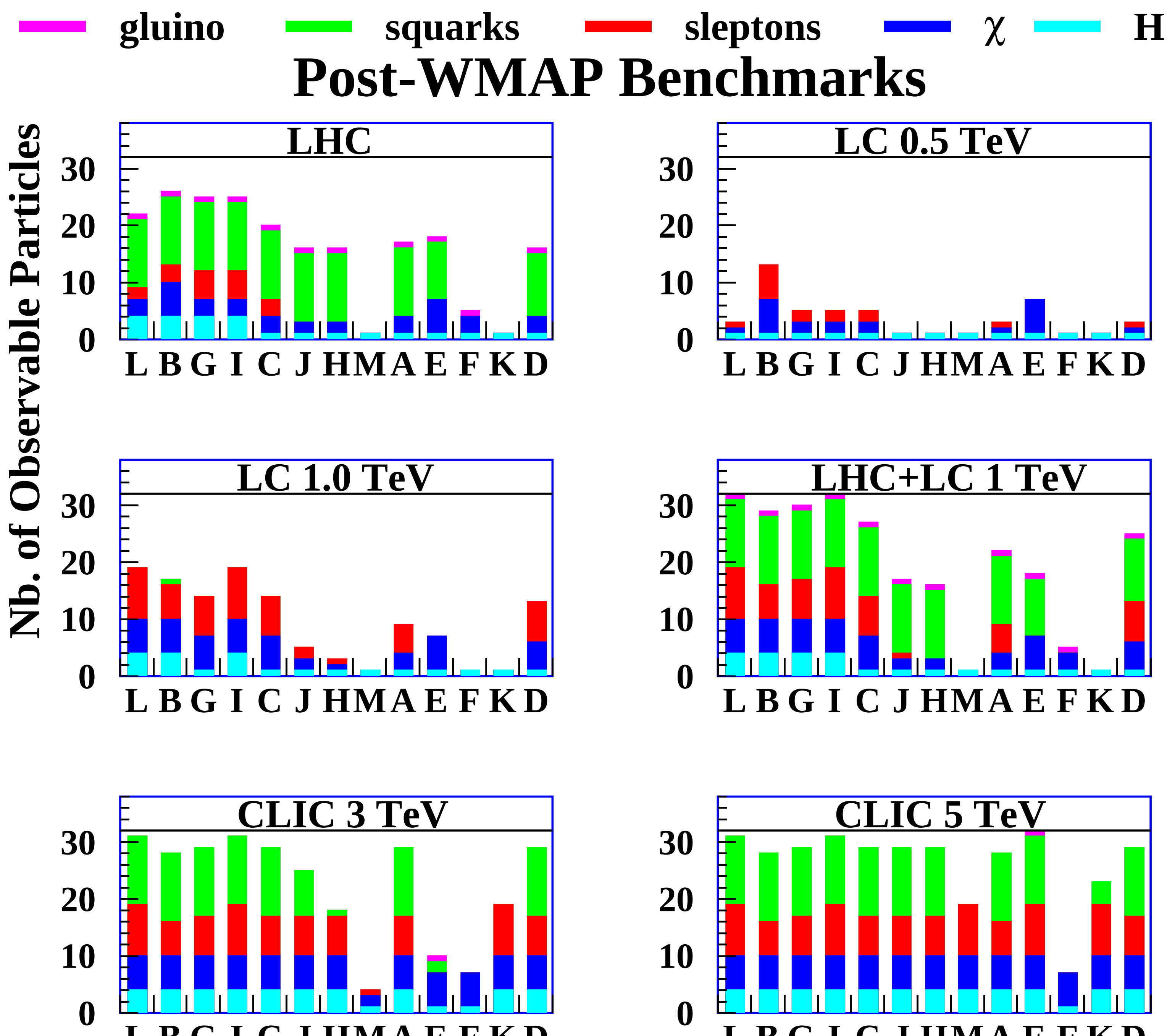
What fraction of the new particle spectrum lies within the kinematical reach of the ILC?

No definitive answer exists today. However, there is every expectation that LHC will be able to provide us with sufficient information to permit an informed response. To realize this expectation, a workshop entitled "The LHC Early Phase for the ILC" was initiated at Fermilab in April, 2007 and will be renewed this coming spring at SLAC (with a follow-up at CERN).

