Terascale Physics Summary

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Outline

1. Triple Higgs Coupling Error Versus Jet Energy Resolution, Timothy BARKLOW (SLAC)
2. Higgs Boson Decay into Pairs of Leptons: Signal and Backgrounds, Ed BERGER (ANL)
3. The NMSSM $h --> aa$ Scenario, Jack GUNION (UC Davis)
4. High Precision Calculations for the MSSM Higgs Sector: FeynHiggs2.4, Sven HEINEMEYER (Univ. de Zaragoza)
5. Radiative Corrections to Higgs Production at the ILC, HongSheng HOU (Carleton U.)
6. Higher Curvature Effects in the ADD & RS Models, Tom RIZZO (SLAC)
7. A Model-Independent Approach to 2HDM Physics, Howard HABER (UC Santa Cruz)

Introductory Remarks

The physics case for the ILC hinges on three basic goals (cf. Lykken's summary):

- **discovering the secrets of the Terascale;**
- **shedding light on the nature of dark matter;**
- **revealing the ultimate unified theory.**

While the LHC will make tremendous contributions, there seems little doubt that the added capabilities and precision of the ILC will be essential in all three areas.

The Terascale

Terascale physics is typically separated into two broad issues.

- **The generation of mass.**
  - a simple Higgs
  - a complicated Higgs sector (includes supersymmetry)
  - Higgs-less electroweak symmetry breaking
  - . . .

- **The physics behind the Terascale itself.**

  For example, Lykken lists in this latter category

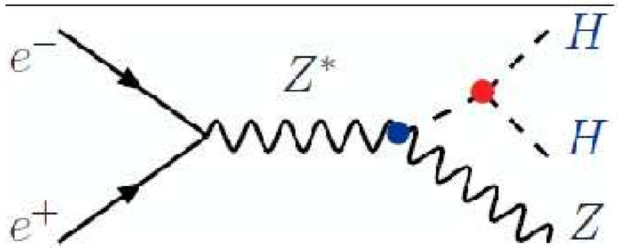
  - supersymmetry
  - extra dimensions
  - new forces

The talks presented in the Terascale session focus on precisely these issues.

Jet energy resolution and the g_{HHH} coupling: Barklow

- This self coupling plays a prominent role in electroweak baryogenesis.
- If a simple Higgs is seen, and if the coupling is of SM strength, then electroweak baryogenesis is not possible.
- However, if g_{HHH} is sufficiently enhanced, then EWBG becomes possible.
- If nature chooses a SM Higgs, it will be crucial to check this aspect of the theory.
- So, how good should the detector be to do the best job?

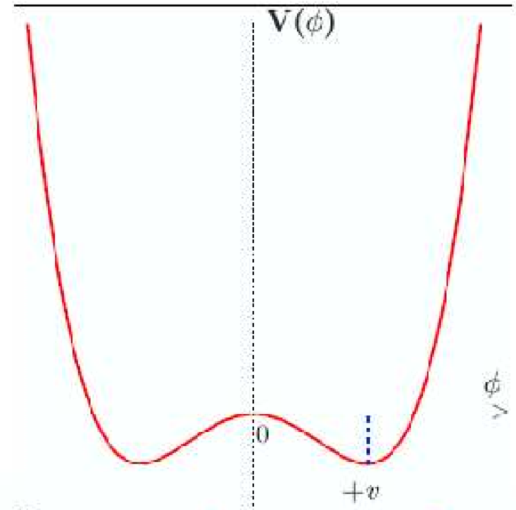
  Barklow's study appears to disagree with an earlier TESLA study that claims a huge improvement in the precision of the g_{HHH} measurement by going from jet energy resolution of $\Delta E/\sqrt{E} = 60\%$ to 30%.



$g_{HHH} = -6\mu^2 / \mathrm{v}$

Standard Model:

$M_H^2 = 2\lambda \mathrm{v}^2 = -2\mu^2$



$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

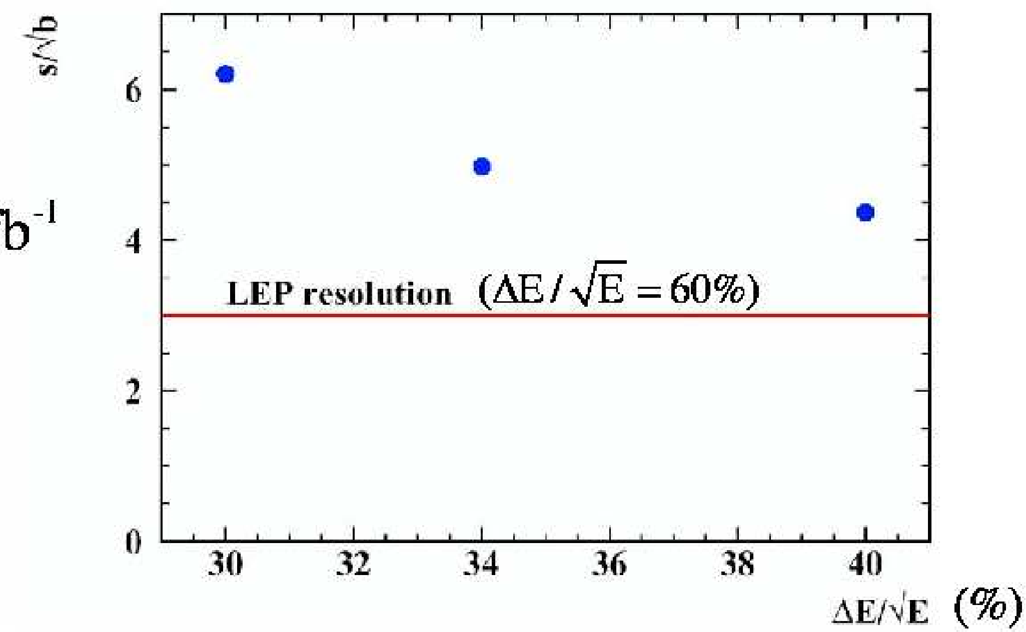
$e^+e^- \to ZHH \to q\bar{q}b\bar{b}b\bar{b}$

$\sqrt{s}$ = 500 GeV, L=1000 fb^{-1}

$\Delta E/\sqrt{E} = 60\% \to 30\%$

equiv to $4\times$ Lumi

C. Castanier et al. hep-ex/0101028



Barklow finds less improvement. Differences between the analyzes?

- Barklow focuses on just the $qqb\bar{b}b\bar{b}$ final state of $e^+e^- \to ZHH$, whereas more final states are included in the TESLA analysis.

- Barklow finds that at least 3 of the 4 b-jets must be tagged in order to begin to control the $t\bar{t}$ background, given his preselection cuts.

- There may also be a difference in the $B(H \to b\bar{b})$ branching ratio employed.

- The discrepancy is reduced (but not by much) if one employs the core jet energy resolution rather than the total r.m.s.

- This is a crucial issue for detector design.

  It also impinges on ability to separate W's from Z's at the ILC. Barklow is not so confident that this can be done even with $30\%/\sqrt{E}$.

- Using core r.m.s. rather than total r.m.s., Barklow finds ....

