Higgs Physics in the NMSSM

Jack Gunion
Davis Institute for High Energy Physics, U.C. Davis

Collaborators: U. Ellwanger, C. Hugonie, S. Moretti

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Outline

- Why go beyond the MSSM?
- NMHDECAY
- Difficult NMSSM scenarios due to $h \to aa$ or $h \to h'h'$ decays
- The LHC $WW \to h \to aa \to jj\tau^+\tau^-$ signal
- The Linear collider signal
- The role of a low energy γC
- Conclusions

Why go beyond the MSSM?

- **The attractive features of the minimal supersymmetric model (MSSM), containing exactly two Higgs doublets, are well known (see [1] and references therein).**

  In particular, the MSSM yields nearly exact coupling constant unification and automatic EWSB via radiative evolution.

- **However, the CP-conserving (CPC) MSSM is being pushed into an uncomfortable corner in several ways.**

  1. **First, the rather substantial lower bound on the mass of the light h^0 from LEP [2] is only easily accommodated in the restrictive part of the MSSM parameter space characterized by large $\tan\beta$ combined with large top squark masses and mixing.**
  2. **This part of parameter space cannot be reconciled with that for which the CP-conserving (CPC) MSSM provides adequate baryogenesis. A brief review of the situation and references appears in [3, 4, 5].**

3. A “little” fine tuning problem arises for this part of parameter space. This was extensively discussed in Thursday’s sessions.
4. A final problem for the MSSM is that no really attractive source for the superpotential μ parameter has been proposed.
   Most explanations involve some extension of the MSSM.

- Keeping to the supersymmetric context, but going beyond the MSSM, the above issues have led to consideration of:

1. introducing CP-violation (CPV) into the MSSM Higgs sector (from CP-violating soft-SUSY loops) — this allows for adequate baryogenesis [3, 4] and leads to interesting new Higgs sector phenomenology [8];
2. the next-to-minimal supersymmetric model (NMSSM) in which one extra singlet superfield is added to the MSSM [9], thereby allowing a natural explanation for the μ parameter (see [1] for a discussion and early references) — an acceptable level of baryogenesis can be achieved, for example due to weaker lower bounds on Higgs masses;
3. taking seriously the prediction common to many string models of many extra $SU(2)_L \times U(1)$ singlets and/or doublets (see, for example, [10]); Higgs mass bounds would be weaker and the increased parameter space would clearly allow for adequate dark matter and baryogenesis.
4. More radical extensions such as those discussed on Thursday.

The NMSSM is the simplest!

- A common feature of all of these extensions is that they lead to possible difficulties for detecting even one of the supersymmetric Higgs bosons at the LHC. **In particular, one can choose parameters so that the following problems arise**
  - *The easily produced Higgs boson(s), e.g. those with large WW/ZZ coupling, can decay dominantly to two lighter Higgs bosons, as first noted in [12] and later examined by [13, 14, 15] in somewhat more detail.*
    * **For example, for a CPC Higgs sector, $h \to aa$ and $h' \to hh$ decays are both possible in general.**
    * **$h \to h'V$ decays are generically present, although they tend to be much less dangerous than the Higgs to Higgs-pair decays.**
    * **In both the CPC and CPV cases, the Higgs potential can be such that these lighter Higgs bosons have WW/ZZ couplings that are very weak or zero ($e.g.$ they can be pseudoscalars in the CPC case) while at the same time their Yukawa couplings to $t\bar{t}$ and $b\bar{b}$ are not very different from SM-like values.**
    * **In this case, it will typically be very difficult to detect them directly.**
  - *When there are multiple mixed CP-even Higgs bosons in a CPC Higgs sector or mixed CP-even and CP-odd Higgs bosons in a CPV Higgs sector, the Higgs*

bosons will generically tend to share the $\boldsymbol{WW/ZZ}$ *coupling strength.*

  * **At the LHC, this leads to a corresponding reduction of the W-loop contribution to the $h\gamma\gamma$ couplings which will then strongly cancel against the t-loop contribution resulting in a dramatic decrease in the rate for the excellent resolution $gg \to h \to \gamma\gamma$ channels.**
  * **In addition, the $gg \to h \to ZZ^* \to 4\ell$ rate is also suppressed relative to the poorer resolution $b\bar{b}$ and $t\bar{t}$ channel branching ratios (not to mention any possible $h \to Vh'$ or $h \to h'h''$ decays).**

- *In addition, the Higgs bosons can differ in mass so that signals in, for example,* $\boldsymbol{gg \to t\bar{t}h}$ *and* $\boldsymbol{WW \to h}$ *with* $\boldsymbol{h \to b\bar{b}}$ *or* $\boldsymbol{h \to \tau^+\tau^-}$ *are overlapping as well as reduced in magnitude.*
  * **Such overlaps can obviate many of the standard discovery modes.**
- **If these problems result in the LHC failing to detect a signal for any of the Higgs bosons, the LC can still succeed in searching for the h using $e^+e^- \to Zh$ production by looking for a bump, or at least a broad enhancement, in the reconstructed M_X mass distribution in the inclusive $e^+e^- \to ZX$ channel.**

  The inclusive M_X peak or broad excess is independent of how the Higgs bosons decay.
- **Even in this maximally difficult situation, the LHC will have played an important role.**

If light Higgs bosons more or less saturate the WW/ZZ coupling ($\sum_i g^2_{h_i WW} = g^2_{h_{SM} WW}$), $W_L W_L \to W_L W_L$ scattering will be perturbative at the LHC.

