Physics Landscape at a Linear Collider

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Physics Landscape at a Linear Collider

- Introduction:
  Physics Landscape $\Longrightarrow$ the state of the art
- The role of the LC in the search for new physics

– Precision Measurements

$\star$ Gauge bosons Couplings $\star$ Contact interactions

– Direct Searches for New Particles

$\star$ SM and extended Higgs sectors $\star$ Supersymmetry

$\star$ Extended Gauge sectors $\star$ Strong Dynamics

$\star$ Extra Dimensions

– Precision measurements at the "low energy" linear collider (**Andre's talk**)

Introduction

• Standard Model $\Longrightarrow$ the pillar of particle physics that explains data collected in the past several years and provides explanation of nature up to energies of $\approx$ 100 GeV.
But, is only an effective theory

• Many open questions $\Longrightarrow$ crucial to get the complete picture valid up to higher energies, M_{Pl}

$\star$ origin of EWSB
$\star$ generation of stabilization of hierarchies:
M_{weak} Vs M_{Planck}
$\star$ connection of electroweak and strong interactions with gravity
$\star$ generation of fermion masses and mixings
$\star$ explanation of baryon asymmetry of the universe
$\star$ dark matter

• **Collider Experiments**:
Tevatron, LHC, LC (TeV reach)
are our most robust handle to reveal the new physics that should answer most of these questions

EWSB occurs at the TeV scale

In the abscence of big fine-tuning of scales

$\Longrightarrow$ New Phenomena should lie in the TeV range or below

Numerous theories have been proposed:

two broad classes:

- weakly coupled dynamics
- strongly coupled dynamics

• Standard Model $\rightarrow$ example of weak EWSB

self interacting complex scalar doublet, v.e.v. of the neutral component, $v \Longrightarrow$ scale of EWSB

gives mass to W/Z and also to fermions via Yukawa int.

one physical state left in the spectrum $\equiv$ <u>HIGGS Boson</u>

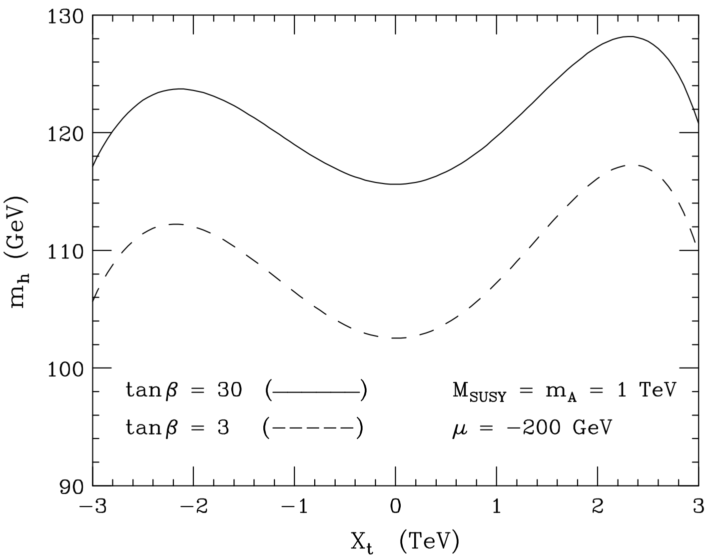
<u>Present Data</u> $\rightarrow$ no direct evidence of Higgs but can be used to discriminate among different approaches

- SM with weakly coupled Higgs is in excellent agreement with precision data $\Longrightarrow m_{H_{SM}} \leq 210$ GeV at 95 % C.L.

• In weakly coupled approach, SM most probably embedded in SUSY theory

fermion-boson symmetry $\rightarrow$ stabilization of hierarchy between v and M_{Pl}

SUSY Theories $\Longrightarrow$ larger Higgs sector with lightest Higgs having (usually) SM-like properties and $m_h \leq 200$ GeV
MSSM: simplest extension ($m_h \leq 135$ GeV)



SUSY must be broken in the ground state so that SUSY partners heavier than SM particles

However, if SUSY exists, many of its most important motivations

- ⋆ solve hierarchy problem
- ⋆ play central role in unification of couplings
- ⋆ provide a good dark matter candidate
- ⋆ provide a possible solution to baryogenesis

demand some SUSY particles at the TeV range or below

Many mechanisms of SUSY breaking proposed $\Longrightarrow$ different patterns of SUSY breaking masses yield totally different phenomenology at collider energies