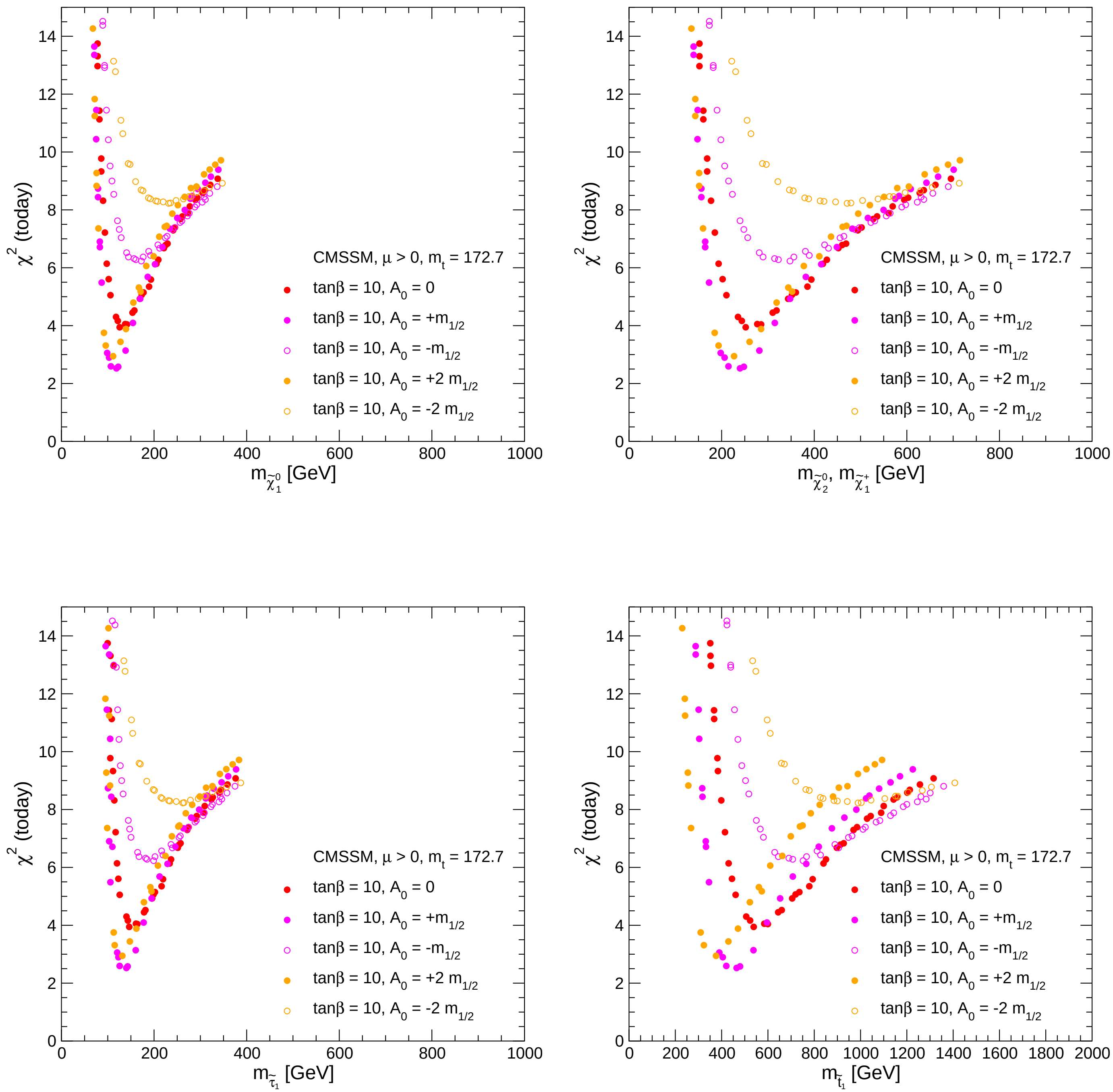
Nevertheless, it is fun to speculate based on all available constraints today in some framework for the new physics. Often, the same authors come to substantively different conclusions depending on the constraints employed. Consider the results of an analysis of expectations for super-partner masses:

Exhibit 1: M. Battaglia, A. De Roeck, J.R. Ellis, F. Gianotti, K.A. Olive and L. Pape, "Updated post-WMAP benchmarks for supersymmetry," Eur. Phys. J. **C33**, 273 (2004)

Exhibit 2: J.R. Ellis, S. Heinemeyer, K.A. Olive and G. Weiglein, "Phenomenological indications of the scale of supersymmetry," JHEP **0605**, 005 (2006)