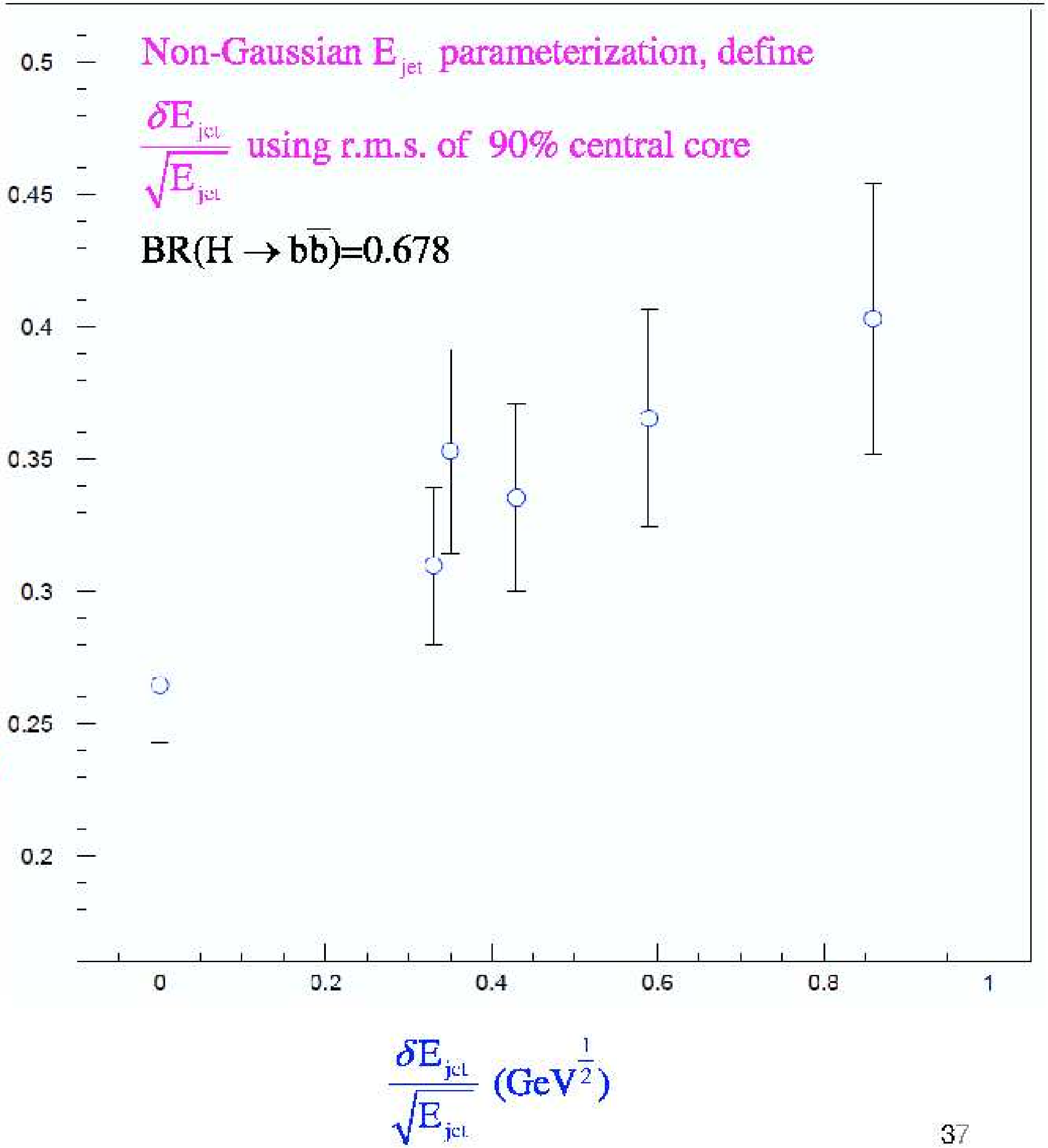
$$e^+e^- \to ZHH$$
$$\to qqb\bar{b}b\bar{b}$$

$$\sqrt{s} = 500\ GeV$$
$$L = 2000\ fb^{-1}$$

$$\frac{\Delta g_{hhh}}{g_{hhh}}$$

$\Delta E/\sqrt{E} = 60\% \to 30\%$

equiv to $1.4\times$ Lumi



$h \to WW^* \to \ell^+\ell^-\nu\bar{\nu}$: Berger w. Sullivan

- For $m_h > 135~\mathrm{GeV}$, this becomes the dominant decay mode.

- For $m_h \sim 160 - 170~\mathrm{GeV}$, other modes are greatly suppressed.

- Are we sure we can see it at the LHC?

  Berger argues that backgrounds from heavy flavor processes could be more of a concern than imagined — they are not really in current ATLAS/CMS estimates.

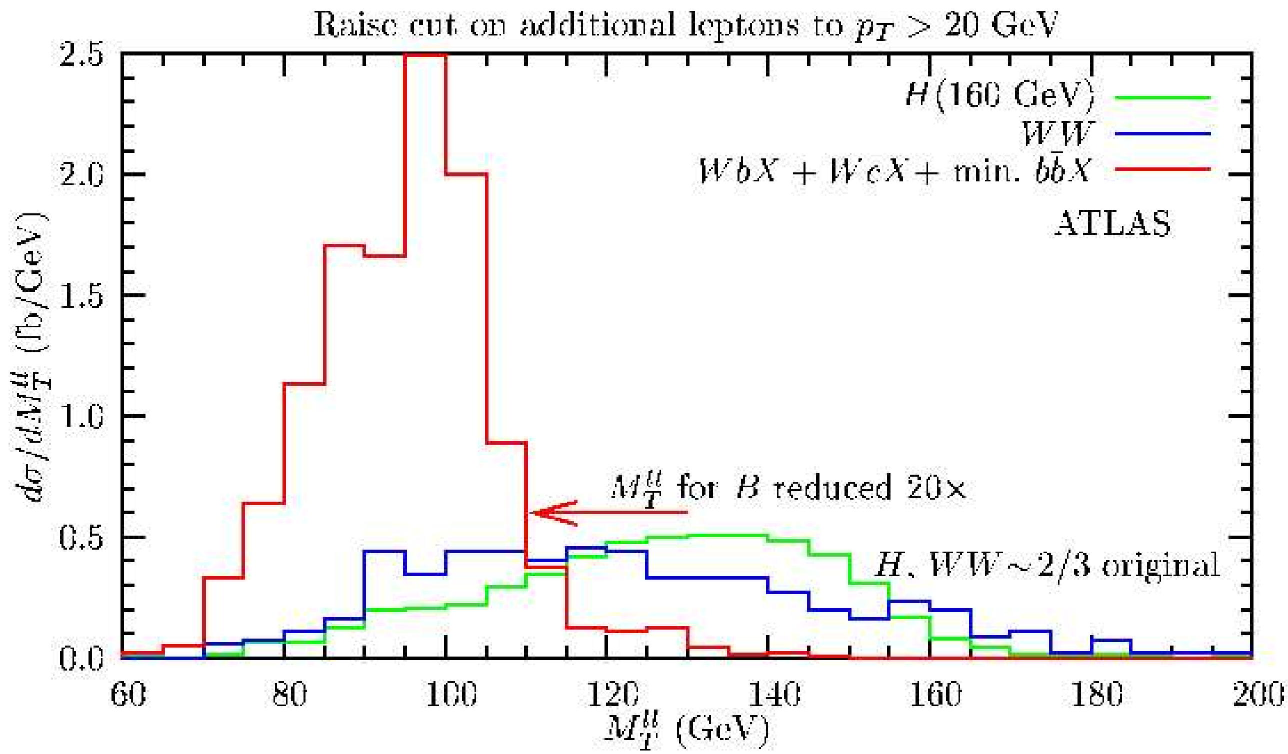
  The backgrounds at issue are such processes as $Wb\bar{b} \to \ell\nu b\bar{b}$, $Wc\bar{c} \to \ldots$, $WC \to \ldots$ and inclusive $b\bar{b}$ and $c\bar{c}$.

- Isolation in $b \to \ell X$ even at the 0.5% level leaves $\ell^+\ell^-\not{E}_T$ background $> 10^4\times$ signal.

  They use the D0 and ATLAS analysis chains but with all heavy flavors included.

- They suggest increasing p_T cut on 2nd lepton to $20~\mathrm{GeV}$.