– Strongly Coupled Dynamics

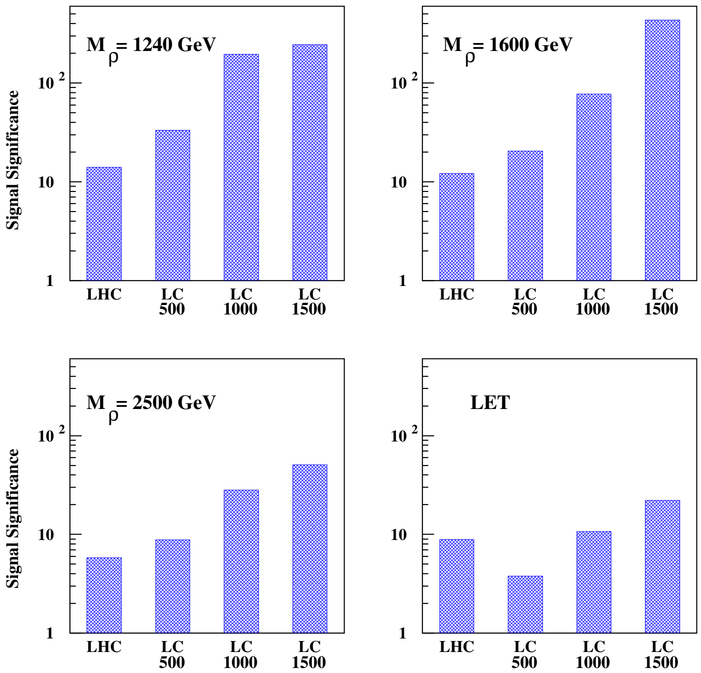
(a) Models which do not require a Higgs Boson

$\Longrightarrow$ Strong interactions at the TeV scale: Technicolor

Generic idea: new gauge interaction which is asymp. free and becomes strong at scales of order 1 TeV
$\rightarrow$ new fermions (technifermions) feel this interaction and form condensates which break the EW Symmetry

$\star$ Severely constrained by precision measurements.

Robust prediction: vector resonance with mass $\lesssim$ 2 TeV (unitarizes WW scatt.)

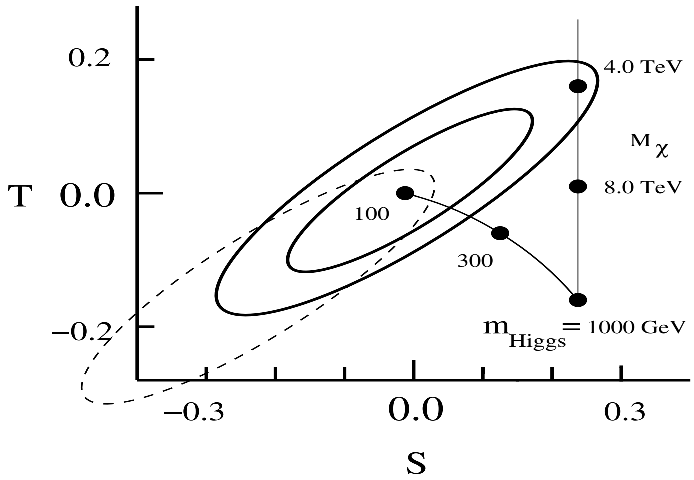


Key components: Strong WW scattering; Anomalous gauge couplings; Extra scalars $\rightarrow$ composites of underlying strongly coupled fermions

(b) Strong interactions above TeV scale give rise to bound states $\Longrightarrow$ including Higgs boson:
Composite Higgs Models

Higgs could be light and weakly coupled at EW scale.

Top quark seesaw theory: Higgs is a bound state of left-handed top and right-handed component of a new vector like fermion
$m_H \simeq 500$ GeV, but new contributions from add. quarks $\rightarrow$ agreement with precision data.

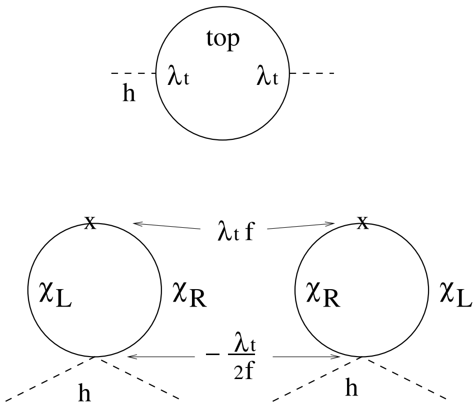


Low energy possible signatures:
Extended Higgs sector at TeV scale or below $\rightarrow$ mixing can bring the SM-like Higgs down to 200 GeV;
Extra Fermions; Heavy vector bosons.

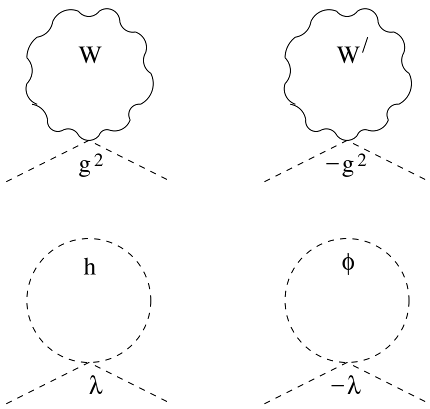
(c) Little Higgs Models:

Higgs as a Pseudogoldstone Boson

Non-linearly realized symmetry yields cancel. quadratically divergent quantum corrections between fields of same spin $\Longrightarrow$ new fermionic partners for SM quarks and leptons and new gauge boson partners for SM gauge fields at the TeV scale or below.



