DOE site visit, October 3, 2006
Research in Theory and Phenomenology

Jack Gunion
U.C. Davis

Oct. 3, 2006

Broad Summary

- **The work of the phenomenology/model-building side of the group has been at the forefront of many exciting developments.**
- **For many year, including the last three years, we have generated many important ideas regarding new physics and how to search for the relevant signals, and, as a result, we have had a big impact upon signals being searched for at the Tevatron and especially on search strategies that will be appropriate at the LHC.**
- **Thus, we have been extremely active in working groups related to the Large Hadron Collider.**
- **In addition, a natural outgrowth of detailing LHC expectations**

is the development of how the LHC will interact with and influence the physics program at the planned linear e^+e^- collider (LC).

- As a result we have had significant impact on the long-range DPF planning initiatives and have provided substantial input to the the EPP2010 review.

- Much of the recent impact has been through my membership and editorship of the LHC / LC working group and report.

- I have also played a major role in studies of the e^-e^- and $\gamma\gamma$ options at the LC and has provided much input into the physics of a $\mu^+\mu^-$ collider.

- I am a member of both the CMS detector for the LHC and the U.S. Muon Collider Collaboration and have strong ties to the

ECFA/DESY, NLC and Muon Collider studies/collaborations in Europe.

In addition, I am a long standing member of the $\gamma\gamma$ collider working group in the U.S.

- **Most recently, I was a major contributor to the CPNSH (CP-violating and Non-Standard Higgs Boson) CERN yellow book.**

Research Program

General Research Philosophy and Goals

While we await new data that will guide us in constructing the correct theory beyond the Standard Model, one of the most important avenues of theoretical research is the development of new theoretical paradigms and determining the types of accelerators, detectors, triggers and analysis scenarios that will guarantee our ability to explore them.

This has been one of the most important focuses of our work over the last few years. I have, in particular, specialized in hunting for (and finding) theoretical models and scenarios that might make detection of new physics unusually difficult and challenging at one type of accelerator or another. Such scenarios typically result in particularly strong arguments for having a full complement of accelerators:

- **the LHC;**
- **a ~ 1 TeV linear collider;**
- **a $\gamma\gamma$ collider facility at the ILC;**
- **a e^-e^- collider option at the ILC;**
- **and possibly a muon collider, initially as a Higgs factory but expandable to the multi TeV energy range.**

Scenarios exist for which new physics is completely obscure at one accelerator while being extremely clear and easy to study in detail at another.

Working Group Reports

Thus, in the last few years, I have contributed quite significantly to most of the studies of prospects for the Tevatron, the LHC, the ILC, a $\gamma\gamma$ collider, a e^-e^- collider and the muon collider /

neutrino factory. Often my role has been that of a key organizer or convener and/or plenary speaker.

Two recent or fairly recent items of this type are the following:

- **ILC/LHC Complementarity:**

  The long (400+ pages) LHC/ILC report has appeared and is proving a very useful document.

  A group of the editors prepared a condensed summary designed for the EPP panel.

  EPP Questions Response Editors:

  John Conway, Jack Gunion, Howard Haber, Sven Heinemeyer, Gudrid Moortgat-Pick, Georg Weiglein

Summary of The EPP Questions Report

Basic Questions:

- How would the combination of the LHC and a Linear Collider answer questions that could not be addressed by either machine alone? Synergy

  Subsidiary Questions:

  1. What will we learn from the LHC alone?
  2. How much will our knowledge be improved with the addition of ILC data?
- What physics would a Linear Collider address that would be impossible to probe at the LHC? Uniqueness
- Are there physics arguments for operating a Linear Collider during the same time frame as the LHC? Concurrency

- **CP-Violating and Non-Standard Higgs Bosons**

  As noted, I am a major contributor to this CERN Yellow Book report, as author or coauthor of several sections of the book.

  In particular, I was main author of the section on triplet Higgs bosons and one of three authors of the NMSSM section.

  Some specific research topics

  The NMSSM

- The MSSM is being pushed into an awkward corner of parameter space characterized by the little hierarchy problem, lack of electroweak baryogenesis, ...

  Also, a satisfactory explanation of the μ term in the MSSM superpotential, $\mu \widehat{H}_u \widehat{H}_d$, remains elusive.

The NMSSM introduces an extra singlet superfield, with superpotential $\lambda \widehat{S}\widehat{H}_u\widehat{H}_d$. The μ parameter is then automatically generated by $\langle S\rangle$ leading to $\mu_{eff}\widehat{H}_u\widehat{H}_d$ with $\mu_{eff} = \lambda\langle S\rangle$.

Another substantial motivation for something like the NMSSM is that extra singlet fields are common in string models.

The single extra singlet superfield of the NMSSM contains an extra neutral gaugino (the singlino) ($\Rightarrow \widetilde{\chi}^0_{1,2,3,4,5}$), an extra CP-even Higgs boson ($\Rightarrow h_{1,2,3}$) and an extra CP-odd Higgs boson ($\Rightarrow a_{1,2}$).

The result is that the NMSSM is much less constrained than the MSSM, and does not require awkward parameter choices in general. In my opinion, the NMSSM should be adopted as the more likely benchmark minimal SUSY model and it should be explored in detail. There is much to do even after a number of years of working on this.

- **To further this study, Ellwanger, Hugonie and I constructed NMHDECAY**

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

  `http://higgs.ucdavis.edu/nmhdecay/nmhdecay.html`

  It is proving very useful to the community – many people are using it.