Observation of this perturbativity at the LHC will imply that such light Higgs (or some other type of perturbative EWSB) are present below the TeV scale, implying the absolute need for a linear collider to observe them.

Of all the possibilities being proposed, I remain convinced that the NMSSM is the most attractive, and a group of us (JFG, Ellwanger, Hugonie, Moretti) have been pursuing its phenomenology.

In fact, we have gotten serious enough to construct the NMSSM analogue of HDECAY.

References

[1] J.F. Gunion, H.E. Haber, G. Kane and S. Dawson, *The Higgs Hunter's Guide* (Perseus Publishing, Reading, MA, 2000).

[2] See the LEP Higgs Working Group web pages, http://lephiggs.web.cern.ch/LEPHIGGS, especially LHWG Note/2001-04 (2001).

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[12] J. F. Gunion, H. E. Haber and T. Moroi, arXiv:hep-ph/9610337.

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[14] U. Ellwanger, J. F. Gunion and C. Hugonie, arXiv:hep-ph/0111179.

[15] U. Ellwanger, J. F. Gunion, C. Hugonie and S. Moretti, arXiv:hep-ph/0305109.

NMHDECAY

We begin by specifying our conventions for parameters in the NMSSM.

a) Apart from the usual quark and lepton Yukawa couplings, the scale invariant superpotential is

$$\lambda \ \widehat{S}\widehat{H}_u\widehat{H}_d + \frac{\kappa}{3} \ \widehat{S}^3 \tag{1}$$

depending on two dimensionless couplings λ, κ beyond the MSSM. (Hatted capital letters denote superfields, and unhatted capital letters will denote their scalar components).

b) The associated trilinear soft terms are

$$\lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3 \, . \tag{2}$$

c) The final two input parameters are

$$\tan\beta = \ \langle H_u \rangle / \langle H_d \rangle \ , \ \mu_{\rm eff} = \lambda \langle S \rangle \ . \tag{3}$$

These, along with M_Z, can be viewed as determining the three SUSY breaking masses squared for H_u, H_d and S through the three minimization equations of the scalar potential.

Thus, as compared to two independent parameters in the Higgs sector of the MSSM (often chosen as $\tan\beta$ and M_A), the Higgs sector of the NMSSM is described by the six parameters

$$\lambda\ ,\ \kappa\ ,\ A_\lambda\ ,\ A_\kappa,\ \tan\beta\ ,\ \mu_{\mathrm{eff}}\ . \tag{4}$$

We will choose sign conventions for the fields such that λ and $\tan\beta$ are positive, while κ, A_λ, A_κ and μ_{eff} should be allowed to have either sign.

In addition, values for the gaugino masses and of the soft terms related to the squarks and sleptons that contribute to the radiative corrections in the Higgs sector and to the Higgs decay widths must be input.

- We provide two forms of the NMHDECAY program:
  - NMHDECAY_SLHA.f — for study of one parameter point in the SLHA conventions for particle labeling etc. familiar to experimentalists;
  - NMHDECAY_SCAN.f — designed for general phenomenological work including scanning over ranges of NMSSM parameters.

The programs, and associated data files, can be downloaded from the two web pages:

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

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

The web pages provide simplified descriptions of the programs and instructions on how to use them. The programs will be updated to include additional features and refinements in subsequent versions. We welcome comments with regard to improvements that users would find helpful.