A fermion loop cancels a fermion loop. Similarly, the gauge and Higgs loops are canceled by diagrams with new bosons in loops.



Cancellation of quadratic divergences works at one loop: New Dynamics needed at scales of order 10 TeV or so.

A daring alternative:Extra Dimensions

If sufficiently small they are compatible with data.
They provide novel explanations to the SM puzzles.

- if seen by SM particles $\longrightarrow$ they should be quite small: R $\leq 10^{-17} cm \approx 1/TeV$
- if not seen by SM particles, only by gravity $\longrightarrow$ they can be larger: R $\leq 1mm$

After compactification of the ED: extra tower of states (KK modes of graviton or SM particles) propagate in 3+1 d.

Solution to hierarchy of scales: M_{weak} scale results from the fact that some gravity mass scale in higher dim., either size of new dim. or the intrinsic mass scale of gravity, is order 1 TeV

- If gravity propagates in the extra dimensions $\Longrightarrow$ Newton's law modified: $M_{Pl}^2 = (M_{Pl}^{fund.})^{2+d} R^d$

$\Longrightarrow$ this lowers the fundamental Planck scale, depending on the size and number of ED

- solution to hierarchy problem: but why is R so large!?

Possible solution to hierarchy problem $\rightarrow$ warped space:

Metric: $ds^2 = e^{-2\sigma} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2$

$\Longrightarrow$Solution to 5d Einstein eqs.

5d Planck mass relates to M_{Pl}:

$$M_{Pl}^2 = \frac{(M_{Pl}^{fund.})^3}{2k}(1 - e^{-2kL})$$

Assuming fundamental scales of the same order:
$M_{Pl} \sim M_{Pl}^{fund.} \sim v \sim k$ (k: warp factor)
$\Longrightarrow$ Physical Higgs v.e.v. suppressed by e^{-kL}

$$\tilde{v} = v\ e^{-kL} \simeq M_{Pl}\ e^{-kL}$$

$kL \approx 34 \Longrightarrow$ good solution to the hierachy problem

- TeV-scale Extra dimensions or warped extra dimensions

$\Longrightarrow$ Standard Model fields may feel their effects

In the search for new particles, the LC is not only complementary to the LHC but **it provides unique pathways which may be the only opportunity to unravel complex scenarios beyond the SM**

• Precision measurements of gauge boson couplings

Anomalous Trilinear Gauge Couplings (WWγ or WWZ vertices)
Anomalus Quartic GC's from genuine 4 and 6 dim op.

extremely useful in understanding new physics processes:
– if many new particles discovered (SUSY) $\rightarrow$ to reflect particle properties via rad. correc.
– if no new particle or even Higgs resonances $\rightarrow$ self coupling may provide window to EWSB

• Direct Searches for new particles

⋆ **New gauge bosons from extended gauge sectors: Z', W'**

in GUT's, Left-Right symmetric models, Topcolor, KK excitations of SM gauge bosons in ED

Model independent studies of Z' at threshold: LC sensitivity even for very small couplings **Ayres' talk**

Also indirectly via 4-Fermi interactions: W' and Z' beyond threshold (corrections to $e^+e^- \rightarrow f\bar{f}$ and $e^+e^- \rightarrow \nu\bar{\nu}\gamma$)

⋆ **Exotic Fermions:** (**Bogdan's talk**)

• Sequential repetition of SM generations (same q.n. assignments)

• Mirror fermions (chiral properties opposite to SM counterparts)

• Vector-like Fermions (same weak isospin representation for left- and right-handed components).

⋆ **Techni-fermions, techni-pions, techni-rhos**

⋆ **Leptoquarks**

⋆ **KK modes from Extra Dimensional Theories**

– In flat ED

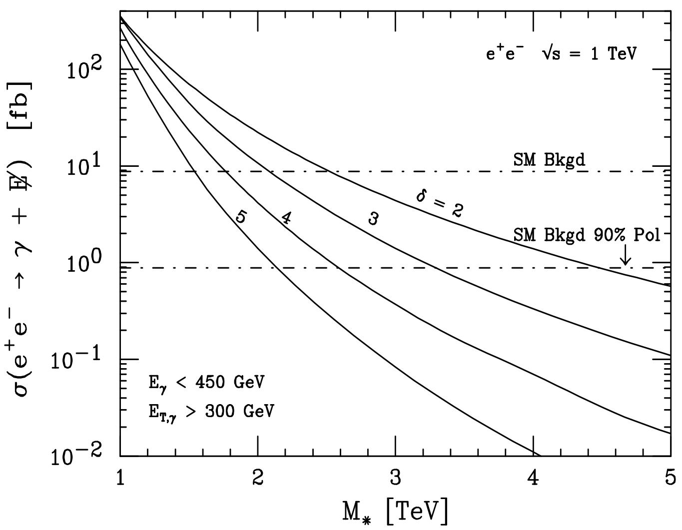
$\Longrightarrow$ coupling of gravitons to matter with $1/M_{Pl}$ strength

$M_{G_n} \simeq 10^{-2}$ GeV (d=2); $M_{G_n} \simeq 10^{-4}$ eV (d=6);

(a) Emission of KK graviton tower states

$e^+e^- \rightarrow \gamma/Z + G_n$ (Graviton $\longrightarrow$ missing energy)

Cross section summed over full KK tower $\Longrightarrow \sqrt{s}/M_{Pl}^{fund}$ emitted graviton appears as continuous mass distribution.