Fine-Tuning **(with Dermisek)**

- **Aside from the fact that the NMSSM provides a solution to the μ problem, we have also shown that it eliminates the fine-tuning problem of the MSSM.**

  The standard measure of fine-tuning employed is

$$F = \mathrm{Max}_p F_p \equiv \mathrm{Max}_p \left| \frac{d \log m_Z}{d \log p} \right| , \qquad (1)$$

where the parameters p comprise the GUT-scale values of λ, κ, A_λ, A_κ, and the usual soft-SUSY-breaking gaugino, squark, slepton, . . . masses.

- How do we get small fine-tuning?

1. F is minimum for $m_{h_1} \sim 100 \div 104~\mathrm{GeV}$ (in a totally unconstrained scan of parameter space this is just what one finds for moderate $\tan\beta$). Neither lower nor higher!
   For $m_{h_1} \sim 100~\mathrm{GeV}$, $\sqrt{m_{\widetilde{t}_1} m_{\widetilde{t}_2}} \sim 350~\mathrm{GeV}$.
2. $m_{h_1} \sim 100~\mathrm{GeV}$ is only LEP-allowed if $h_1 \to a_1 a_1$ and $a_1 \to \tau^+\tau^-$ ($2m_\tau < m_{a_1} < 2m_b$) or $gg, q\overline{q}$ ($m_{a_1} < 2m_\tau$) so as to hide the h_1 in this mass range.

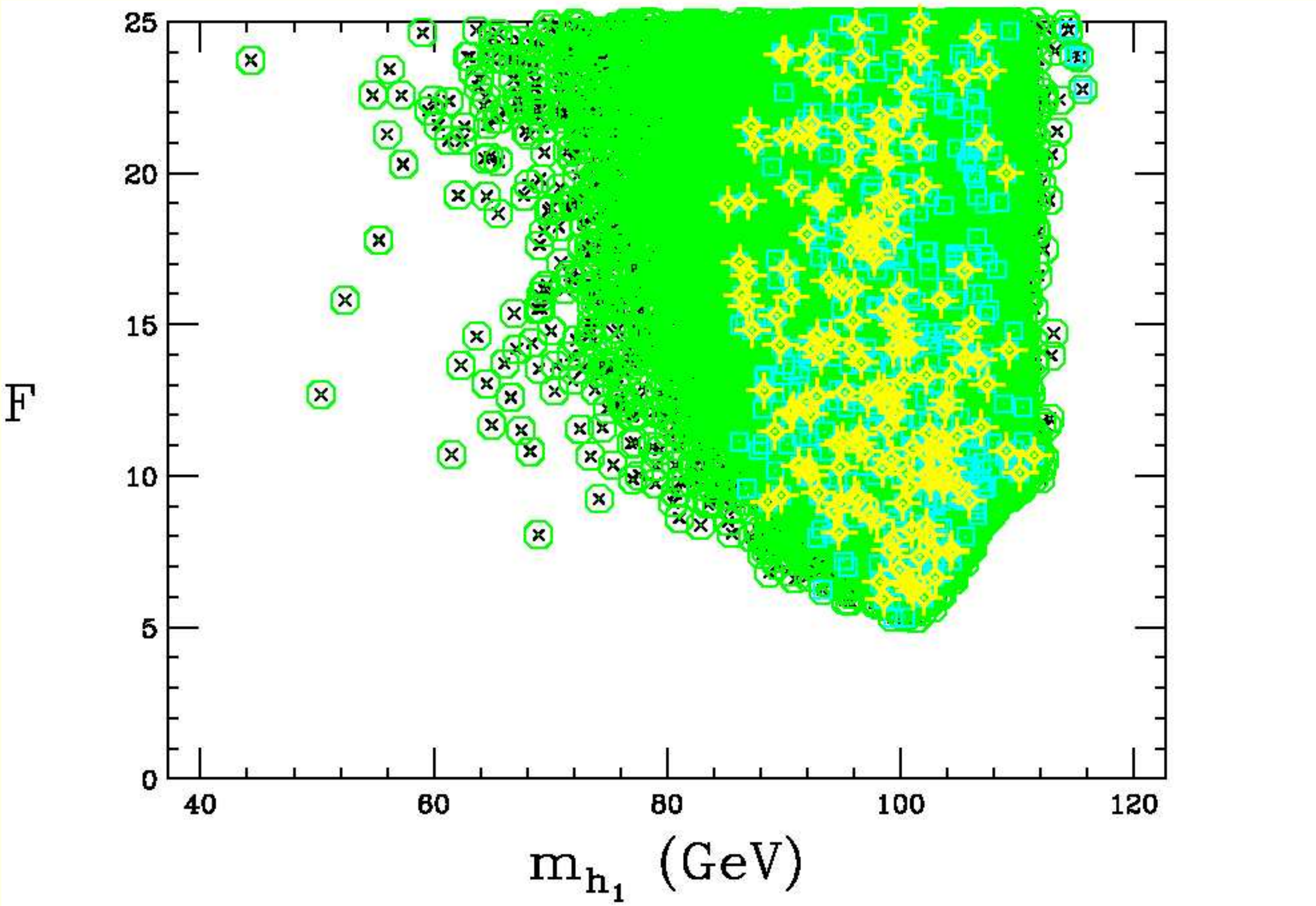

Figure 1: F vs. m_{h_1} for $M_{1,2,3} = 100, 200, 300$ GeV and $\tan\beta = 10$. Small $\times$ = no constraints other than global and local minimum, no Landau pole before M_U and neutralino LSP. The O's = stop and chargino limits imposed, but NO Higgs limits. The □'s = all single channel Higgs limits imposed. The large FANCY CROSSES are after requiring $m_{a_1} < 2m_b$.