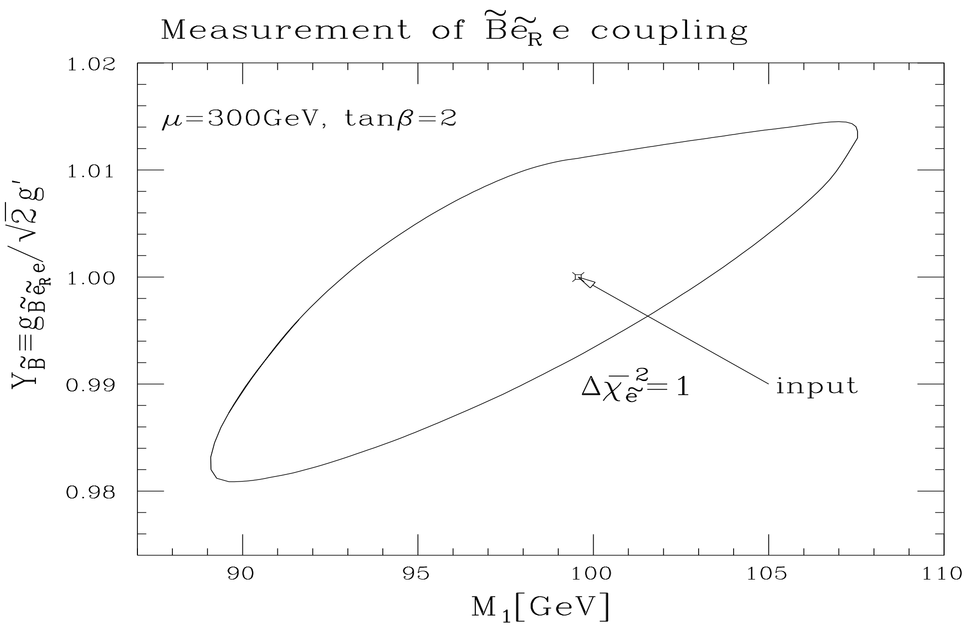
gluino
squarks
sleptons
χ
H
Post-WMAP Benchmarks
Nb. of Observable Particles
LHC
LC 0.5 TeV
LC 1.0 TeV
LHC+LC 1 TeV
CLIC 3 TeV
CLIC 5 TeV
0
10
20
30
L B G I C J H M A E F K D



CMSSM, μ > 0, m_t = 172.7
tanβ = 10, A_0 = 0
tanβ = 10, A_0 = +m_1/2
tanβ = 10, A_0 = -m_1/2
tanβ = 10, A_0 = +2 m_1/2
tanβ = 10, A_0 = -2 m_1/2
χ^2 (today)
m_χ̃⁰_1 [GeV]
m_χ̃⁰_2, m_χ̃⁺_1 [GeV]
m_τ̃_1 [GeV]
m_t̃_1 [GeV]

Project: confirming and elucidating weak-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.
  - Confirm SUSY expectations for the Higgs sector [model-dependent].
  - Verify that particle/sparticle interaction vertices are related to the corresponding SM vertices by the expected supersymmetric relations.



[Nojiri, Fujii and Tsukamoto]