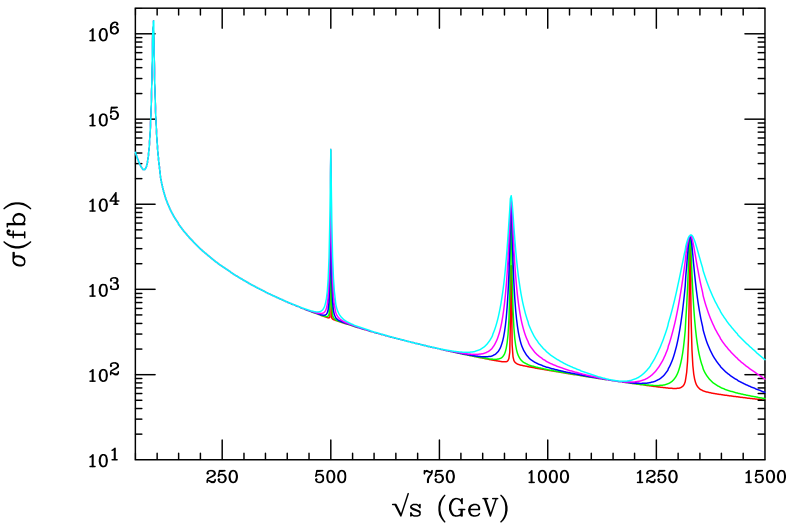


(b) Graviton exchange in $2 \to 2$ scattering
deviations for $e^+e^- \to f\bar{f}$ or new decays into hh or $\tilde{g}\tilde{g}$
Limitation: integral over sum of state is divergent $\Longrightarrow$ sensitivity to UV physics.

If SUSY also present $\Longrightarrow$ KK tower of gravitinos as well, important in light gravitino SUSY breaking scenarios
(example: $e^+e^- \to \tilde{e}^-\tilde{e}^+$)

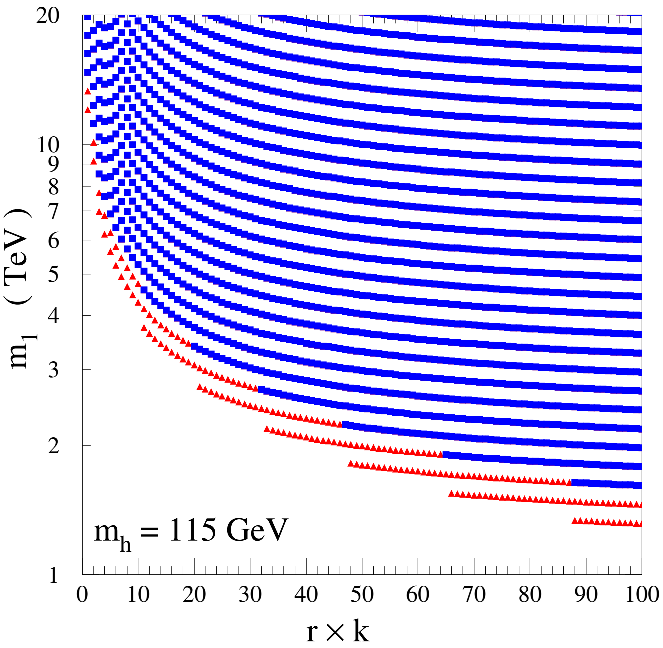
- In warped ED $\Longrightarrow$ Graviton KK modes have 1/TeV coupling strength to SM fields and unequally spaced masses starting with a few hundred GeV

(a) KK graviton states produced as resonances or, if too heavy, may give contributions to fermion pair production



$e^+e^- \to \mu^+\mu^-$ including KK graviton exchange, $m_1 = 500$ GeV.

(b) SM gauge fields also propagate in the bulk, keeping SM fermions and the Higgs on the TeV brane. Sizeable gauge brane kinetic terms ($r \times k \geq 10$) to have KK modes of order TeV compatible with precision data