- **Input files are** `slhainp.dat` **and** `scaninp.dat`**, respectively. They are simple!**

```
#  INPUT FILE FOR NMHDECAY
#  BASED ON SUSY LES HOUCHES ACCORD, MODIFIED FOR THE NMSSM
#  IN EXTPAR: LINES 61-64: NMSSM YUKAWA COUPLINGS AND TRILIN. SOFT TERMS
BLOCK MODSEL
  3     1     # NMSSM PARTICLE CONTENT
BLOCK SMINPUTS
  1   137.036 # ALPHA_EM^-1(0)
  2   1.16639D-5   # GF
  3   0.12    # ALPHA_S(MZ)
  4   91.187  # MZ
  5     4.24  # MB(MB), RUNNING B QUARK MASS
  6   175.    # TOP QUARK POLE MASS
  7   1.7771  # MTAU
BLOCK MINPAR
  3    5.     # TANBETA
BLOCK EXTPAR
  1   5.D2    # M1
  2   1.D3    # M2
  3   3.D3    # M3
  11  1.5D3   # ATOP
  12  1.5D3   # ABOT
  13  1.5D3   # ATAU
  23  180.    # MU
  31  1.D3    # LEFT SELECTRON
  32  1.D3    # LEFT SMUON
  33  1.D3    # LEFT STAU
  34  1.D3    # RIGHT SELECTRON
  35  1.D3    # RIGHT SMUON
  36  1.D3    # RIGHT STAU
  41  1.D3    # LEFT 1ST GEN. SQUARKS
  42  1.D3    # LEFT 2ND GEN. SQUARKS
  43  1.D3    # LEFT 3RD GEN. SQUARKS
  44  1.D3    # RIGHT U-SQUARKS
  45  1.D3    # RIGHT C-SQUARKS
  46  1.D3    # RIGHT T-SQUARKS
  47  1.D3    # RIGHT D-SQUARKS
  48  1.D3    # RIGHT S-SQUARKS
  49  1.D3    # RIGHT B-SQUARKS
  61  .3D0    # LAMBDA
  62  .3D0    # KAPPA
  63  200.    # A_LAMBDA
  64  0.0     # A_KAPPA
```

Table 1: Sample `slhainp.dat` file.

```
#
#  Total number of points scanned
#
1000
#
#  Output format 0=short 1=long (not recommended for big scannings)
#
0
#
#  lambda
#
0.5
0.5
#
#  kappa
#
-0.15
-0.15
#
#  tan(beta)
#
3.5
3.5
#
#  mu
#
200.
200.
#
#  A_lambda
#
780.
780.
#
#  A_kappa
#
150.0
250.0
```

Table 2: Sample `scaninp.dat` file — 1st half for sample case #2.

```
#
#  Remaining soft terms (no scan)
#
mQ3=  1.D3
mU3=  1.D3
mD3=  1.D3
mL3=  1.D3
mE3=  1.D3
AU3=  1.5D3
AD3=  1.5D3
AE3=  1.5D3
mQ=   1.D3
mU=   1.D3
mD=   1.D3
mL=   1.D3
mE=   1.D3
M1=   5.D2
M2=   1.D3
M3=   3.D3
```

Table 3: The 2nd half of `scaninp.dat` file for sample case #2.

NMHDECAY performs the following tasks:

1. **It computes the masses and couplings of all physical states in the Higgs, chargino and neutralino sectors.**[1]
   Error messages are produced if a Higgs or squark mass squared is negative.
2. **It computes the branching ratios into two particle final states (including charginos and neutralinos — decays to squarks and sleptons will be implemented in a later release) of all Higgs particles.**
3. **It checks whether the Higgs masses and couplings violate any bounds from negative Higgs searches at LEP, including many quite unconventional channels that are relevant for the NMSSM Higgs sector.**
   It also checks the bound on the invisible Z width (possibly violated for light neutralinos).
   In addition, NMHDECAY checks the bounds on the lightest chargino and on neutralino pair production.
   Corresponding warnings are produced in case any of these phenomenological constraints are violated.

[1] For the Higgses, we have included the leading two-loop effects, but neglected subleading two-loop contributions and subleading one-loop purely electroweak contributions. In MSSM limit, our Higgs masses agree to within a few GeV with HDECAY.

4. **It checks whether the running Yukawa couplings encounter a Landau singularity below the GUT scale.**
   A warning is produced if this happens.
5. **Finally, NMHDECAY checks whether the physical minimum (with all vevs non-zero) of the scalar potential is deeper than the local unphysical minima with vanishing $\langle H_u \rangle$ or $\langle H_d \rangle$.**
   If this is not the case, a warning is produced.

- **Below, I discuss the two examples we employ to illustrate the use of these programs.**

  They represent two particularly interesting scenarios in which Higgs to Higgs decays make LHC Higgs detection either very different compared to the MSSM or simply very difficult.

- **To recall, normal MSSM Higgs detection at the LHC relies on:**

  1) $gg \to h/a \to \gamma\gamma$;
  2) associated Wh/a **or** $t\bar{t}h/a$ **production with** $\gamma\gamma\ell^{\pm}$ **in the final state;**
  3) associated $t\bar{t}h/a$ **production with** $h/a \to b\bar{b}$;
  4) associated $b\bar{b}h/a$ **production with** $h/a \to \tau^+\tau^-$;
  5) $gg \to h \to ZZ^{(*)} \to$ **4 leptons;**

6) $gg \to h \to WW^{(*)} \to \ell^+\ell^-\nu\bar{\nu}$;
7) $WW \to h \to \tau^+\tau^-$;
8) $WW \to h \to WW^{(*)}$.