3. It turns out that a light a_1 is quite natural since it is a pseudo-Nambu-Goldstone boson associated with a symmetry that is explicitly broken by the A_κ and A_λ soft-SUSY-breaking terms, implying $m_{a_1} \to 0$ for $A_\kappa, A_\lambda \to 0$.
   Further, RGE's naturally yield A_κ and A_λ of the required size to give small m_{a_1}. In fact, if $A_\kappa(M_U), A_\lambda(M_U) \sim 0$ then $A_\kappa(m_Z) \ll A_\lambda(m_Z) \sim M_2$ is automatic and is what is needed.
4. At the same time, the correlated $A_\kappa, A_\lambda \neq 0$ values generated by the RGE's are just what are needed for large $B(h_1 \to a_1 a_1)$ and small enough m_{a_1} that $a_1 \to \tau^+\tau^-$ or $jets$, both being required for h_1 with $m_{h_1} \sim 100~\mathrm{GeV}$ to escape LEP limits on $Zh_1 \to Zb\overline{b}$ and the closely tied $Zh_1 \to b\overline{b}b\overline{b}$ channel.

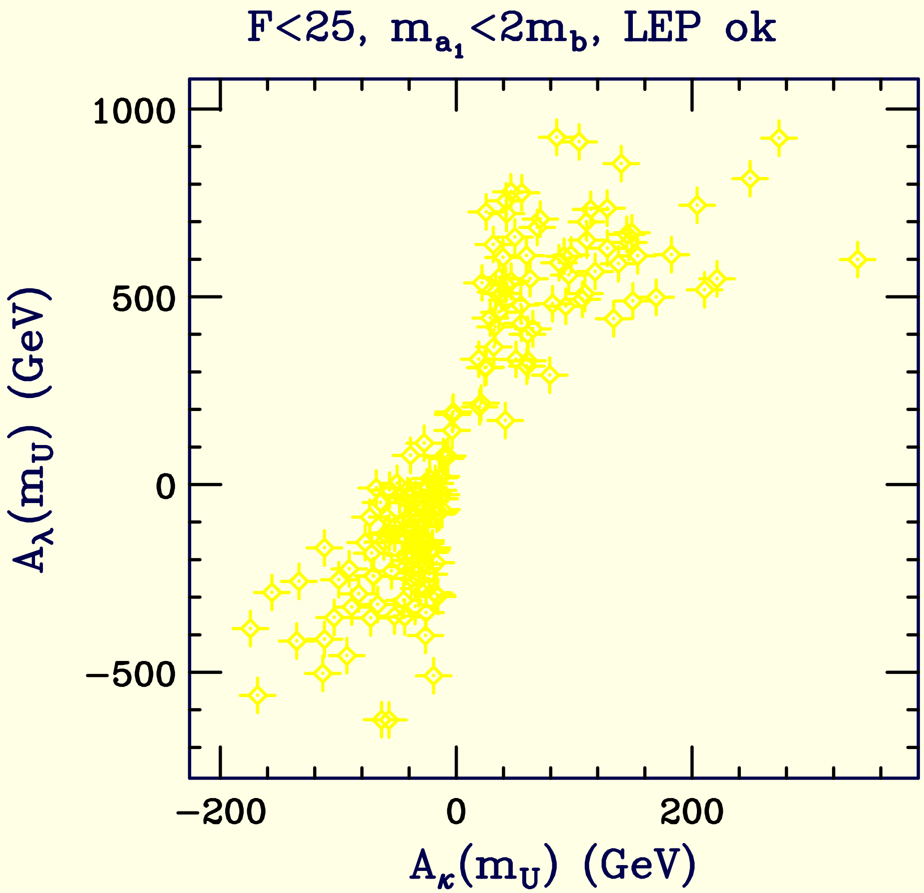

Figure 2: $A_\kappa(M_U)$ vs. $A_\lambda(M_U)$ for $F < 25$ fully ok $m_{a_1} < 2m_b$ solutions in case of $M_{1,2,3} = 100, 200, 300~\mathrm{GeV}$ and $\tan\beta = 10$.

5. The typical very low F points have $B(h_1 \to b\bar{b}) \sim 0.1$ and $B(h_1 \to a_1 a_1) \sim 0.85$.
   The former is precisely what is needed to explain the old LEP

excess at $b\bar{b}$ mass of about 100 GeV.