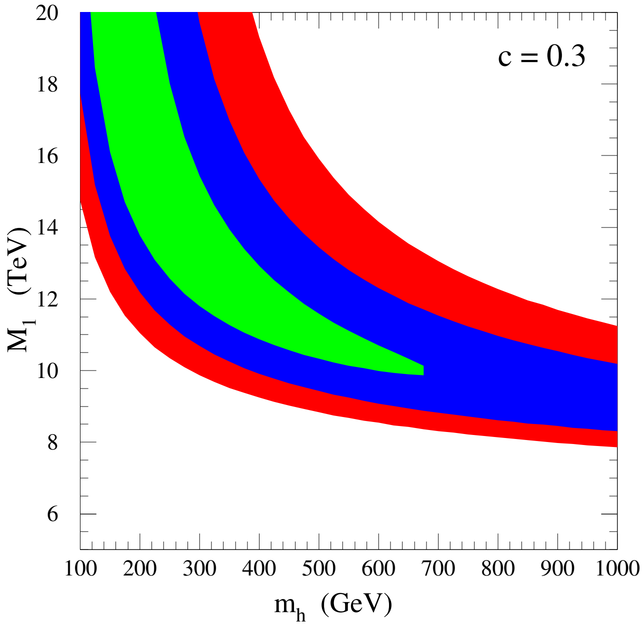


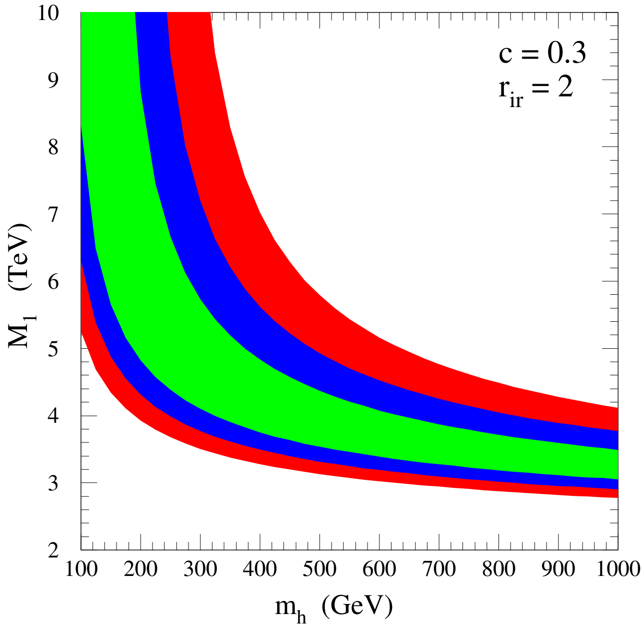
Regions of 2σ, 3σ (blue,red) agreement with precision EW observables, in the plane $r \times k$ and the 1st KK photon mass. (**M.C, Ponton, Tait, Wagner**)

- For $r \to 0 \Longrightarrow m_1 \gtrsim 20$ TeV.

- For $r \times k \sim 20$ and $m_1 \sim 3.5$ TeV $\Longrightarrow$ fit to the entire data set as good as in the SM

(c) SM fermions and gauge fields in the bulk: phenomenology depends on the 5d fermion mass. Strong constraints from precision meas., FCNC, perturbativity of Yukawa couplings, etc.
Possible to have theories with some KK modes in the few TeV range





Regions of 1σ, 2σ, 3σ (green,blue,red) agreement with the electroweak fit in the the Higgs–1st KK mode mass plane

- Fit to data significantly improved for $m_h \geq 300$ GeV

Larger gauge kinetic term in TeV-brane allows for a light KK mode mass of a few TeV (**M.C, Ponton, Tait, Wagner**)

TeV extra dimensions

$\Longrightarrow$ many possibilities for SM fields in the bulk

• SM gauge fields propagate in ED $\Longrightarrow$ extra gauge bosons contribute to EW corrections (masses of a few TeV)
Sizeable brane kinetic terms $\rightarrow$ allow masses of a few 100 GeV

• Higgs in the bulk; or in the wall (expected in warped ED) $\rightarrow$ effects on precision meas. due to deformation of W/Z zero mode wave functions

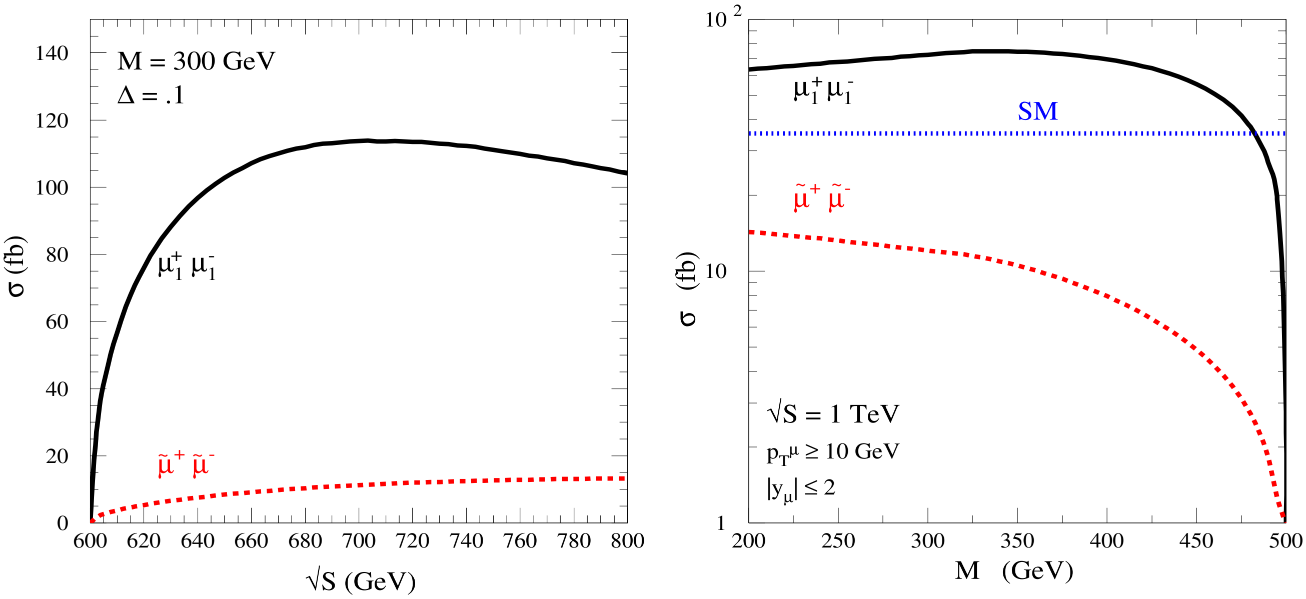
• fermions in the wall; or in localized points in the bulk