- We estimated the expected statistical significances at the LHC in all Higgs boson detection modes 1) – 8) by rescaling results for the SM Higgs boson and/or the the MSSM h, H and/or A.

- **Scenarios for which LHC Higgs detection is "easy".**

If Higgs decays to Higgs and/or SUSY are forbidden, then [14]: We can always detect at least one of the NMSSM Higgs bosons.

Both the $t\bar{t}h \to t\bar{t}b\bar{b}$ mode (We have had the experimentalists extrapolate this beyond the usual SM mass range of interest.) and the WW fusion modes are critical to this statement.

- **The difficult scenarios: Higgs to Higgs (or SUSY) decays**

For some earlier scenarios of this type and discussion, see Refs. [14, 15].

- **The first illustrates the potentially crucial importance of the LHC $h \to aa$ detection mode (that is dominant over a significant, not fine-tuned, range of parameters of the NMSSM).**
- **The second exposes a limited portion of parameter space for which Higgs discovery would not have occurred at LEP and will probably not be possible at the LHC.**

Sample case #1

- **To reveal cases where h_1 is SM-like and $h_1 \to a_1 a_1$ is dominant, it will be convenient to fix all but one of the parameters (which allows for a reasonable graphical representation), and perform a scan over the remaining parameter.**

- **In some sense, the input parameter A_λ is the most natural one to vary, since the mass of the MSSM like pseudoscalar depends quite strongly on A_λ (and hence A_λ plays the role of M_A in the MSSM).**

- **Let us first consider the following choice of the NMSSM parameters: $\lambda = \kappa = 0.3$, $\tan\beta$ = 5, $\mu_{\rm eff}$ = 180 GeV, A_κ = 0.**

  For the squark masses and trilinear couplings, we take 1 TeV and 1.5 TeV, respectively.

  Varying A_λ between 0 and 1000 GeV, we obtain the branching ratios for h_1 as shown in fig. 1.