M_T^{ll} distribution with a harder p_T^l cut



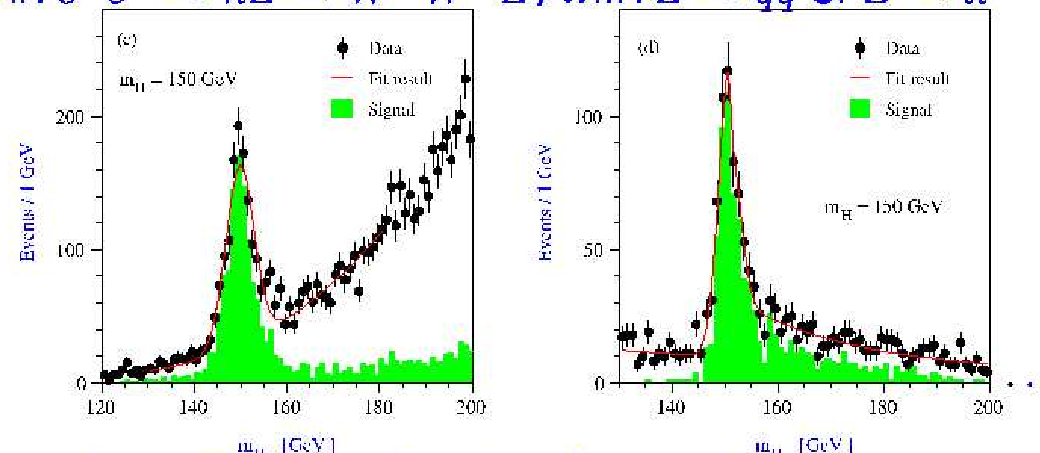
- Harder cut on the p_T of the second lepton suppresses the heavy flavor background, by a factor of about 20, but has only a small effect on the $h \to WW$ and continuum WW contributions.
- The leading edge of the heavy flavor contribution drops to lower $M_T^{l\bar{l}}$

Edmond Berger, Argonne – p.12

- **If m_h is in the critical mass range and the LHC has trouble cleaning up the signal, the ILC will save the day.**

$h \to W^+W^-$ final states at the ILC

- $h \to W^+W^-$ decays dominate for $m_h > 150$ GeV
  Higgs boson decay can be fully reconstructed from hadronic W decays in $e^+e^- \to hZ \to W^-W^-Z$, with $Z \to q\bar{q}$ or $Z \to ll$



- (c), $Z \to q\bar{q}$; (d) $Z \to l\bar{l}$; $\sqrt{s} = 350$ GeV and $\int L dt = 500$ fb^{-1}
  Garcia-Abia, Lohmann, Raspereza, LC-PHSM-2000-062
- Branching fraction $BR(h \to WW^*)$ can be measured to $\sim 4\%$in $e^+e^- \to hZ \to WW^*Z$, with $WW^* \to 4$ jets or $WW^* \to l\nu + 2$ jets
- Can also use the Higgs-strahlung process to determine g_{hZZ} and the WW fusion process (plus a known branching fraction) for g_{hWW}

Edmond Berger, Argonne – p.15

Anything (e.g., J^{PC}) to learn from $h \to W^+W^- \to l^+l^- + E_{\rm miss}$ at the ILC?

- $e^+e^- \to hZ$, with $Z \to l^+l^-$, with $h \to W^+W^- \to l^+l^- + E_{\rm miss}$, has interesting kinematic signatures in the 4 charged lepton final state, especially near threshold .
- In $W \to l\nu$ (unlike $W \to q\bar{q} \to 2$ jets), we can identify the electric charge of the lepton, whether l^+ or l^-. The electric charge tells us the helicity (right- or left-handed). In $W^- \to l^-\nu$, the decay l^- goes in the direction opposite to the spin orientation of the W
- Determination of the charges of the two leptons in $h \to W^+W^- \to l^+l^- + E_{\rm miss}$ tells us the spin orientations of each of the W's
- Work in progress
- Request to the audience: if anyone knows of studies of $h \to W^+W^- \to l^+l^- + E_{\rm miss}$ at the ILC, please let me know

FeynHiggs2.4: Heinemeyer w. Hahn, Hollik and Weiglein

- **Goal: a program that computes radiative corrections to all couplings, masses, production processes, branching ratios, ... for the SM and the MSSM.**

  These will all be needed to make use of the high precision that will be reached by the ILC, e.g. $\delta m_H \sim 50~\mathrm{MeV}$, δB's $\sim few\%$.

- **Bringing the theory to the required level is a continuing process with many contributors.**

- **FeynHiggs2.4.2 (available in about 2 weeks at www.feynhiggs.de) assembles all known results for the SM, the CP-conserving MSSM, and the CP-violating MSSM. In particular, it has**
  - **full 1-loop corrections**
  - **all available 2-loop corrections**
  - **very leading 3-loop corrections**

- **In the MSSM, m_{h^0} can in principle be computed in terms of other MSSM parameters, with strong dependence on the stop sector.**

  But, getting below the level of $\delta m_{h^0} \sim 1$ GeV will be exceedingly difficult. However, you never know. We have some more years.

  Currently, $\delta m_{h^0}(theory) \sim 1.5$ GeV.

  This would already be highly constraining on the stop and other sectors of the MSSM given a measurement of m_{h^0}.

- **For branching ratios, widths, production processes, . . . , theory is now very close to the required accuracy.**

  FeynHiggs2.4.2 will have everything along this line except (currently — they are working on it) the radiative corrections for ILC production processes.

- **The main new features of FeynHiggs2.4.2 are given in Heinemeyer's transparency.**

*FeynHiggs*2.2 → *FeynHiggs*2.4: main new features

- Complex contributions to Higgs mass matrix taken into account (from $\mathrm{Im}\, B_0(\ldots) \neq 0$)
- Higgs masses are now the real part of the complex pole
- $\Rightarrow$ complex 3×3 mixing matrix Z $\Rightarrow$ on-shell Higgs bosons
  unitary 3×3 mixing matrix U $\Rightarrow$ internal Higgs bosons
- $\Rightarrow$ included in all Higgs production and decay
- inclusion of full one-loop NMFV effects
- Preliminary implementation of LEP Higgs exclusion bounds (to be refined)
- extended implementation of $(g-2)_\mu$: leading SM fermion two-loop contributions
  [*S.H., D. Stöckinger, G. Weiglein '04*]

- **For a full summary of all features, you should look at Sven's transparencies.**

  The main thing missing at the moment, but being implemented, are the radiative corrections to ILC processes. Many results are now available (more in a moment) and it is simply a matter of encoding them.

  His transparencies also show how convenient it is to download or run interactively the program.

- **This work means that ILC (and LHC) measurements in the Higgs sector will allow us to search for small deviations from MSSM sector predictions.**

  This will be a powerful probe of possible new physics beyond the MSSM! — such as the NMSSM.

Included in *FeynHiggs*2.4 (IV):

Evaluation of theory error on masses and mixing

$\to$ estimate of uncertainty in M_{h_i}, U_{ij}, Z_{ij} from unknown higher-order corr.

Evaluation of masses, mixing and decay in the NMFV MSSM

NMFV: Non Minimal Flavor Violation [*Hahn, S.H., Hollik, Merz, Peñaranda '04-'06*]
$\Rightarrow$ Connection to Flavor physics

Evaluation of additional constraints (rMSSM/cMSSM)

- ρ-parameter: $\Delta\rho^{\mathrm{SUSY}}$ at $\mathcal{O}(\alpha)$, $\mathcal{O}(\alpha\alpha_s)$, ..., including NMFV effects
  $\Rightarrow M_W$, $\sin^2\theta_{\mathrm{eff}}$ via SM formula + $\Delta\rho^{\mathrm{SUSY}}$, including NMFV effects
- anomalous magnetic moment of the μ: $(g-2)_\mu$
- BR($b \to s\gamma$) , including NMFV effects [*T. Hahn, W. Hollik, J. Illana, S. Peñaranda '06*]
- LEP Higgs constraints [*LEP Higgs WG '06*]

Planned:

- ILC production cross sections
- EDMs of electron, neutron, Hg, ...

3. How to install FeynHiggs2.4

1. Go to www.feynhiggs.de
2. Download the latest version
3. type `./configure`, `make`, `make install`
   $\Rightarrow$ library `libFH.a` is created
4. 4 possible ways to use *FeynHiggs*:

   A) Command-line mode

   B) called from a Fortran/C++ code

   C) called within Mathematica

   D) WWW mode

   processing of Les Houches Accord data possible
5. Detailed instructions and help are provided in the man pages

Radiative corrections to ILC H production processes: Hongsheng Hou

- Much of the necessary LHC work has been done, and it is time to get such corrections under control at the ILC to complement the expected precision of the ILC measurements.

- They have looked at $e^+e^- \to t\bar{t}H$ (SM), $e^+e^- \to t\bar{t}h^0$ (MSSM), $e^+e^- \to ZHH$ and $e^+e^- \to ZZH$.

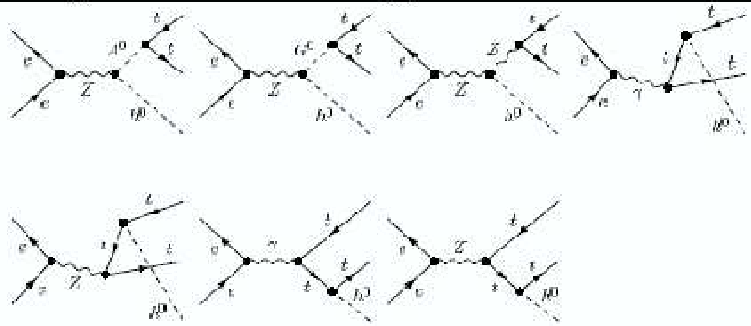
- Most of the QCD corrections are already known and so they have done the electroweak (EW) corrections.