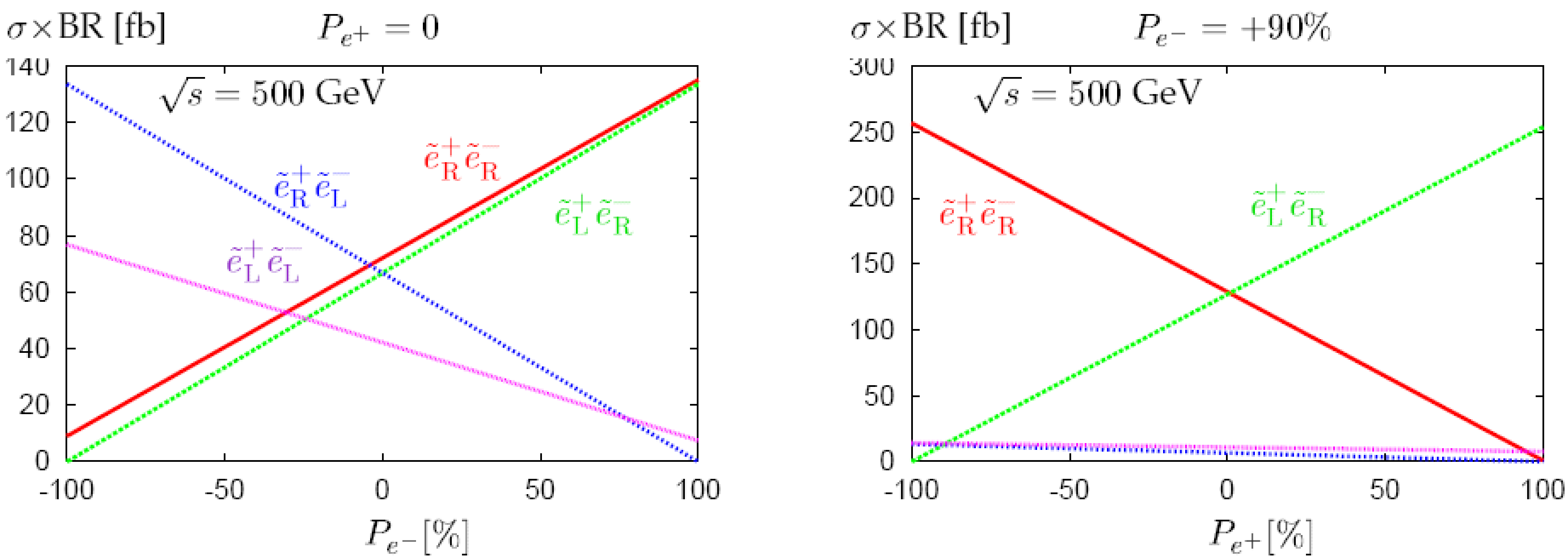
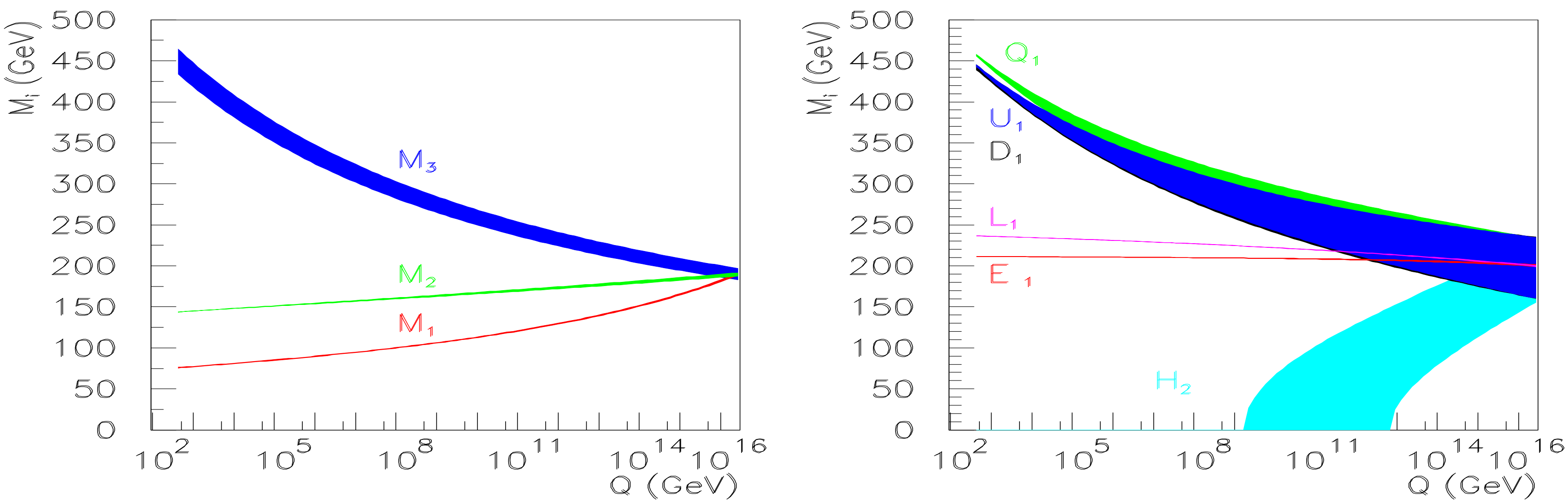


Figure 3.2: Separation of the selectron pair $\tilde{e}_L^+\tilde{e}_R^-$ in $e^+e^- \to \tilde{e}_{L,R}^+\tilde{e}_{L,R}^- \to e^+e^-2\tilde{\chi}_1^0$ is not possible with electron polarization only (left panel). If, however, both beams are polarized, the cross sections (right panel) differ and the RR configuration separates the pair $\tilde{e}_L^+\tilde{e}_R^-$ [84]. The SUSY parameters are chosen as in scenario S1, table 3.1.

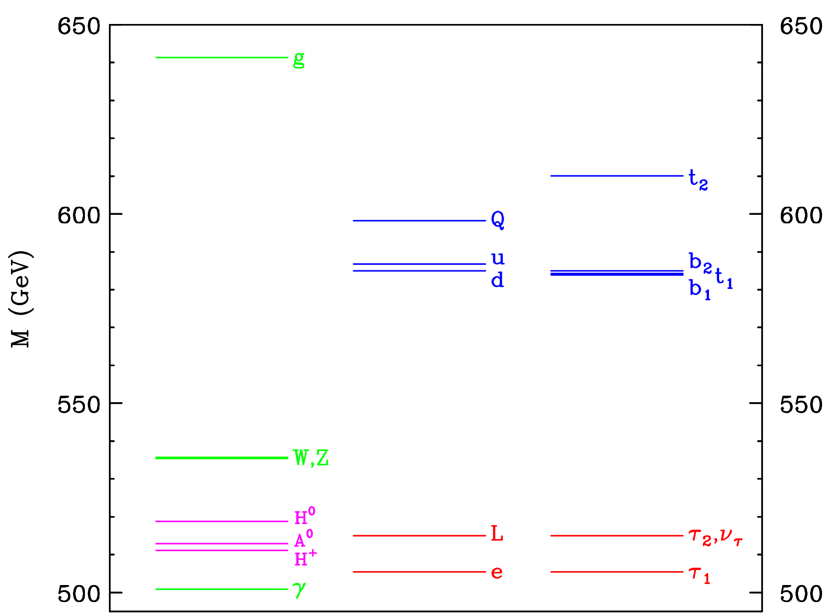
- Do supersymmetric breaking parameters exhibit any definite organizing principle?
  - Are there simplifications when low-energy parameters are extrapolated to the GUT/Planck scale?