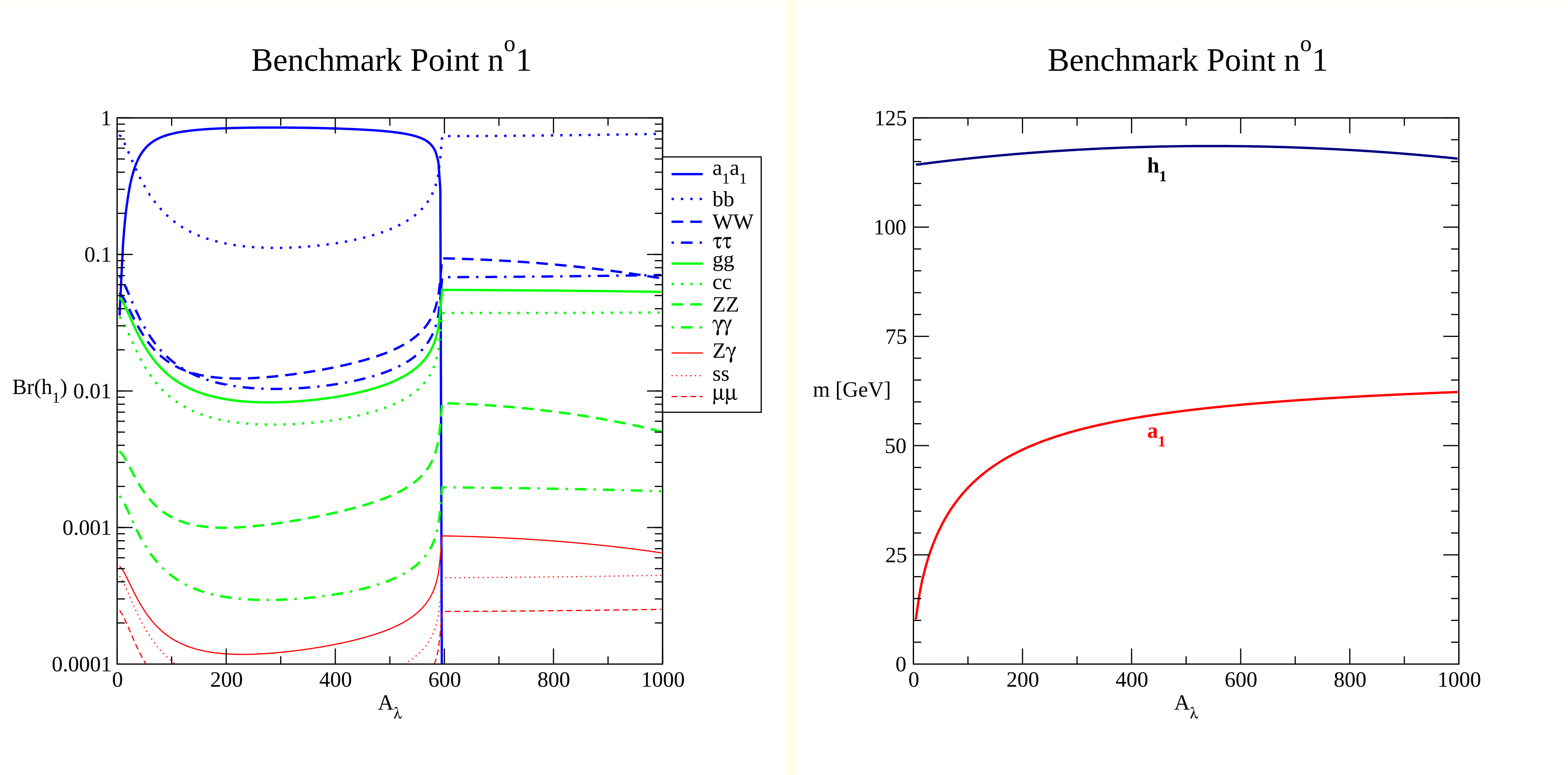


Figure 1: Left: Branching ratios of h_1 as a function of A_λ for $\lambda = \kappa = 0.3$, $\tan\beta = 5$, $\mu_{\rm eff} = 180$ GeV, $A_\kappa = 0$, $m_{\rm squark} = 1$ TeV, and $A_t = 1.5$ TeV. Right: m_{h_1} and m_{a_1} as a function of A_λ for the same parameters.

These show clearly that, for $A_\lambda \lesssim 600$ GeV, the decay $h_1 \to a_1\, a_1$ is dominant.

None of the points in these two graphs are excluded by LEP.

For the A_λ range where $h_1 \to a_1 a_1$ is dominant, this h_1 signal should be visible at the LHC using the techniques we have developed for isolating the $WW \to h \to aa$ type of signal.

- **The LHC $WW \to h \to aa \to jj\tau^+\tau^-$ mode**

  - We actually studied 6 points of this general type that would not be seen in any of the standard LHC modes 1) – 8).
    For points 1,3,4,5, $a_1 \to b\bar{b}$ is allowed.
    For points 2 and 6, $a_1 \to b\bar{b}$ is kinematically forbidden and only $a_1 \to \tau^+\tau^-$ is allowed. $\Rightarrow$ harder to tag the $\tau^+\tau^-$ jets for the 2nd a_1 means smaller signal rates than for 1,3,4,5 where 2nd a_1 actually decays directly to jets.
  - After many cuts, including forward / backward jet tagging and various vetoes, but before b-tagging, we were able to eliminate the potentially serious DY $\tau^+\tau^- + jets$ background.

– **In the end, we obtained the signals shown relative to the backgrounds in the $M_{jj\tau^+\tau^-}$ distributions of Fig. 2.**
Note: $M_{jj\tau^+\tau^-}$ is really an effective mass computed by looking at the $\tau \to \ell\nu\overline{\nu}$ decays and projecting $\not{p}_T$ onto ℓ directions.