  Other groups have also been working in this area, and some cross checks are possible (and agreement is generally good).

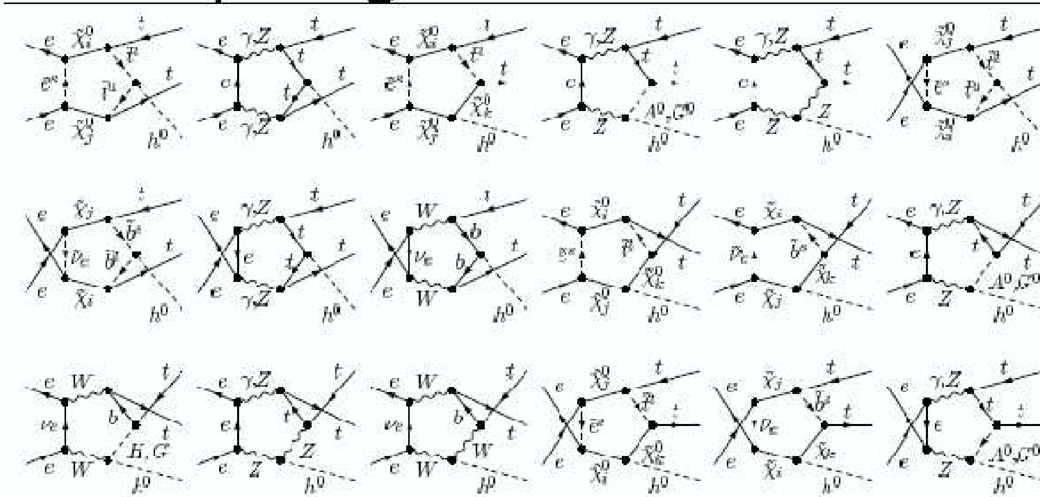
- The $e^+e^- \to t\bar{t}h^0$ calculation is particularly demanding — lots of diagrams.

EW corrections to $e^+e^- \to t\bar{t}h^0$ in MSSM

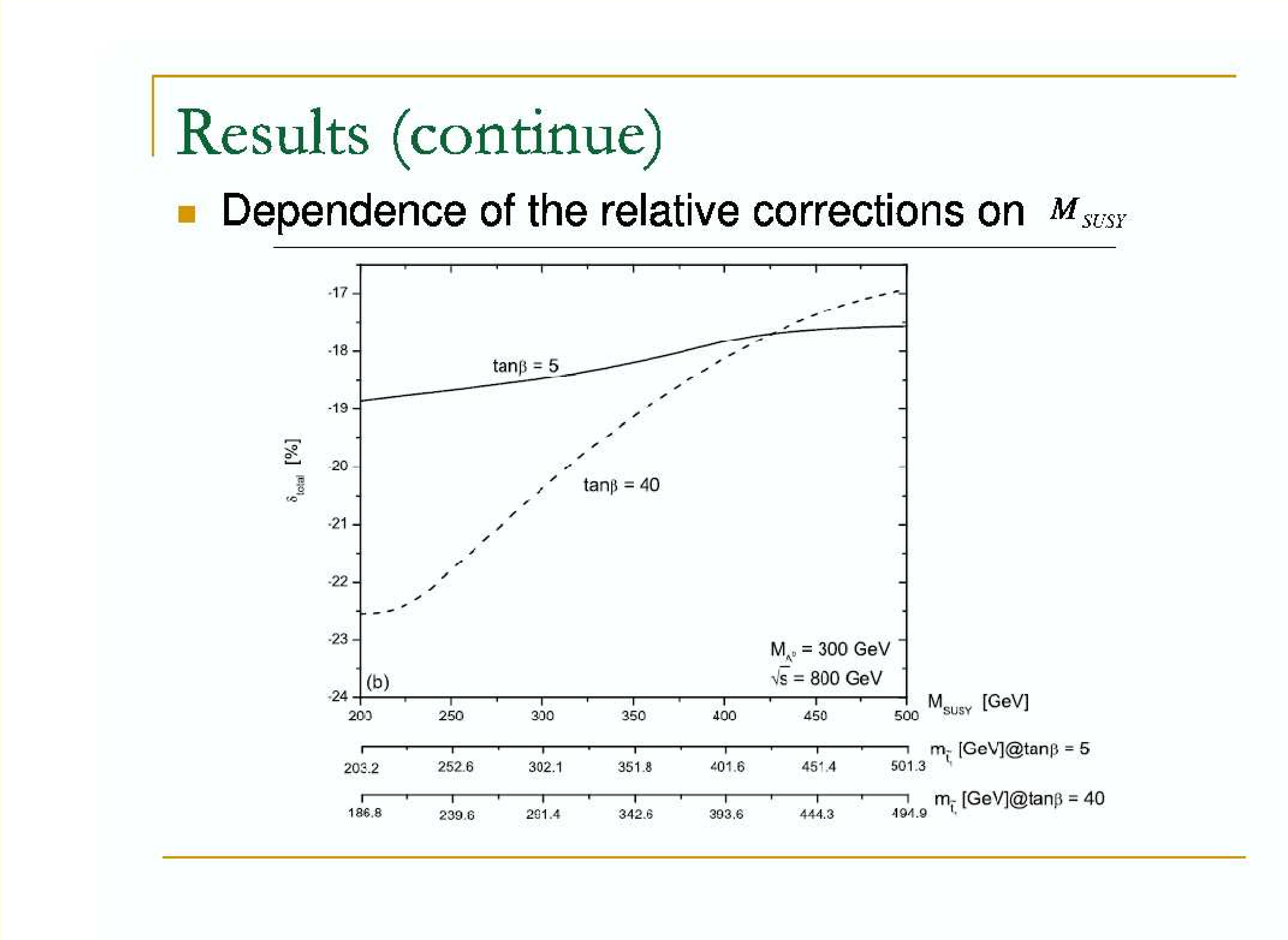
Tree-level Feynman diagrams



Sample one-loop diagrams



• $t\bar{t}h^0$ **illustrates that EW corrections are typically fairly significant.**



For details, please see Hongsheng's talk and hep-ph references therein.

A model-independent approach to the 2HDM: Haber w. Davidson, O'Neil and others

- A model builder is likely the write down his 2HDM Higgs fields Φ_1 and Φ_2 in some basis that is convenient to his model or manner of analysis.
- A second model builder would do the same.
- Different basis choices can be connected to one another by a $U(2)$ rotation in the (Φ_1, Φ_2) space.
- How can you conveniently see the extent to which the two models differ and check whether or not they are the same?
- A good approach is to construct basis independent invariants, i.e. quantities that are invariants (or pseudo invariants) under the $U(2)$ rotations.
- An interesting example is provided by the MSSM with CP violation and substantial radiative corrections that mix up the meaning of the up and down Higgs fields.

The General Two-Higgs-Doublet Model

Consider the 2HDM potential in a *generic* basis:

$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2$$

$$+\tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$

$$+ \left\{ \tfrac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)\right] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\}$$

A basis change consists of a U(2) transformation $\Phi_a \longrightarrow U_{a\bar{b}} \Phi_b$ (and $\Phi_a^\dagger = \Phi_b^\dagger U_{ba}^\dagger$). Rewrite $\mathcal{V}$ in a U(2)-covariant notation:

$$\boxed{\mathcal{V} = Y_{a\bar{b}} \Phi_a^\dagger \Phi_b + \tfrac{1}{2} Z_{a\bar{b}c\bar{d}} (\Phi_a^\dagger \Phi_b)(\Phi_c^\dagger \Phi_d)}$$

where $Z_{a\bar{b}c\bar{d}} = Z_{c\bar{d}a\bar{b}}$ and hermiticity implies $Y_{a\bar{b}} = (Y_{b\bar{a}})^*$ and $Z_{a\bar{b}c\bar{d}} = (Z_{b\bar{a}d\bar{c}})^*$. The barred indices help keep track of which indices transform with U and which transform with $U^\dagger$. For example, $Y_{a\bar{b}} \longrightarrow U_{a\bar{c}} Y_{c\bar{d}} U_{d\bar{b}}^\dagger$ and $Z_{a\bar{b}c\bar{d}} \longrightarrow U_{a\bar{e}} U_{f\bar{b}}^\dagger U_{c\bar{g}} U_{h\bar{d}}^\dagger Z_{e\bar{f}g\bar{h}}$.