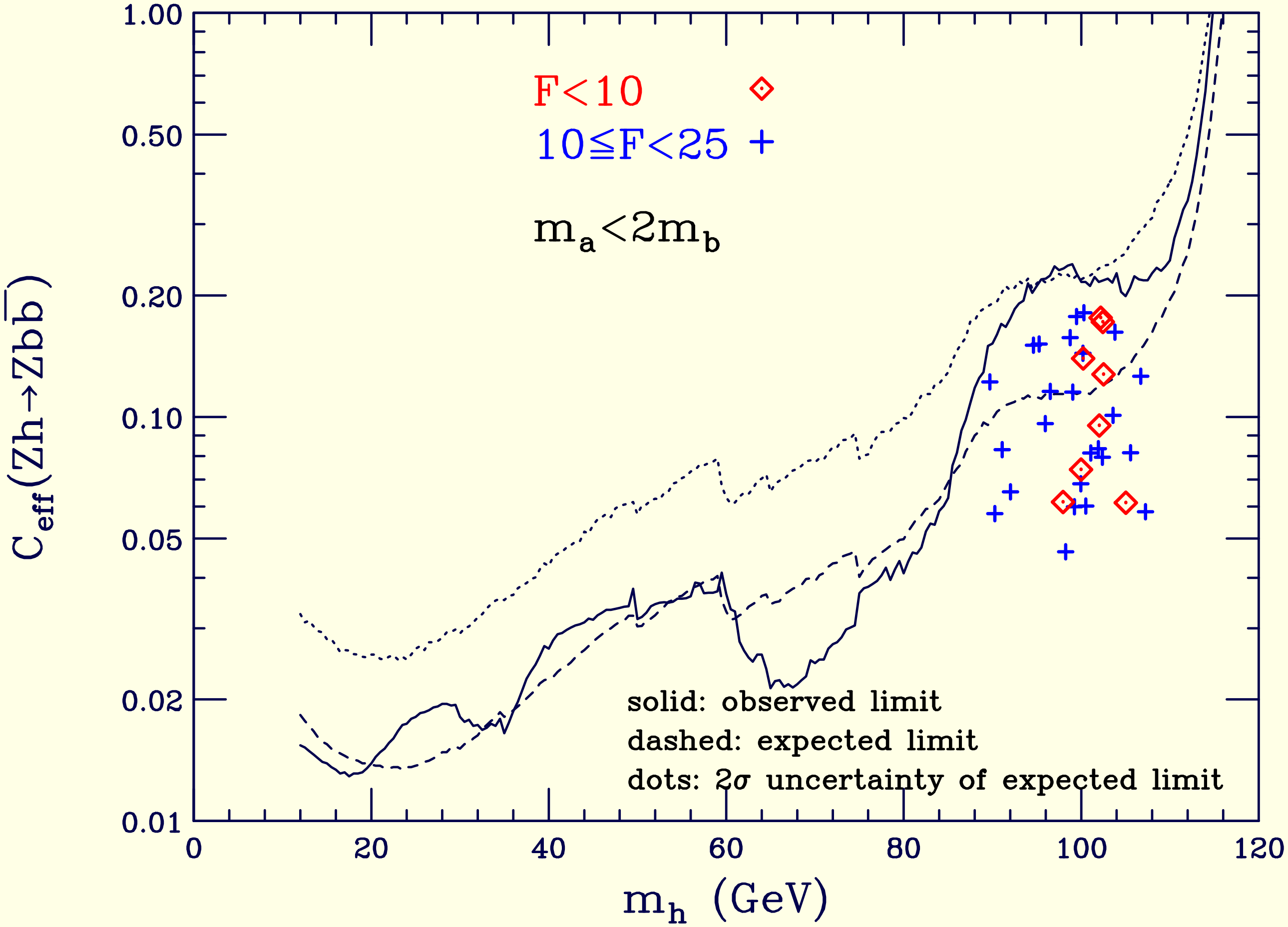

Figure 3: Observed LEP limits on C_{eff}^{2b} for the low-F points with $m_{a_1} < 2m_b$.

So just how consistent are the $F < 10$ points with the observed event excess. Although it is slightly misleading, a good place to begin is to recall the famous $1 - CL_b$ plot

for the $Z2b$ channel. (Recall: the smaller $1 - CL_b$ the less consistent is the data with expected background only.)