LHC, $\sqrt{s_{pp}} = 14$ TeV

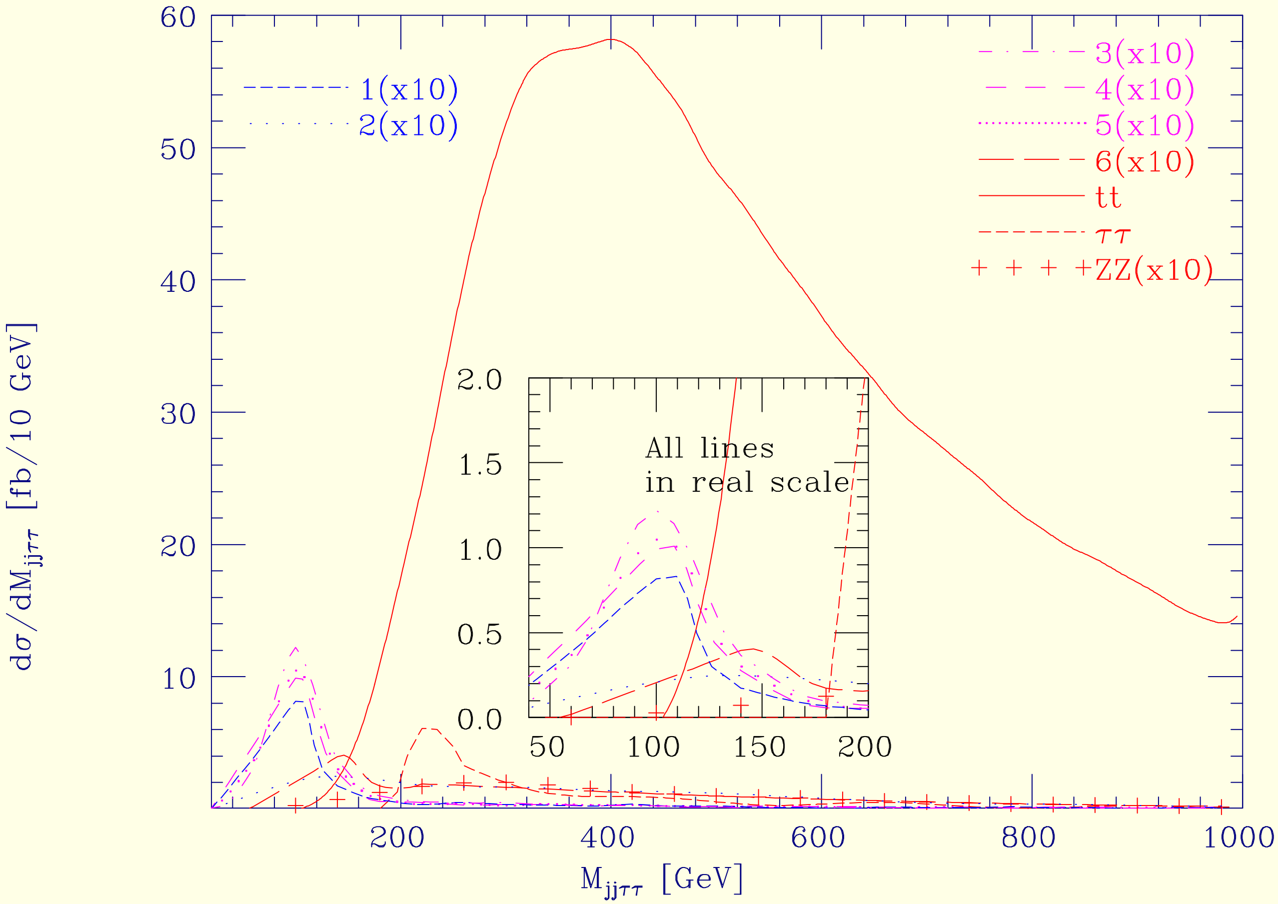


Figure 2: *Reconstructed mass of the $jj\tau^+\tau^-$ system for signals and backgrounds before b-tagging. No K factors are included.*

- **Remarks:**

  For all six NMSSM setups, the Higgs resonance produces a bump at low $M_{jj\tau^+\tau^-}$.

  For $S/\sqrt{B}$ estimates, we assume $L = 300~\mathrm{fb}^{-1}$, a K factor of 1.1 for WW fusion and a K factor of 1.6 for the $t\bar{t}$ background.

  (These K factors are not included in the plots of Fig. 2.)

- **We sum events over the region $40 \leq M_{jj\tau^+\tau^-} \leq 130$ GeV. (We include a few bins with non-zero $t\bar{t}$ background as a conservative way of being sure that we have overestimated the tails of this background at low $M_{jj\tau^+\tau^-}$.)**

- **For points 1, 2, 3, 4, 5 and 6, we obtain signal rates of about $S = 1544$, 498, 2048, 1920, 1886, and 405, respectively.**

  The $t\bar{t}$+jets background rate is $B_{tt} \sim 410$.

  The ZZ background rate is $B_{ZZ} \sim 6$.

  The DY $\tau^+\tau^-$ background rate is negligible. (We are continuing to increase our statistics to get a fully reliable estimate.)

- **The resulting $N_{SD} = S/\sqrt{B}$ values for points 1-6 are 66, 21, 87, 82, 81, and 17, respectively.**

  The smaller values for points 2 and 6 are simply a reflection of the difficulty of isolating and reconstructing the two jets coming from the decay of a very light a_1.

- **There are also cases not excluded by LEP (so far as we can tell, but we are asking LEP people) in which $m_{a_1} < 2m_\tau \Rightarrow a_1 \to c\bar{c}, gg$.**

  Not sure if we can find a signal in this case.

Sample case #2: no LHC signal

- For a second sample set of plots, figs. 3–4, we take $\lambda = 0.5$, $\kappa = -0.15$, $\tan\beta = 3.5$, $\mu_{\rm eff} = 200~{\rm GeV}$, $A_\lambda = 780~{\rm GeV}$ and $A_\kappa \in [150~{\rm GeV}, 250~{\rm GeV}]$.

  The `scaninp.dat` file for this case was given in Table 2.

- For much of this parameter range, neither the h_1 nor the h_2 would have been observable at LEP.

  In particular, fig. 3–right shows that $m_{h_2} \gtrsim 120~{\rm GeV}$ implying that the h_2 is beyond the LEP kinematical reach.

  The h_1 is lighter, but $h_1 \to b\bar{b}$ ok. However, this light Higgs is not excluded by LEP over most of the above A_κ range since: a) its reduced coupling to gauge bosons is small; and b) $h_1 \to b\bar{b}$ is suppressed so that $h_1 \to jj$ decays are dominant (see fig. 3–left).