(a) Universal Extra Dimensions: All fields in the bulk, no wall or branes $\rightarrow$ momentum conserved in ED $\rightarrow$ KK modes produced by pairs, no big corrections to EW obs., good dark matter candidate

Important property:
Spectrum of 1st KK excitations can mimic a SUSY spectrum, but particles have different spin

LC has the unique opportunity of distinguishing SUSY from UED: examine p- versus s-wave production wave

Comparison of cross section production for smuon pairs Vs first KK mode muon pairs (Tait et al. in prep.)



(left) $e^+e^- \to \mu_1^+\mu_1^- (\tilde{\mu}^+\tilde{\mu}^-)$ as a function of $\sqrt{S}$, for $M = 300$ GeV. (right) $e^+e^- \to \mu_1^+\mu_1^- (\tilde{\mu}^+\tilde{\mu}^-)$ at a 1 TeV LC, as a function of M.

⋆ **Supersymmetry**

(a) Measurements of SUSY particles masses

$\Longrightarrow$ sleptons, charginos, neutralinos with accuracies of 1 % or less

- via Kinematic Endpoints : from energy distributions of the products of on-shell superpartner decays
- from threshold scans
- from contributions of virtual superpartners to σ's or decay amplitudes (more model dependent)

(b) Measurement of SUSY parameters

- from chargino/neutralino productions and subsequent decays $\rightarrow$ measure masses and gaugino higgsino mixing angles

$\Longrightarrow$ determine MSSM parameters : μ, M_2 and $\tan\beta$ with about 1 % accuracy ($\tan\beta$ also input from Higgs sector)

- Slepton and Squark mixing angles: from measuring production cross section with polarized beams

(c) Spin of SUSY particles:

Simplicity of production reactions makes spin determination possible from angular distributions

(e) Tests of SUSY, investigating coupling relations

SUSY implies that SM gauge coupling, g_i are equal to their SUSY analogues: gaugino-fermion-sfermion couplings, h_i

At the loop level the above hard susy relations receive corrections which vanish in the SUSY limit $\rightarrow$ Super-oblique correc. analogous to oblique correc. in SM

$$\tilde{U}_i \equiv \frac{g_i(m)}{h_i(m)} - 1 \simeq \frac{g_i^2(m)}{16\pi^2} \Delta b_i \ln(M/m)$$

where some scalar-fermion has high mass M and the rest have m $\simeq M_{weak}$ and Δb_i is the one loop β function of all particles with heavy superpartners

Super-oblique parameters are non-decoupling with large M and they can provide a rare window on heavy sfermions!!

Different methods to verify SUSY coupling relations at LC (see Ayres' talk)

(f) Interesting possibilities in Symmetry Violating Phenomena

- R-parity Violation
- CP Violation
- Lepton Flavour Violation

What do we need to know about the Higgs?

i) *Observe the Higgs*

ii) *Measure its basic properties*

- mass
- width
- spin
- CP quantum numbers

iii) *Measure its Couplings*

- to gauge bosons and fermions
- Higgs self couplings $\longrightarrow$ reconstruct Higgs Potential

and *Measure the Higgs branching ratios*

iv) *Use measured properties and couplings to learn about the basic model of nature*
$\Longrightarrow$ *define benchmark scenarios to explore models beyond the SM*

- Disentangle between the SM, the MSSM, others
- Investigate the existence of explicit CP-violation, beyond the SM, via effects in the Higgs sector
- Study possible mixing of the Higgs with other scalars (radion in ED)

Back to the crucial point

First fundamental evidence of EWSB

$\Longrightarrow$ masses of gauge bosons

HIGGS $\equiv$ particle with coupling of order one which gives mass to W and Z bosons

Hence, we need to detect the Higgs

in association with gauge bosons

The other particle whose mass is related to the source of EWSB is the top quark $\rightarrow M_{top} \propto v$

$\Longrightarrow$ if there were other particles (Higgs) responsible for it, their v.e.v. would be small (not responsible for W,Z masses), hence their couplings to the top would need to be too strong.