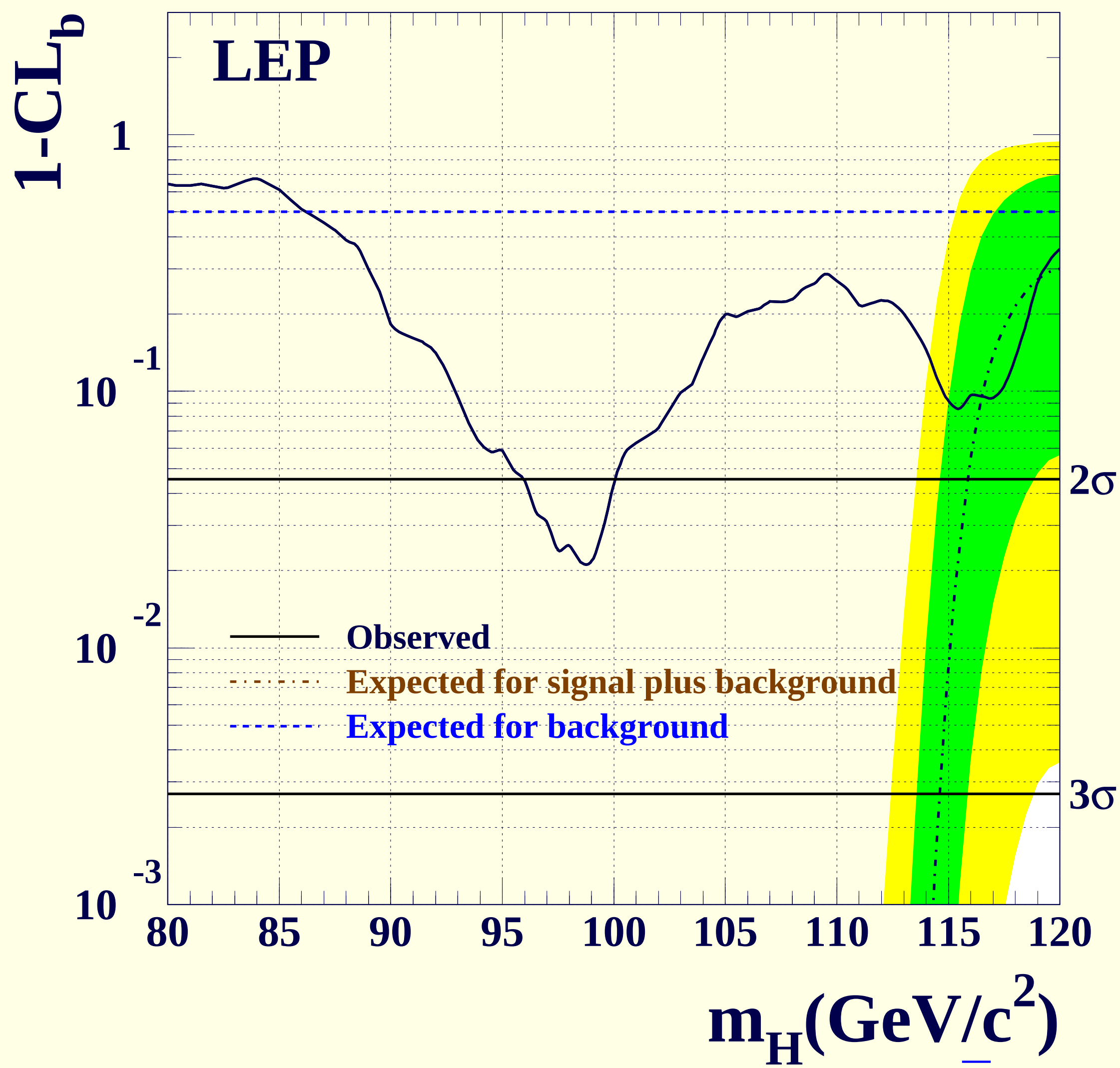

Figure 4: Plot of $1 - CL_b$ for the $Zb\bar{b}$ final state.

6. **There is an observed vs. expected discrepancy exactly where we want it! And because $B(h_1 \to b\bar{b})$ is $1/10$ the SM value, the discrepancy is of about the right size.**
7. **Are there other relevant limits on the kind of scenario we envision?**

   If the $a_1 a_1 \to 4\tau$ decay is the relevant scenario, the LEP limits run out for $m_h > 87~\mathrm{GeV}$.

   If the $a_1 a_1 \to (gg, q\bar{q}) + (gg, q\bar{q})$ decay is relevant, then we have the hadronic decay limits. They run out for $m_h > 80~\mathrm{GeV}$.
8. **To see how well the $F < 10$, $m_{a_1} < 2m_b$ points describe the LEP excesses we have to run them through the full LHWG code. Well, we didn't do it, but Philip Bechtle did it for us.**

   He tells us a large fraction of our points with low F, ...,

describe the observed excess perfectly.

Summary

- We can have a SM-like (as regards WW and ZZ couplings) Higgs with $m_{h_1} \sim 100~\mathrm{GeV}$, perfect for precision EW.
- $B(h_1 \to b\bar{b})$ is naturally of order the value of 0.1 needed to explain old LEP excess.
- The dominant $h_1 \to a_1 a_1 \to 4\tau$ or $4~jets$ decays have so far escaped LEP (we are working on the former with Chris Tully).
- The LHC standard modes will not work.
  Maybe $pp \to ppX$ will see a decay independent signal in the M_X distribution?
  Much work to be done.
- At the ILC, observation in $e^+e^- \to ZX$ via bump in M_X will be trivial.

Unitarity Challenges the Randall Sundrum Model

(w. Grzadkowski)

- **The RS model with two branes is an alternative and attractive solution to the hierarchy problem.**
  There is a TeV brane and a $M_{\rm P}$ brane.
  We consider the original version with matter confined to the "TeV" brane.
  Gravity lives in the bulk.
  The TeV scale arises from $M_{\rm P}$ by virtue of an exponential warp factor that converts scales of order $M_{\rm P}$ on the Planck brane to TeV scales (in particular, $v = 246~\mathrm{GeV}$) on the TeV brane.
- **The model implies a tower of KK excitations due to the fact that gravitons are confined to be modes between the two**

branes.

- The model has a radion (fluctuation of interbrane separation) as well as a Higgs boson.
- The question? Are the KK gravitons and the RS model as a whole constrained by unitarity in $W_L W_L \to W_L W_L$ scattering.
- The crucial parameters of the model are Λ_ϕ (a cutoff scale) and $m_0/M_{\rm P}$ (the ratio of the 5D curvature to the 4D Planck mass).

  We expect Λ_ϕ in the 2 to 20 TeV range. Above this calls into question the model's original purpose. Below is hard to reconcile with precision data.

  To be an accurate effective theory, the RS model certainly requires $m_0/M_{\rm P} < 1$ and probably < 0.1 — string estimates are more in the range of 0.01.

  So what is the problem?

– Plot Rea_0 to see.