  In fig. 4–right, we plot $\xi^2 = C_V(h_1)^2 \times BR(h_1 \to jj)$ for our selected points as well as the region excluded by LEP searches in this channel.

  We see that only if $m_{h_1} \lesssim 53~{\rm GeV}$, which corresponds to $A_\kappa \gtrsim 235~{\rm GeV}$, would the h_1 be excluded by LEP data.

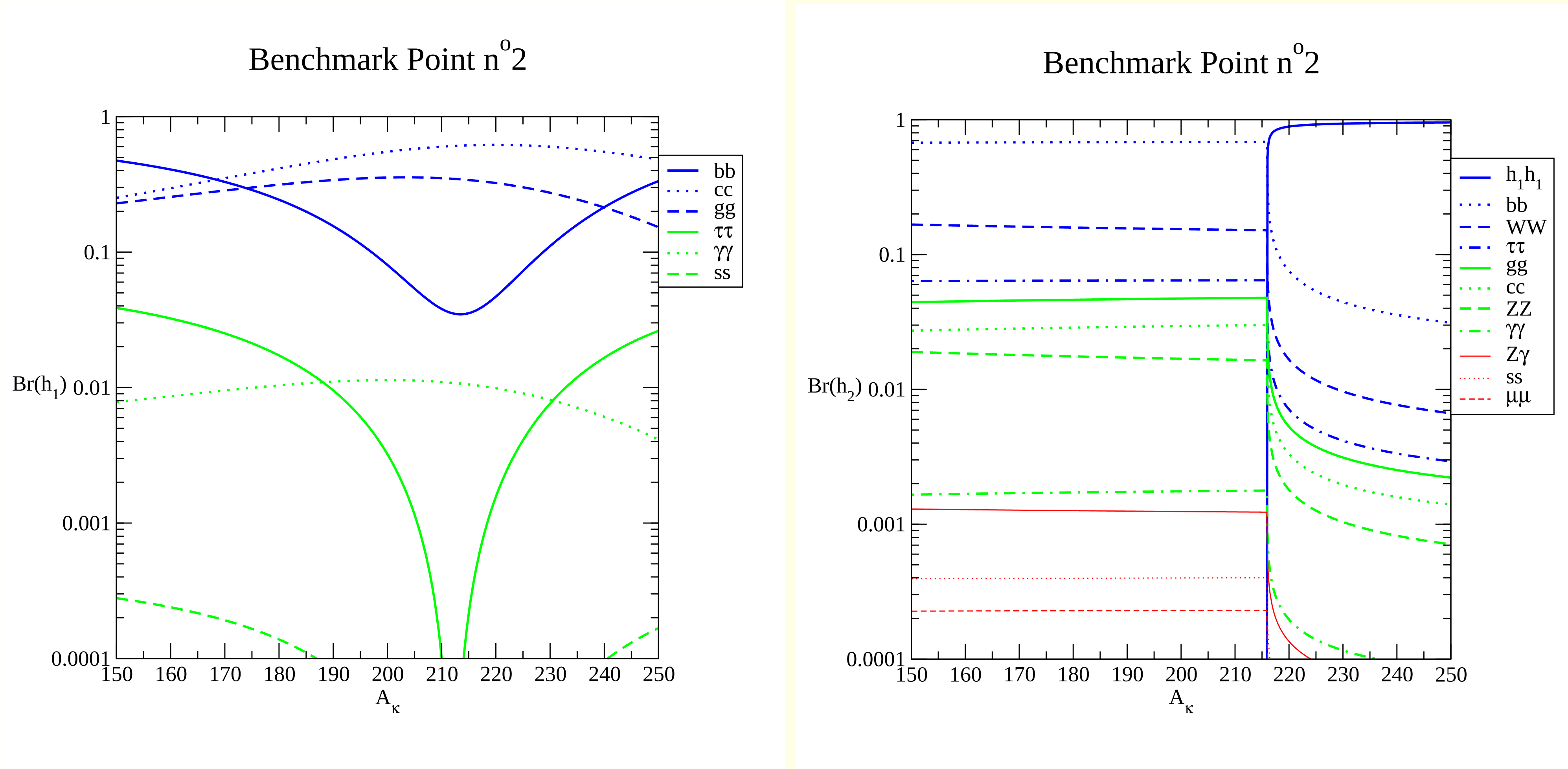


Figure 3: Left: Branching ratios of h_1 as a function of A_κ for $\lambda = 0.3$, $\kappa = -0.15$, $\tan\beta$ = 3.5, $\mu_{\rm eff}$ = 200 GeV, $A_\lambda = 780$ GeV, $m_{\rm squark} = 1$ TeV, and $A_t = 1.5$ TeV. Right: Branching ratios of h_2 as a function of A_κ for the same parameter choices.