$\Longrightarrow$ if theory remains perturbative $\rightarrow$ top mass will mainly come from Higgs with SM-like couplings to W/Z bosons

At the LC:

Extraction of absolute couplings of Higgs boson is straightforward

SM-like Higgs produced via Higgs strahlung $e^+e^- \to Z\phi$ and weak boson fusion $e^+e^- \to \nu_e \bar{\nu}_e \phi$

- $g_{\phi ZZ} \Longrightarrow \sigma_{\phi Z}$: using the recoil mass method

$\to$ independent of H decay modes !!

This is the most powerful feature unique to the LC

Also from observed decay rates $\phi \to WW, b\bar{b}$, etc plus cross section meas. $\Longrightarrow$ Branching ratios

- $g_{\phi WW} \Longrightarrow \sigma_{\phi \nu_e \bar{\nu}_e}$: using different spectra for $\nu\bar{\nu}$ invariant mass in $b\bar{b}\nu\bar{\nu}$ final state

Ratio: $\frac{g_{\phi WW}}{g_{\phi ZZ}}$ relevant test of SU(2) symmetry

Higgs decay width $\Longrightarrow$ combining Higgs coupling meas. with corresponding branching ratio

$\Gamma_{tot} = \Gamma_W / BR(\phi \to WW)$

- $g_{\phi t\bar{t}} \Longrightarrow$ direct meas. from $e^+e^- \to \phi t\bar{t}$ cross section (needs $\sqrt{s}$ = 800–1000 GeV)

Accurate measurement of couplings and branching ratios $\Longrightarrow$ Powerful tool to reconstruct SM Higgs profile or quantify departure from the SM behavior.

Decay mode:	$b\bar{b}$	WW^*	$\tau^+\tau^-$	$c\bar{c}$	gg	$\gamma\gamma$
LC	2.4%	5.1%	5.0%	8.5%	5.5%	19%
LC	2.9%	9.3%	7.9%	39%	18%	
LC (scaled)						14%
th. un.	1.4%	2.3%	2.3%	23%	5.7%	2.3%

Table 1: Expected fractional uncertainty of BR measurements at an e^+e^- LC for a 120 GeV SM-like Higgs boson. Results for 500 fb^{-1} at $\sqrt{s}$ = 350 GeV (first row); 500 fb^{-1} at $\sqrt{s}$ = 500 GeV (second row); 1 ab^{-1} at $\sqrt{s}$ = 500 GeV, scaled to 500 fb^{-1}) (third row).

	g^2_{hbb}	g^2_{hWW}	g^2_{hZZ}	g^2_{hcc}	$g^2_{h\tau\tau}$	g^2_{hgg}	g^2_{htt}
LHC	- %	11 %	11%	- %	19 %	28%	16%
LC	4.4%	2.4%	2.4%	7.4%	6.6%	7.4%	10%
th. un.	3.5%	–	–	24%	–	3.9%	2.5%

Table 2: Expected uncertainty of measurements of squared couplings (equivalently partial widths) for a 120 GeV SM-like Higgs boson assuming 500 fb^{-1} at $\sqrt{s}$ = 500 GeV, except for the measurement of g^2_{htt} which assumes 1000 fb^{-1} at $\sqrt{s}$ = 800 GeV.

Other important Higgs properties to measure:

Possible at the LC:

- **Higgs Quantum Numbers: Spin and Parity**

– threshold dependence of the excitation curve:

$$\sigma(e^+e^- \to Z\phi) \sim \beta \sim \sqrt{s - (M_\phi + M_Z)^2}$$

– angular distributions $e^+e^- \to Z\phi$; $e^+e^- \to f\bar{f}\,\phi$

$$\frac{d\sigma(Z\phi)}{d\cos\theta} \propto \sin^2\theta \qquad \frac{d\sigma(f\bar{f}\,\phi)}{d\cos\theta\, d\cos\theta^*} \propto \sin^2\theta\, \sin^2\theta^*$$

one can determine unambiguously the spin and parity of the particle produced.

- **CP Nature of the Higgs Boson**

– analyzing kinematics of Higgs bosons in $t\bar{t}\,\phi$ production

– direct observation of $f\bar{f} \to Z\,H_1/Z\,H_2$ and $f\bar{f} \to H_1\,H_2$ at LC & LHC.

– indirectly via deviations in $\sigma \times BR$'s

– $\gamma\gamma$ collider (?)