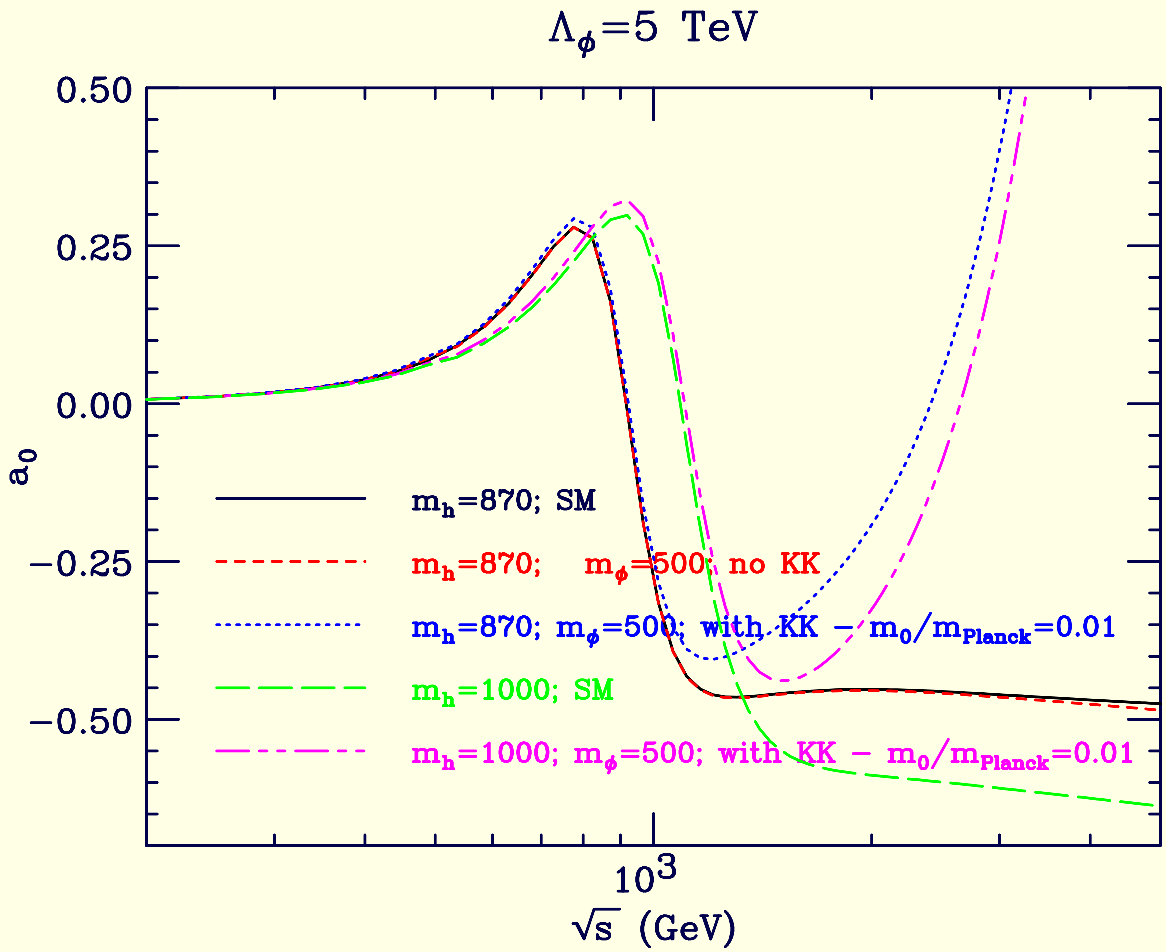

Figure 5: We plot $\mathrm{Re}\, a_0$ as a function of $\sqrt{s}$ for five cases: 1) solid (black) $m_h = 870\ \mathrm{GeV}$, SM contributions only ($\gamma = 0$); 2) short dashes (red) $m_h = 870\ \mathrm{GeV}$, with an unmixed radion of mass $m_\phi = 500\ \mathrm{GeV}$ included, but no KK gravitons (we do not show the very narrow ϕ resonance); 3) dots (blue) as in 2), but including the sum over KK gravitons; 4) long dashes (green) $m_h = 1000\ \mathrm{GeV}$, with an unmixed radion of mass $m_\phi = 500\ \mathrm{GeV}$, but no KK gravitons); 5) as in 4), but including the sum over KK gravitons.