The most general $U(1)_{\rm EM}$-conserving vacuum expectation value (vev) is:

$$\langle\Phi_a\rangle = \frac{v}{\sqrt{2}}\left(\begin{array}{c} 0 \\ \widehat{v}_a \end{array}\right), \qquad \text{with} \qquad \widehat{v}_a \equiv e^{i\eta}\left(\begin{array}{c} c_\beta \\ s_\beta\, e^{i\xi} \end{array}\right),$$

where $v \equiv 2m_W/g = 246$ GeV. The overall phase η is arbitrary (and can be removed with a $U(1)_{\rm Y}$ hypercharge transformation). If we define the hermitian matrix $V_{a\bar b} \equiv \hat v_a \hat v_{\bar b}^*$, then the scalar potential minimum condition is given by the invariant condition:

$$\mathrm{Tr}\,(VY) + \tfrac{1}{2}v^2 Z_{a\bar b c\bar d} V_{b\bar a} V_{d\bar c} = 0\,.$$

The orthonormal eigenvectors of $V_{a\bar b}$ are $\hat v_b$ and $\widehat{w}_b \equiv \widehat{v}_{\bar c}^*\,\epsilon_{cb}$ (with $\epsilon_{12} = -\epsilon_{21} = 1$, $\epsilon_{11} = \epsilon_{22} = 0$). Note that $\hat v_{\bar b}^* \hat w_b = 0$. Under a U(2) transformation, $\hat v_a \to U_{a\bar b}\hat v_b$, but:

$$\widehat{w}_a \to (\det\, U)^{-1}\, U_{a\bar b}\, \widehat{w}_b\,,$$

where $\det U \equiv e^{i\chi}$ is a pure phase. That is, $\widehat{w}_a$ is a pseudo-vector with respect to U(2). One can use $\widehat{w}_a$ to construct a proper second-rank tensor: $W_{a\bar b} \equiv \hat w_a \hat w_{\bar b}^* \equiv \delta_{a\bar b} - V_{a\bar b}$.

Remark: $U(2) \cong SU(2)\times U(1)_{\rm Y}/\mathbb{Z}_2$. The parameters m_{11}^2, m_{22}^2, m_{12}^2, and $\lambda_1, \ldots, \lambda_7$ are invariant under $U(1)_{\rm Y}$ transformations, but are modified by a "flavor"-SU(2) transformation; whereas $\hat v$ transforms under the full U(2) group.

The invariants and pseudo-invariants in the generic basis are given by:

$$
\begin{aligned}
Y_1 &= m_{11}^2 c_\beta^2 + m_{22}^2 s_\beta^2 - \mathrm{Re}(m_{12}^2 e^{i\xi}) s_{2\beta}\,, \\
Y_2 &= m_{11}^2 s_\beta^2 + m_{22}^2 c_\beta^2 + \mathrm{Re}(m_{12}^2 e^{i\xi}) s_{2\beta}\,, \\
Y_3\, e^{i\xi} &= \tfrac{1}{2}(m_{22}^2 - m_{11}^2) s_{2\beta} - \mathrm{Re}(m_{12}^2 e^{i\xi}) c_{2\beta} - i\,\mathrm{Im}(m_{12}^2 e^{i\xi})\,, \\
Z_1 &= \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + \tfrac{1}{2}\lambda_{345} s_{2\beta}^2 + 2 s_{2\beta}\left[c_\beta^2 \mathrm{Re}(\lambda_6 e^{i\xi}) + s_\beta^2 \mathrm{Re}(\lambda_7 e^{i\xi})\right]\,, \\
Z_2 &= \lambda_1 s_\beta^4 + \lambda_2 c_\beta^4 + \tfrac{1}{2}\lambda_{345} s_{2\beta}^2 - 2 s_{2\beta}\left[s_\beta^2 \mathrm{Re}(\lambda_6 e^{i\xi}) + c_\beta^2 \mathrm{Re}(\lambda_7 e^{i\xi})\right]\,, \\
Z_3 &= \tfrac{1}{4} s_{2\beta}^2 [\lambda_1 + \lambda_2 - 2\lambda_{345}] + \lambda_3 - s_{2\beta} c_{2\beta} \mathrm{Re}[(\lambda_6 - \lambda_7) e^{i\xi}]\,, \\
Z_4 &= \tfrac{1}{4} s_{2\beta}^2 [\lambda_1 + \lambda_2 - 2\lambda_{345}] + \lambda_4 - s_{2\beta} c_{2\beta} \mathrm{Re}[(\lambda_6 - \lambda_7) e^{i\xi}]\,, \\
Z_5\, e^{2i\xi} &= \tfrac{1}{4} s_{2\beta}^2 [\lambda_1 + \lambda_2 - 2\lambda_{345}] + \mathrm{Re}(\lambda_5 e^{2i\xi}) - i c_{2\beta} \mathrm{Im}(\lambda_5 e^{2i\xi})\,, \\
&\quad - s_{2\beta} c_{2\beta} \mathrm{Re}[(\lambda_6 - \lambda_7) e^{i\xi}] - i s_{2\beta} \mathrm{Im}[(\lambda_6 - \lambda_7) e^{i\xi})]\,, \\
Z_6\, e^{i\xi} &= -\tfrac{1}{2} s_{2\beta}\left[\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - \lambda_{345} c_{2\beta} - i\mathrm{Im}(\lambda_5 e^{2i\xi})\right] + c_\beta c_{3\beta} \mathrm{Re}(\lambda_6 e^{i\xi})\,, \\
&\quad + s_\beta s_{3\beta} \mathrm{Re}(\lambda_7 e^{i\xi}) + i c_\beta^2 \mathrm{Im}(\lambda_6 e^{i\xi}) + i s_\beta^2 \mathrm{Im}(\lambda_7 e^{i\xi})\,, \\
Z_7\, e^{i\xi} &= -\tfrac{1}{2} s_{2\beta}\left[\lambda_1 s_\beta^2 - \lambda_2 c_\beta^2 + \lambda_{345} c_{2\beta} - i\mathrm{Im}(\lambda_5 e^{2i\xi})\right] - s_\beta s_{3\beta} \mathrm{Re}(\lambda_6 e^{i\xi}) \\
&\quad + c_\beta c_{3\beta} \mathrm{Re}(\lambda_7 e^{i\xi}) + i s_\beta^2 \mathrm{Im}(\lambda_6 e^{i\xi}) + i c_\beta^2 \mathrm{Im}(\lambda_7 e^{i\xi})\,.
\end{aligned}
$$

where $\lambda_{345} \equiv \lambda_3 + \lambda_4 + \mathrm{Re}(\lambda_5\, e^{2i\xi})$.

The MSSM Higgs sector is a type-III 2HDM

The tree-level Higgs potential of the MSSM satisfies:

$$\lambda_1 = \lambda_2 = -\lambda_{345} = \tfrac{1}{4}(g^2 + g'^2)\,, \lambda_4 = -\tfrac{1}{2}g^2\,, \lambda_5 = \lambda_6 = \lambda_7 = 0\,.$$

But, one-loop radiative corrections generate corrections to these relations, due to SUSY-breaking. *E.g.*, at one-loop, $\lambda_5, \lambda_6, \lambda_7 \neq 0$.

For MSSM Higgs couplings to fermions, Yukawa vertex corrections modify the effective Lagrangian that describes the coupling of the Higgs bosons to the third generation quarks:

$$-\mathcal{L}_{\rm eff} = \epsilon_{ij}\left[(h_b + \delta h_b)\bar{b}_R H_d^i Q_L^j + (h_t + \delta h_t)\bar{t}_R Q_L^i H_u^j\right] + \Delta h_b \bar{b}_R Q_L^k H_u^{k*} + \Delta h_t \bar{t}_R Q_L^k H_d^{k*} + {\rm h.c.}$$

Indeed, this is a general type-III model. For example, in some MSSM parameter regimes (corresponding to large $\tan\beta$ and large supersymmetry-breaking scale compared to v),[‡]

$$\Delta h_b \simeq h_b\left[\frac{2\alpha_s}{3\pi}\mu M_{\tilde{g}}\, I(M^2_{\tilde{b}_1}, M^2_{\tilde{b}_2}, M^2_{\tilde{g}}) + \frac{h_t^2}{16\pi^2}\mu A_t\, I(M^2_{\tilde{t}_1}, M^2_{\tilde{t}_2}, \mu^2)\right]\,.$$

This leads to a modification of the tree-level relation between m_b and h_b. In addition, it leads to a splitting of "effective" $\tan\beta$-like parameters $\tan\beta_b$ and $\tan\beta_t$.