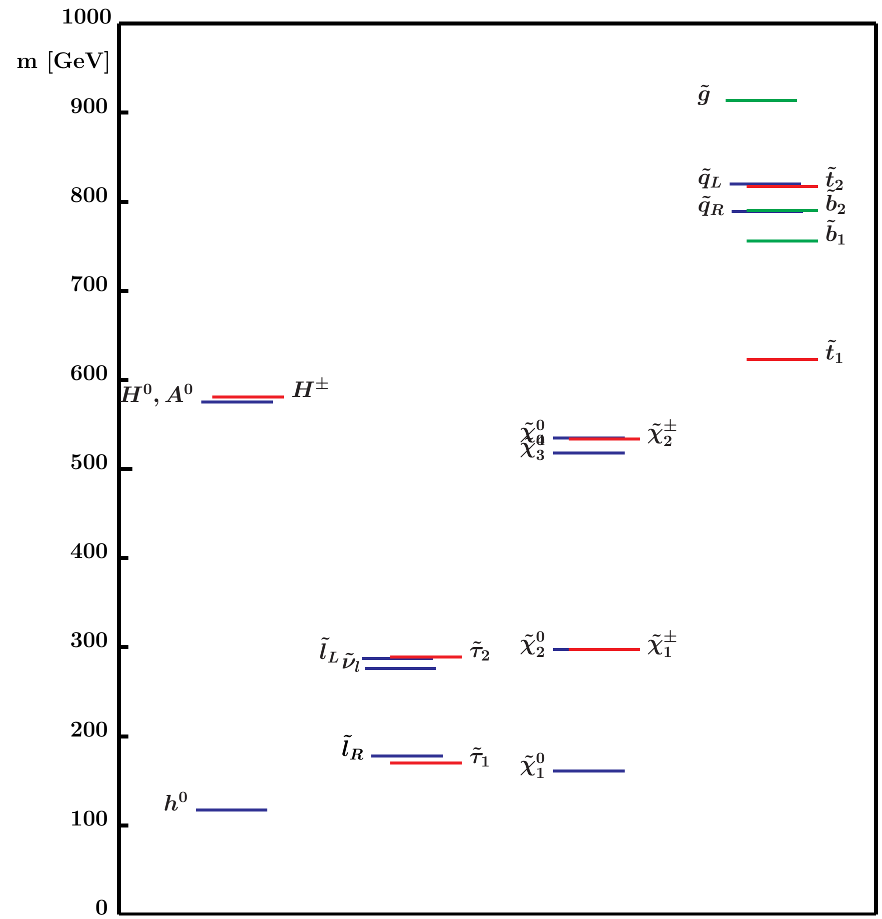
RGE evolution of gaugino (left) and scalar quark and lepton (right) mass parameters from the electroweak scale to the GUT scale in an mSUGRA model with $m_0 = 200$ GeV, $m_{1/2} = 190$ GeV, $A_0 = 500$ GeV, $\tan\beta = 30$ and $\mu < 0$. The bands indicate 95% CL contours. [Blair, Porod and Zerwas].

Project: distinguishing among new physics interpretations

An example: models of weak-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.