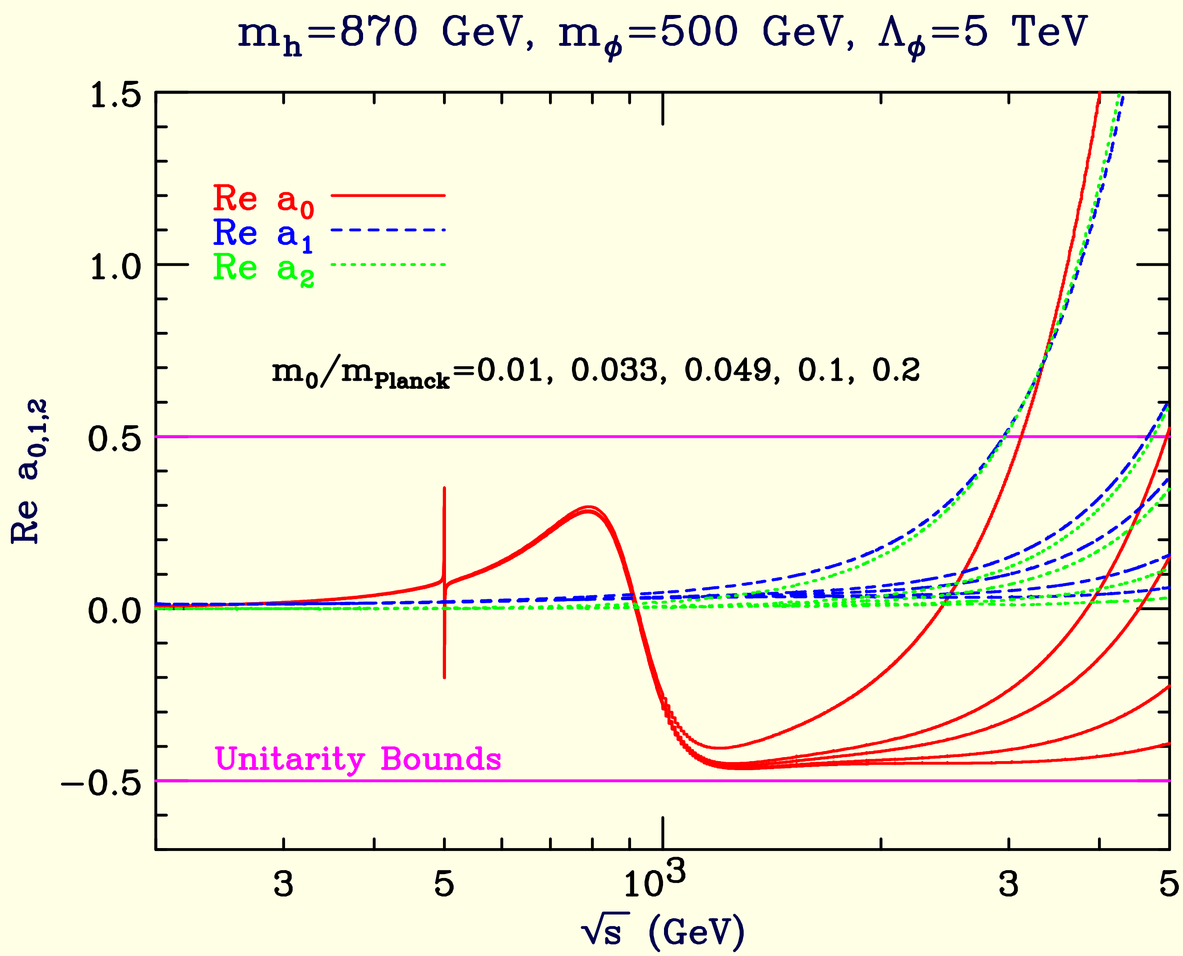

Figure 6: The amplitudes $a_{0,1,2}(s)$ for $m_h = 870~\mathrm{GeV}$, $m_\phi = 500~\mathrm{GeV}$ and $\overline{\Lambda} = \Lambda_\phi = 5~\mathrm{TeV}$ are plotted as a function of $\sqrt{s}$ for the m_0/M_P values indicated on the plot. Curves of a given type become higher as one moves to lower m_0/M_P values. We have included all KK resonances with $m_n < \overline{\Lambda}$ (at all $\sqrt{s}$ values).

– **The KK gravitons make a big contribution if $m_0/M_{\rm P}$ is as small as we would like and unitarity is violated for $\sqrt{s} < \Lambda_\phi$. In particular, one should sum over all KK's with mass below Λ_ϕ — there can be many. And the contribution of each to a_0 grows as s. (It could have been s^5 before all kinds of lovely cancellations.)**

  The large magnitude of the KK sum to the partial wave a_0 implies a more limited range of validity of the model than was previously envisioned.

– **One can turn this around once LHC data is available.**

  At the LHC, we can hope to measure the width and mass of one of these KK modes. These two measurements will determine both Λ_ϕ and $m_0/M_{\rm P}$.

  We will also have measured m_h.

  We can then ask if the model will be consistent with unitarity all the way up to Λ_ϕ or should we anticipate new physics

earlier.