[‡] $I(a,b,c) = [ab\ln(a/b) + bc\ln(b/c) + ca\ln(c/a)]/(a-b)(b-c)(a-c)$.

For illustrative purposes, we neglect CP violation in the following simplified discussion. The tree-level relation between m_b and h_b is modified:

$$m_b = \frac{h_b v}{\sqrt{2}} \cos\beta(1 + \Delta_b) \,,$$

where $\Delta_b \equiv (\Delta h_b/h_b) \tan\beta$. That is, Δ_b is $\tan\beta$-enhanced, and governs the leading one-loop correction to the physical Higgs couplings to third generation quarks. In typical models at large $\tan\beta$, Δ_b can be of order 0.1 or larger and of either sign.

In the approximation scheme above (keeping only the $\tan\beta$-enhanced terms),

$$\tan\beta_b \equiv \frac{v\rho^D}{\sqrt{2}\, m_b} \simeq \frac{\tan\beta}{1+\Delta_b} \,, \qquad \tan\beta_t \equiv \frac{\sqrt{2}\, m_t}{v\rho^U} \simeq \frac{\tan\beta}{1 - \tan\beta\,(\Delta h_t/h_t)} \,.$$

Thus, supersymmetry-breaking loop-effects can yield observable differences between $\tan\beta$-like parameters that are defined in terms of basis-independent quantities. In particular, the leading one-loop $\tan\beta$-enhanced corrections are automatically incorporated into:

$$g_{Ab\bar{b}} = \frac{m_b}{v}\tan\beta_b \,, \qquad g_{At\bar{t}} = \frac{m_t}{v}\cot\beta_t \,.$$

The NMSSM $h \to aa$ Scenario: Gunion w. Dermisek

- **The MSSM has many lovely features:**

  It (like any TeV-scale SUSY model) cures the hierarchy problem.

  It leads to gauge coupling unification (for two doublet Higgs fields).

  It allows for RGE electroweak symmetry breaking.

- **But:**

  - **It is fine-tuned in the sense that GUT scale parameters must be very carefully chosen to get correct value of m_Z.**
  - **There is still no good suggestion as to why the μ parameter of the MSSM ($W \ni \mu \widehat{H}_u \widehat{H}_d$) should be $\sim \mathrm{TeV}$ rather than M_{P} (or 0).**

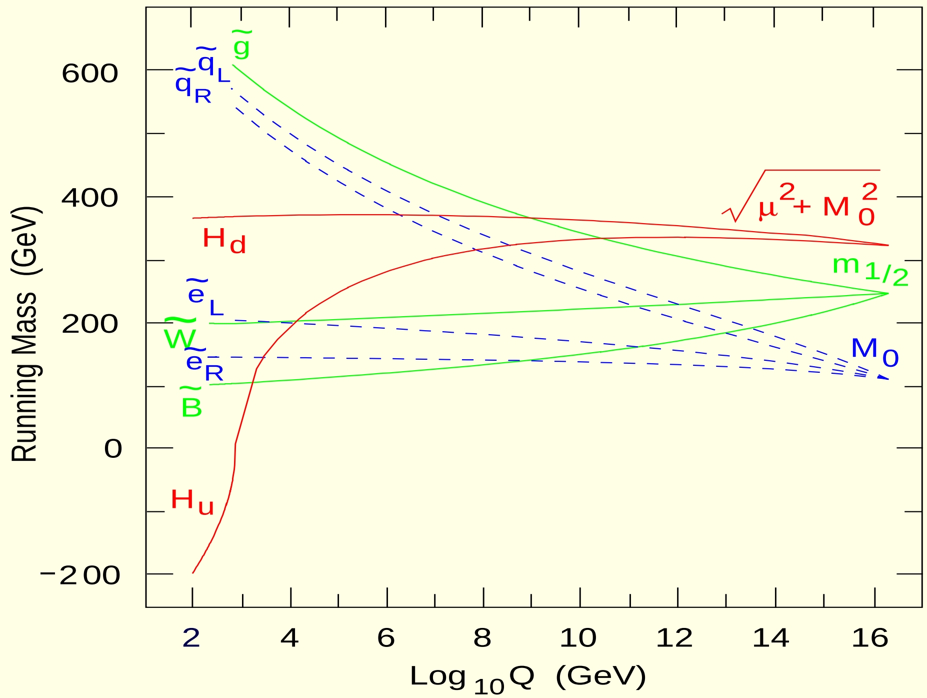


Figure 1: **Evolution of SUSY-breaking masses or masses-squared, showing how $m^2_{H_u}$ is driven < 0 at low $Q \sim \mathcal{O}(m_Z)$.**

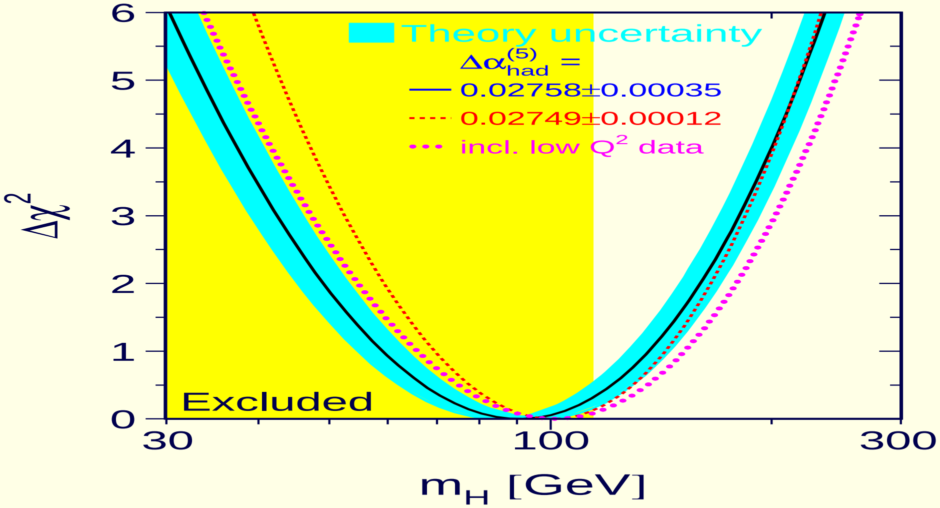
Starting with universal soft-SUSY-breaking masses-squared at M_U, the RGE's predict that the top quark Yukawa coupling will drive one of the soft-SUSY-breaking Higgs masses squared ($m^2_{H_u}$) negative at a scale of order $Q \sim m_Z$, thereby automatically generating electroweak symmetry breaking ($\langle H_u \rangle = h_u, \langle H_d \rangle = h_d$), BUT MAYBE m_Z IS FINE-TUNED.

- **The Higgs Mass**

In the presence of soft-SUSY-breaking, the light Higgs has

$$m_h^2 \sim m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} v^2 y_t^4 \sin^4\beta \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \ldots$$
$$\overset{\text{large}\,\tan\beta}{\sim} (91~\text{GeV})^2 + (38~\text{GeV})^2 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right). \quad (1)$$

A Higgs mass of order $100~\text{GeV}$, as predicted for stop masses $\sim 2m_t$, is in wonderful accord with precision electroweak data.



But, a Higgs of this mass is excluded by LEP. Is SUSY wrong, are stops heavy, or is the MSSM too simple?

We don't like to think that SUSY is wrong.

Heavy stops cause very large fine-tuning (numerically measured by the number F).

We advocate that one should simply go the the NMSSM which contains an extra singlet superfield $\widehat{S}$. (Singlets are abundant in superstring models.)

To further this study, Ellwanger, Hugonie and I constructed NMHDECAY.

`http://www.th.u-psud.fr/NMHDECAY/nmhdecay.html`

It computes all aspects of the Higgs sector and checks against many (but, as we shall see, not all) LEP limits and various other constraints.

This very simple extension can eliminate all the MSSM problems, while preserving all its good features.