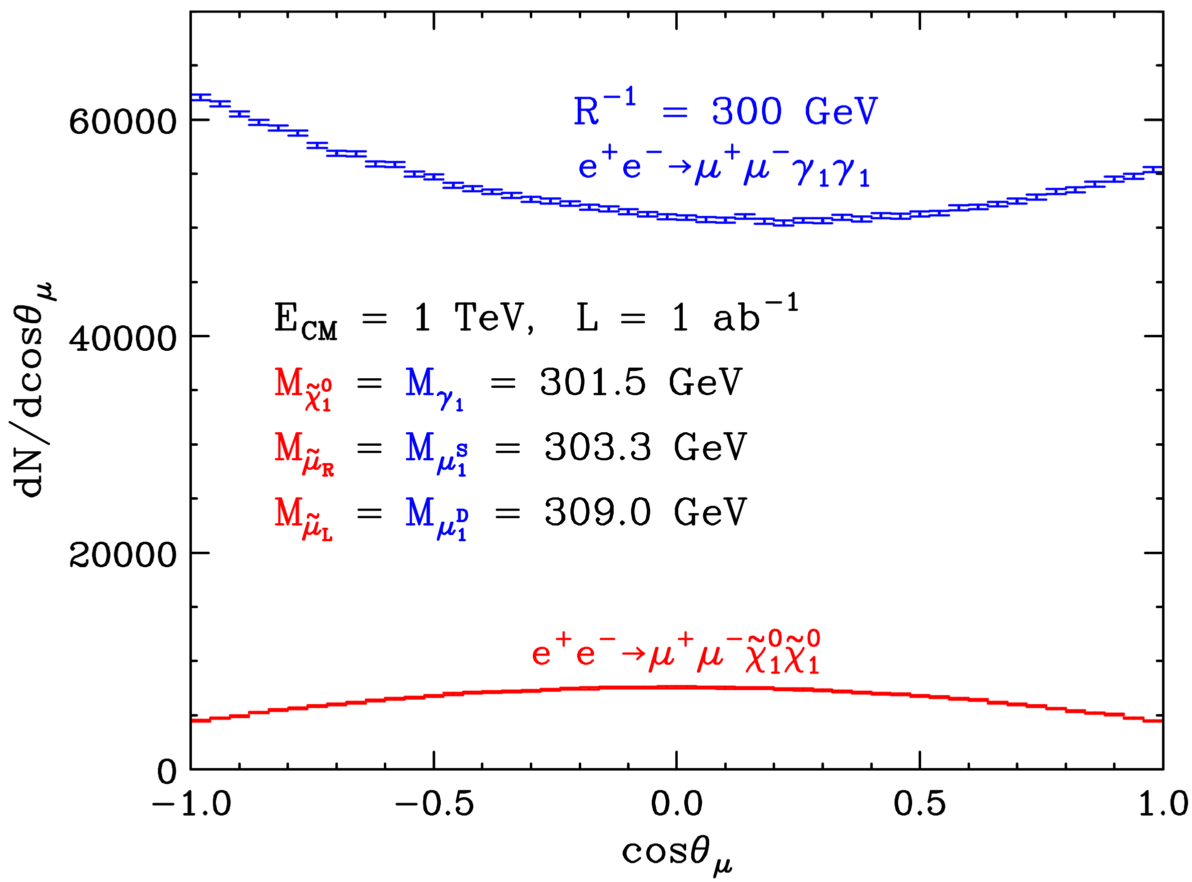


first KK level in minimal UED



mSUGRA benchmark “SPS 3”

Models of weak-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].