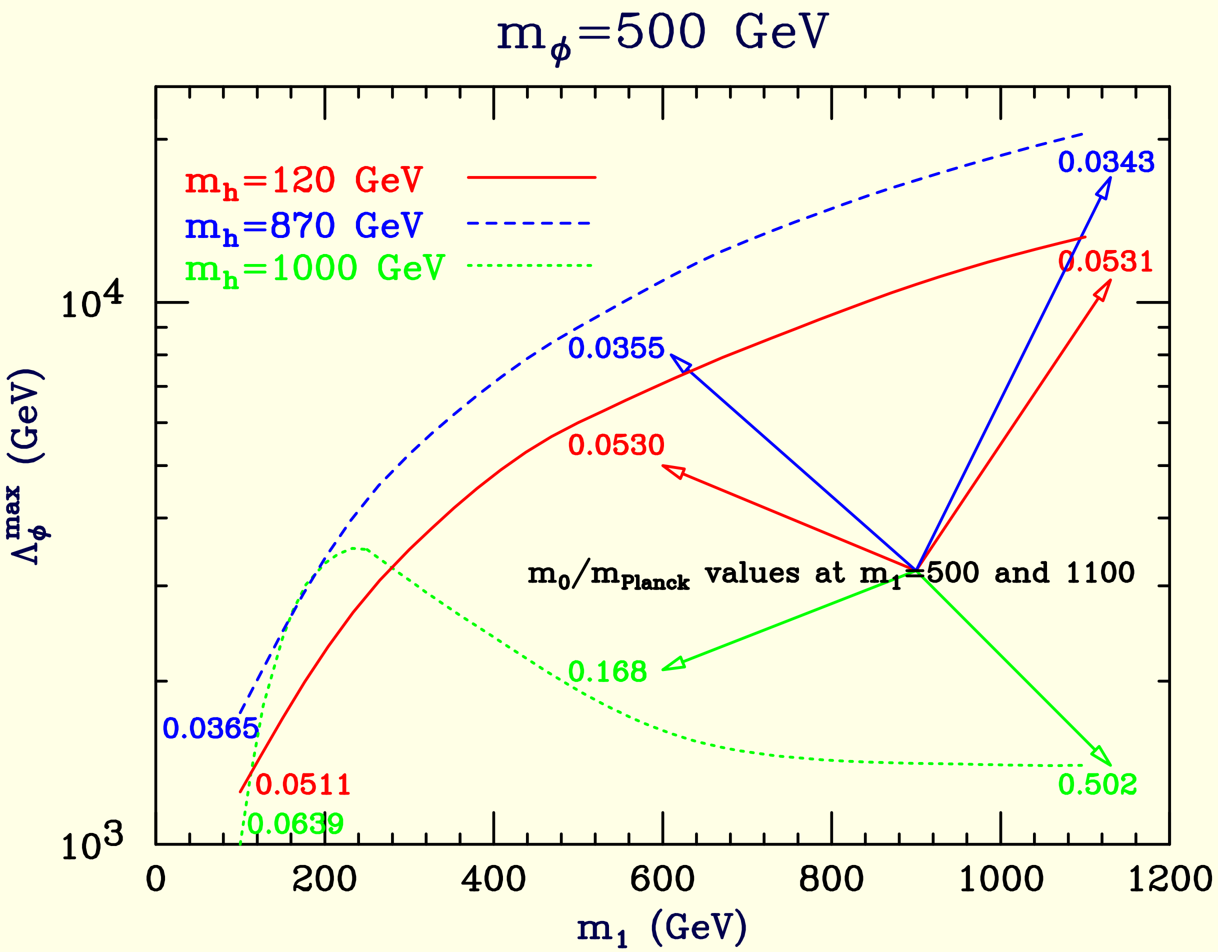

Figure 7: We plot as a function of m_1 the maximum Λ_ϕ values, for which unitarity is satisfied for all $\sqrt{s} < \Lambda_\phi$ for $m_h = 120,\ 870$ and $1000\ \mathrm{GeV}$. The numbers along a given m_h curve are the m_0/M_P values at $m_1 = 100$, 500 and $1500\ \mathrm{GeV}$ corresponding to the value of $\Lambda_\phi^{\max}$ at these respective m_1 values.

The ADD Model of extra dimensions and invisible Higgs decays

(w. D. Dominici)

- In the ADD model, one introduces a certain number, δ, of extra dimensions which are wrapped up on a cycle of length $L = 2\pi R$.

  Gravity sees these extra dimensions and there are so-called graviscalar modes that propagate in the extra dimension, and that would therefore appear invisible to a 4D observer.

- Wells and collaborators showed that if Higgs-graviscalar mixing is introduced (it is certainly not forbidden, and some is implied if you desire a conformally invariant theory), then the decays of the Higgs boson could be dominated by mixing into the invisible graviscalar states.

They find that the width of the Higgs is increased from $\Gamma_h^{\rm tot}$ to $\Gamma_h^{\rm tot} + \Gamma_{\rm inv}$. We define the ratio

$$R \equiv \frac{\Gamma_{\rm inv}}{\Gamma_h^{\rm tot}} . \tag{2}$$

We have verified this by brute force diagonalization of the mass-squared matrix to yield the mass eigenstates h' and $s'_{\vec{n}}$ (there is a rather continuous spectrum of the $s'_{\vec{n}}$).

It is the h' that has this increased width.

Quite reasonable models parameters will give substantial R, although one should become suspicious of calculational accuracy if the model parameters yield $R > 0.5$.

- Using our techniques of mass-squared matrix diagonalization followed by Feynman rule calculations of various processes, we have discovered some features of this physics that are not well-appreciated.

1. The inclusive cross section $\sigma(e^+e^- \to Z + h') + \sigma(e^+e^- \to Z + \sum_{\vec{n}>0} s'_{\vec{n}})$ is enhanced over the SM $e^+e^- \to Zh$ cross section by a factor of $1 + 2R$.
2. The $e^+e^- \to Z + (h' + \sum_{\vec{n}>0} s'_{\vec{n}}) \to Z + SM\ mode$ cross section is suppressed by a factor of $1/(1 + R) \sim 1 - R$.
3. Combining the above, the $e^+e^- \to Z + (h' + \sum_{\vec{n}>0} s'_{\vec{n}}) \to Z + invisible$ cross section is at the level $3R$ relative to the normal SM inclusive cross section.

- How would you measure R?

1. One technique is to measure the $e^+e^- \to Z + X$ total rate and the $e^+e^- \to Z + visible$ and $e^+e^- \to Z + invisible$ rates for which one would expect to find

$$\frac{\sigma(e^+e^- \to Z + visible)}{\sigma(e^+e^- \to Z + visible) + \sigma(e^+e^- \to Z + invisible)} = \frac{\left(\frac{1}{1+R}\right)}{1 + 2R} \sim 1 - 3R\,. \tag{3}$$

2. The most natural technique you might think would be to simply measure the width of the M_X distribution which should be $1+R$ times the SM width $\Gamma_h^{\rm tot}$. This is true for the h' component of X, but apparently not true for the $\sum_{\vec n>0} s'_{\vec n}$ component the width of which is controlled by the SM width alone and not $\Gamma_h^{\rm tot}+\Gamma_{\rm inv}$.

   To be certain of this result, we must calculate to higher order in R.
3. In any case, Higgs physics in the ADD model with Higgs-radion mixing will be quite tricky to analyze; experimentalists will have to be aware of these subtle effects.