- **Invisible decays of the Higgs**

$\longrightarrow$ get invisible width from visible width & total width

- **Higgs self couplings**

$\longrightarrow$ cross section for double Higgs-strahlung $e^+e^- \to Z\phi\phi$

Precise measurements of Γ's and BR's

$\Longrightarrow$ study departure of those quantities from SM expectations

Comparing Γ's and BR's of the SM-like Higgs boson of the MSSM and the SM Higgs of the same mass

$\Longrightarrow$ evaluate sensitivity to various observables

$$\delta\Gamma = |\Gamma^{MSSM} - \Gamma^{SM}|/\Gamma^{SM}$$

$$\delta BR = |BR^{MSSM} - BR^{SM}|/BR^{SM}$$

This will allow us to demonstrate which quantities are most sensible to the non-standard nature of the Higgs boson

- in general, big deviations except in decoupling limit, but onset of decoupling depends strongly on radiative corrections, hence on SUSY parameters

At a LC

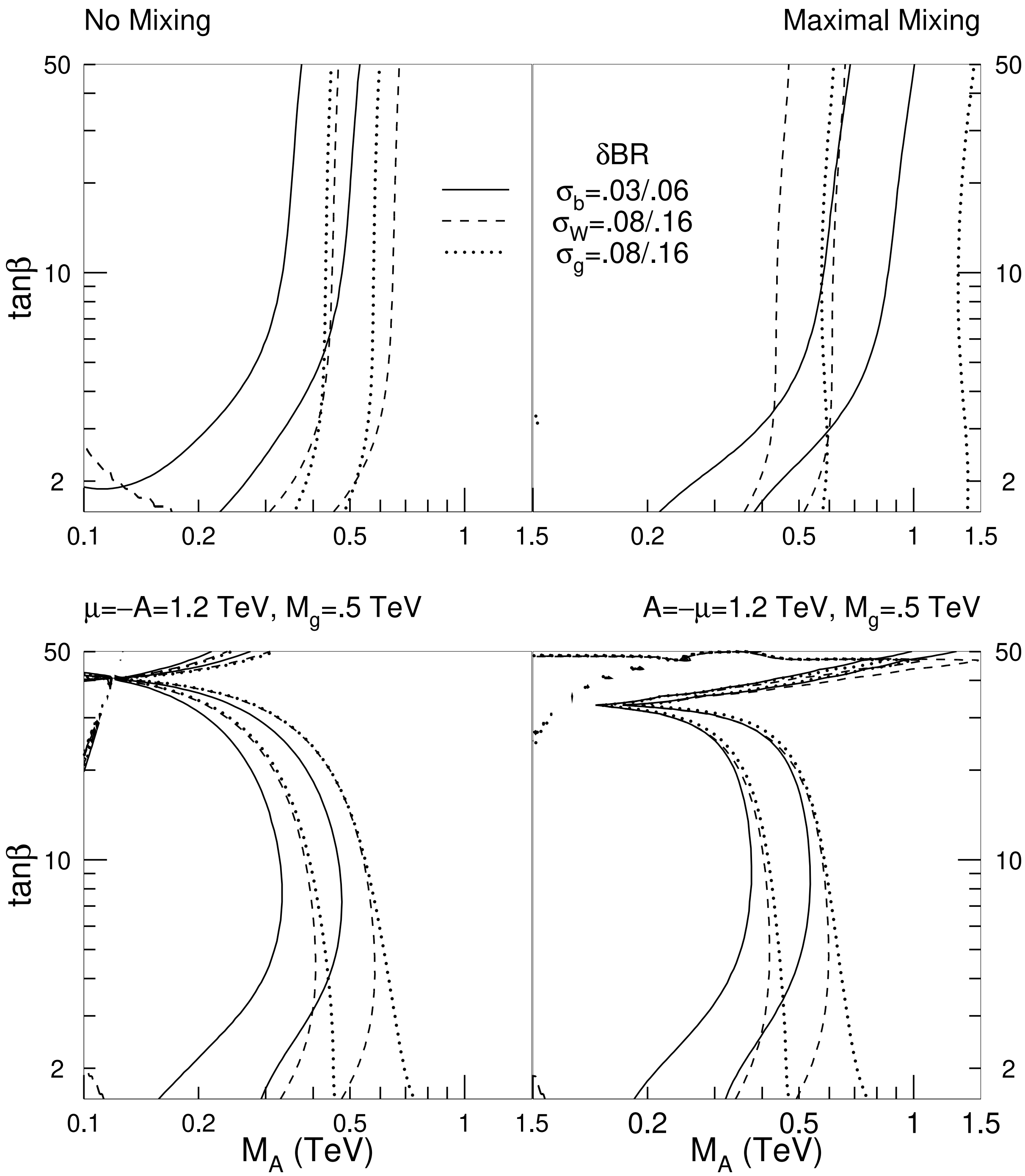
- distinguish MSSM from SM Higgs boson

- provide indirect evidence of m_A beyond the LHC/LC reach

- provide some information on SUSY vertex corrections to bottom Yukawa coupling

Precision Meas. of the SM Higgs BR's at a LC

$\Longrightarrow$ implications for the MSSM Higgs sector



Contours of $\delta BR(b) = [BR_{MSSM} - BR_{SM}]/BR_{SM}$ in the $\tan\beta$–M_A plane

Extracting the SUSY parameter Δ_b

Fractional uncertainty in

$\Delta_b = [\hat{g}_{hbb} - \hat{g}_{h\tau\tau}]/[\hat{g}_{htt} - \hat{g}_{hbb}]$ with $\hat{g}_{hbb} = g_{hbb}/g_{hbb}^{SM}$