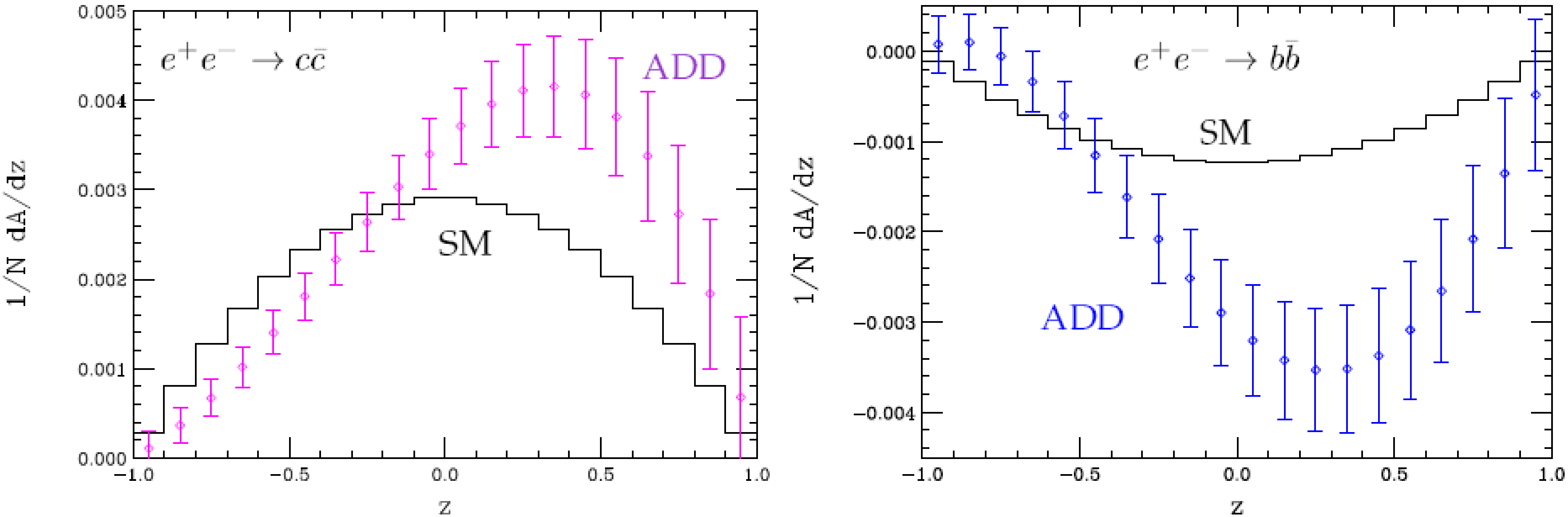
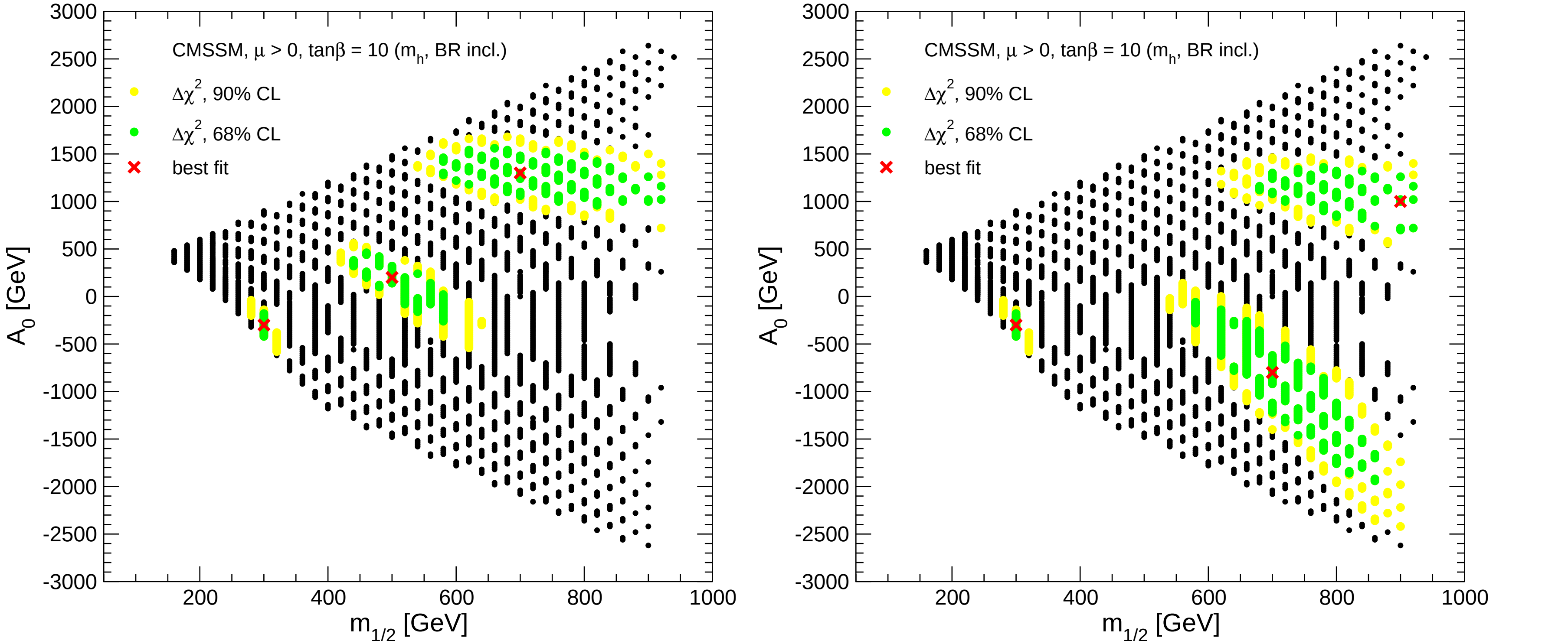


Figure 3.28: Differential azimuthal asymmetry distribution for $e^+e^- \to f\bar{f}$, i.e. $c\bar{c}$ (left) and $b\bar{b}$ (right), at a 500 GeV LC assuming a luminosity of 500 fb^{-1}, $z = \cos\theta$. The histograms are the SM predictions while the data points assume the ADD model with $M_H = 1.5$ TeV; $(P^{\rm T}_{e^-}, P^{\rm T}_{e^+}) = (80\%, 60\%)$ [169].

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, $\sin^2\theta_{\rm eff}$, 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].

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. Consequently, a thorough understanding of the physics of electroweak symmetry breaking and a comprehensive exploration of Terascale physics will have a profound impact on cosmology. Possible contributions of the ILC include:

- 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 profound!