- It solves the μ problem: $W \ni \lambda \widehat{S}\widehat{H}_u\widehat{H}_d \Rightarrow \mu = \lambda s$ when scalar component of $\widehat{S}$ acquires vev s.

- $\widehat{S}$ leads to one more neutralino ($\widetilde{\chi}^0_{1,2,3,4,5}$), one additional CP-even Higgs (h_1, h_2, h_2) and one additional CP-odd Higgs (a_1, a_2).

- **It greatly ameliorates the fine-tuning, eliminating it altogether if $m_{h_1} \sim 100~\mathrm{GeV}$.**

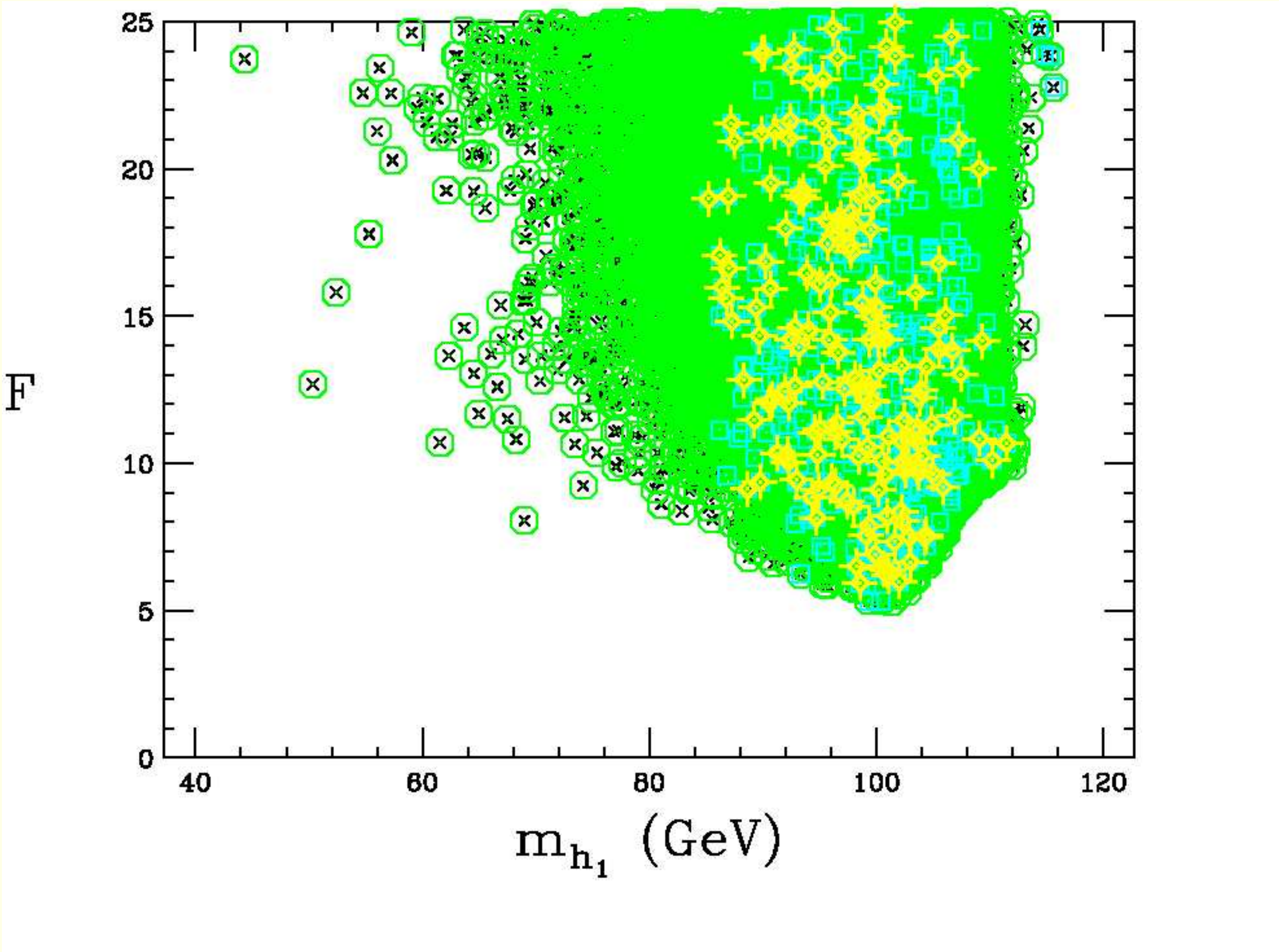


Figure 2: F vs. m_{h_1} for $M_{1,2,3} = 100, 200, 300~\mathrm{GeV}$ and $\tan\beta = 10$. Small $\times$ = "no" constraints. The O's = stop and chargino limits imposed, but NO Higgs limits. The □'s = all single channel Higgs limits imposed. The large FANCY CROSSES are after requiring $m_{a_1} < 2m_b$.

- **Provided $B(h_1 \to b\bar{b}) \sim 0.1 B(h^0_{MSSM} \to b\bar{b})$, the rest being mainly in $B(h_1 \to a_1 a_1) \sim 0.9$, and $m_{a_1} < 2m_b$ (a very natural symmetry limit of the model), so that the a_1 decays to $\tau^+\tau^-$ ($2m_\tau < m_{a_1} < 2m_b$) or jets ($m_{a_1} < 2m_\tau$), a h_1 with mass of $m_{h_1} \sim 100~\mathrm{GeV}$**

  1. **Evades LEP constraints**
  2. **Explains the well-known LEP excess near $100~\mathrm{GeV}$ perfectly.**

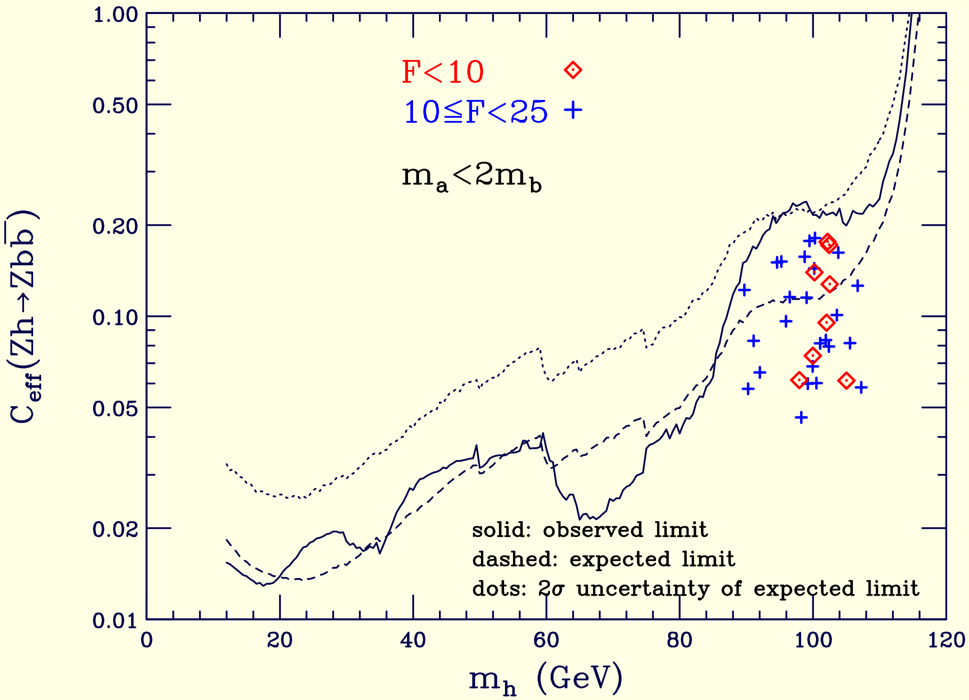


Figure 3: Observed LEP limits on C^{2b}_{eff} for the low-F points with $m_{a_1} < 2m_b$.

  3. **Is ideal for precision electroweak data since the h_1 has SM-like couplings to all SM particles.**

- **An important question is the extent to which the type of $h \to aa$ Higgs scenario (whether NMSSM or other) described here can be explored at the Tevatron, the LHC and a future e^+e^- linear collider.**

In fact, the $h_1 \to a_1 a_1$ decay mode renders inadequate the usual Higgs search modes that might allow h_1 discovery at the LHC.