Complementarity and Synergy

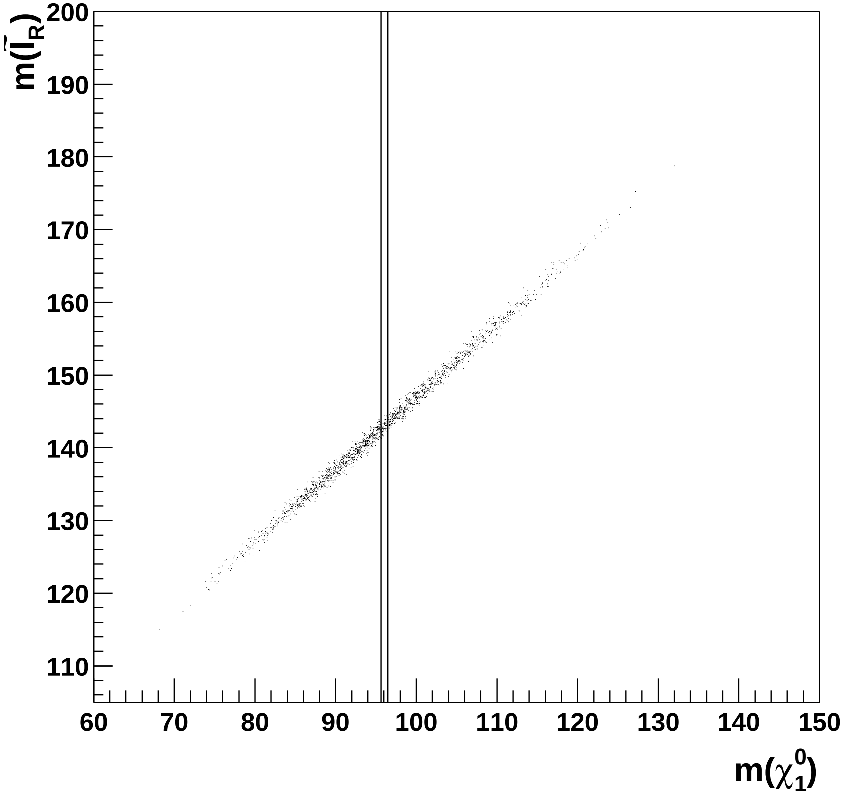
The LHC and ILC provide complementary approaches to the Terascale, in the same way that the CERN S$p\bar{p}$S/Tevatron and LEP/SLC provided complementary approaches to the 100 GeV scale. If the ILC is constructed to operate at some point during the LHC era, then there is potential for a synergetic interplay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

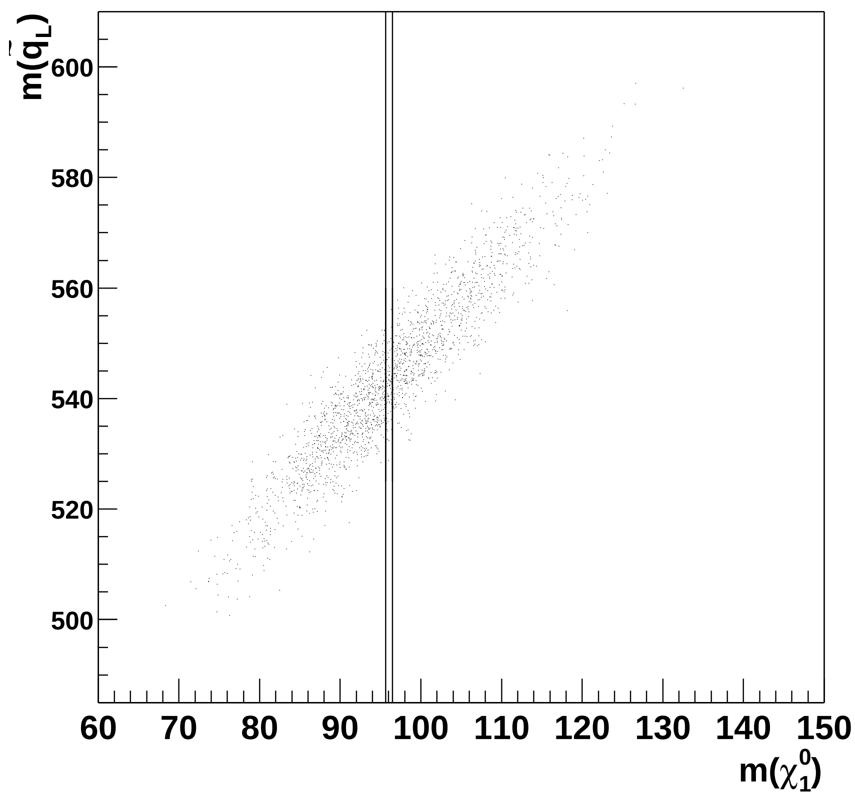
- The combined interpretation of LHC and ILC data can yield a more unambiguous interpretation of the underlying physics than the results of both colliders taken separately.

- 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.

example of LHC/ILC interplay

Precision ILC measurements of the light neutralino/chargino states in weak-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.*].