Even after $L = 300~\mathrm{fb}^{-1}$ of accumulated luminosity, the typical maximal signal strength is at best 3.5σ. This largest signal usually derives from the $Wh_1 + t\bar{t}h_1 \to \gamma\gamma\ell^{\pm}X$ channel.

There is a clear need to develop detection modes sensitive to the $h_1 \to a_1 a_1 \to \tau^+\tau^-\tau^+\tau^-$ and (unfortunately) $4j$ decay channels.

Various 4τ channels may end up providing a signal, but keep in mind the $4j$ case.

- **At the ILC, there will be no problem.**

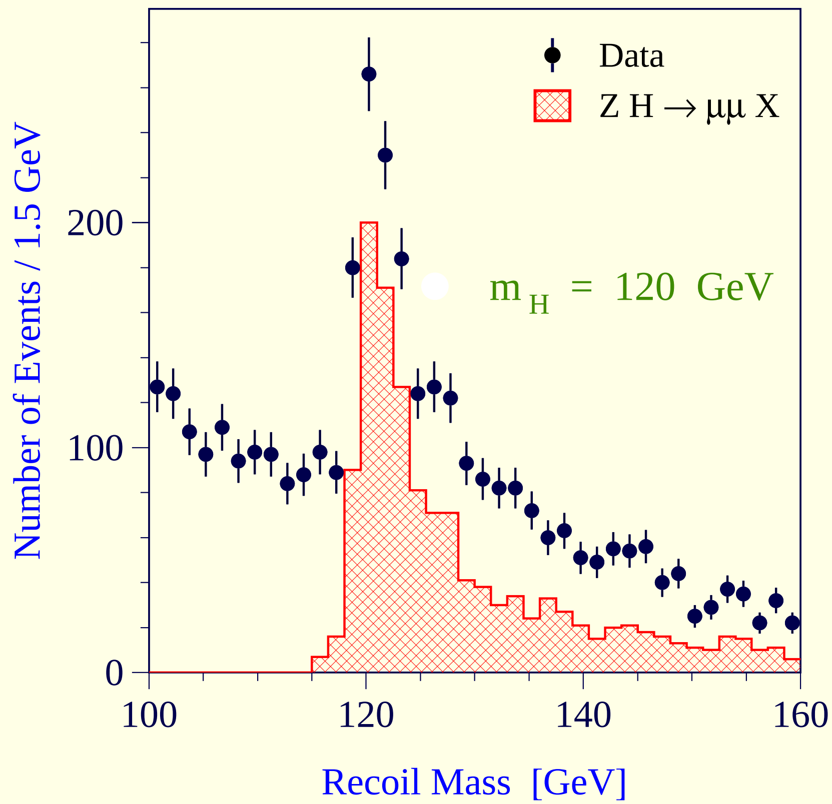


Figure 4: Decay-mode-independent Higgs M_X peak in the $Zh \to \mu^+\mu^- X$ mode for $L = 500~\mathrm{fb}^{-1}$ at $\sqrt{s} = 350~\mathrm{GeV}$, taking $m_h = 120~\mathrm{GeV}$..

There are lots of events in just the $\mu^+\mu^-$ channel (which you may want to restrict to since it has the best mass resolution).

- **Although the $h \to b\bar{b}$ and $h \to \tau^+\tau^-$ rates are $1/10$ of the normal,** the number of Higgs produced will be such that you can certainly see $Zh \to Zb\overline{b}$ and $Zh \to Z\tau^+\tau^-$ in a variety of Z decay modes.

This is quite important, as it will allow you to subtract these modes off and get a determination of $B(h_1 \to a_1a_1)$, which will provide unique information about the crucial NMSSM parameters $\lambda, \kappa, A_\lambda, A_\kappa$.

- Presumably direct detection in the $Zh \to Za_1a_1 \to Z4\tau$ mode will also be possible although I am unaware of any actual studies.

  This would give a direct measurement of $B(h_1 \to a_1a_1 \to \tau^+\tau^-\tau^+\tau^-)$.

- Coupled with the indirect measurement of $B(h_1 \to a_1a_1)$ from subtracting the direct $b\overline{b}$ and $\tau^+\tau^-$ modes would give a measurement of $B(a_1 \to \tau^+\tau^-)$.

  This would allow a first unfolding of information about the a_1 itself.

  Of course, the above assumes we have accounted for all modes.

- Maybe, given the large event rate, one could even get a handle on modes such as $h_1 \to a_1a_1 \to \tau^+\tau^-jj$ ($j = c, g$), thereby getting still more cross checks.

- **At a $\gamma\gamma$ collider, the $\gamma\gamma \to h_1 \to 4\tau$ signal will probably be easily seen (Gunion, Szleper in progress).**

  This could help provide still more information about the h.

- **The whole error analysis for branching ratios and such has to be redone to see just how well the ILC will be able to probe the NMSSM model.**

- **One should not completely ignore the $m_{a_1} > 2_b$ possibility.**

  1. **$m_{h_1} > 110~\mathrm{GeV}$ is needed to escape LEP.**
  2. **$F \gtrsim 25$ (vs. $F \sim 5 - 10$) is not so bad.**
  3. **LHC and ILC analyses are still needed.**

Higher Curvature Effects in the ADD & RS Models: Rizzo

- In both ADD (Minkowski metric) and RS (AdS$_5$ metric), the Einstein Hilbert action is employed:

$$S = \frac{M^{D-2}}{2} \int d^D x \, [R + constant] \tag{2}$$

where R is the Ricci scalar and the "constant" refers to a possible bulk cosmological constant.

- Rizzo asks "How is ADD/RS phenomenology altered if we give up the EH action and generalize $R \to F$, where F is a suitable function constructed from invariants made out of the Ricci tensor.

- Why do this?

  In both models, $\sqrt{s} \sim M$ is possible (assuming TeV size extra dimensions) whereas the EH action is known to be only an effective theory valid for energies below M.

$\Rightarrow$ **"correction" terms should be present.**

Strings predict such terms sub-leading in $1/M^2$.

Correction terms have been considered for other reasons, e.g. cosmology/dark energy issues.

- Rizzo restricts himself to $F(R, P, Q)$, where $P \equiv R_{AB}R^{AB}$ and $Q \equiv R_{ABCD}R^{ABCD}$.

- One must make sure that there are no ghost or tachyonic fields present, which places constraints on F.

- Once done, what changes?

  Take ADD as an example (no cosmo constant). Then

$$F = F_R R + \left[-F_Q + \frac{1}{2}F_{RR}\right] R^2 + F_Q G\,, \tag{3}$$

where $G \equiv R^2 - 4P + Q$ and subscripts denote derivatives.

The most important effect is that one finds

$$M_{\mathrm{P}}^2 = (2\pi r_c)^n M^{n+2} F_R \tag{4}$$

(n is the number of extra dimensions) whereas in EH case $F_R = 1$.

This means that KK masses are shifted so that

$$m_{KK} \to m_{KK} F_R^{1/n} . \tag{5}$$

Also, in units of M, graviton emission cross-sections are modified:

$$d\sigma_{ADD} \to F_R^{-1} d\sigma_{ADD}(M^2, s, t, u) \tag{6}$$

Similarly, graviton exchange amplitudes are modified. Neglecting possible new scalars,

$$\mathcal{A}_{KK} \to F_R^{-1} \mathcal{A}_{KK} \tag{7}$$

- In general, there is also a new tower of scalars beginning at $\sim \mathrm{TeV}$.

  Their effect on LHC/ILC observables is quite small typically since such effects scale as $\sim (m_{external}^2/s)^2 \ll 1$.

- **The phenomenological implications have not been clearly delineated as of yet. $\Rightarrow$ work in progress.**

  One could for instance ask whether we must rethink our ability to determine n and M using measurements at two ILC energies.

- **Tom also presents a series of results for the RS model. There are lots of rescalings of a more complicated nature than in the ADD case.**

  Once again, effects of the new scalars are probably small.

Conclusions

- Theorists are hard at work revealing the full power of the ILC.
- It continues to be the case that the ILC will be crucial to a full understanding of the Terascale.

  Perhaps through precision measurements of a SM-like Higgs.

  Perhaps through observation and detailing of an NMSSM Higgs boson.

  Perhaps through observation of extra dimensions and, in particular, the detailed phenomenology thereof.

  Perhaps ..., and the list goes on.
- We eagerly await the LHC results, but we are quite certain that the ILC will be critical for ultimately understanding the full fundamental theory.