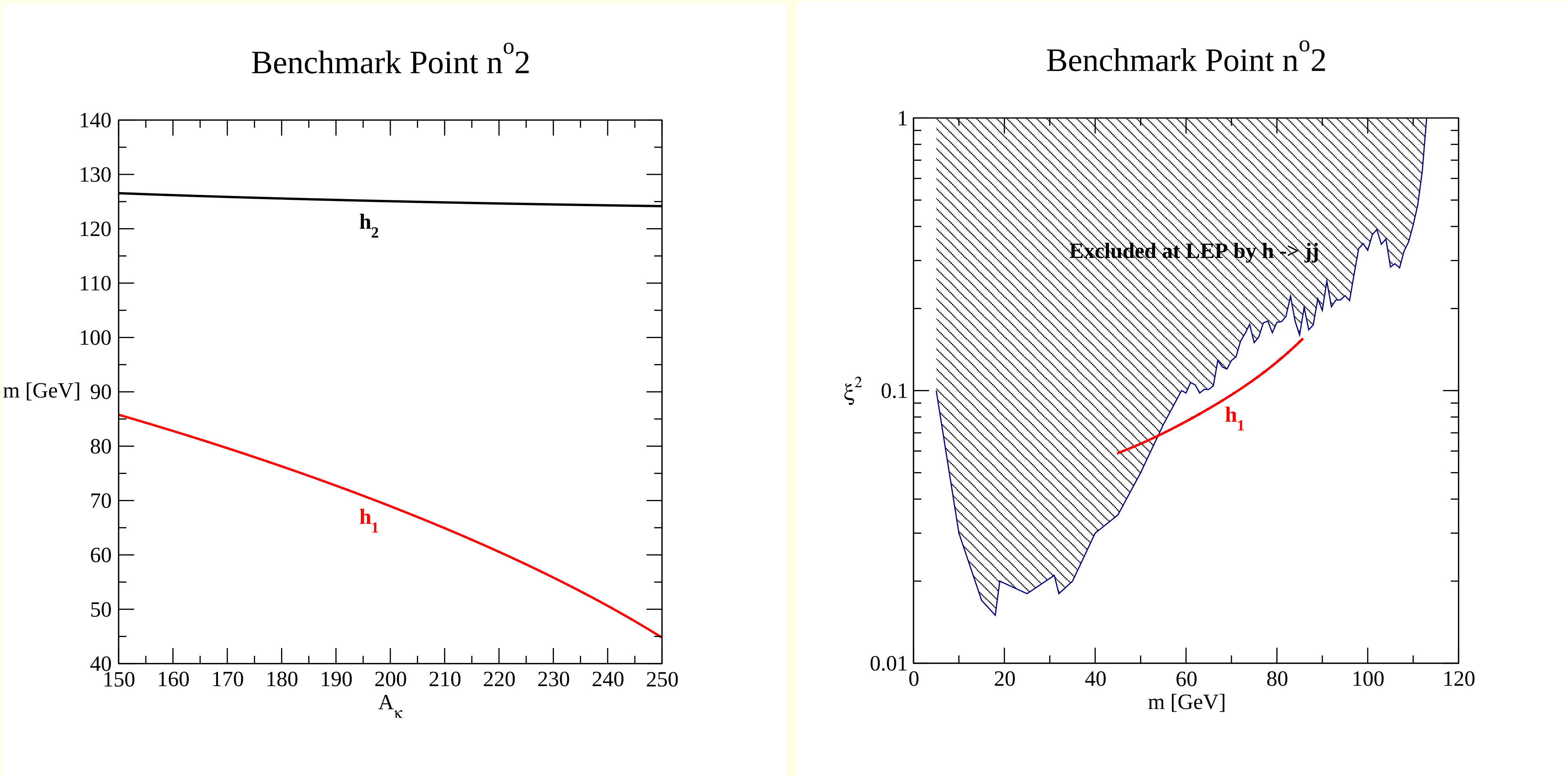


Figure 4: Left: m_{h_1} and m_{a_1} as a function of A_κ for the same parameters as in fig. 3. Right: LEP constraints in comparison to predictions for h_1 for these parameters. Note the correlation of $m = m_{h_1}$ with A_κ given in left-hand graph. New LEPHIGGS results may lower LEP exclusion curve in jj channel and make finding this kind of point very difficult.

- **Will these Higgs bosons be observable at the LHC?**

  In this regard, it is important to note from fig. 3–right that when $A_\kappa \gtrsim 215~\mathrm{GeV}$, $h_2 \to h_1 h_1$ decays are dominant. This occurs because m_{h_1} decreases with A_κ, see fig. 4–left.

  Meanwhile, fig. 3–left shows that $BR(h_1 \to b\bar{b})$ and $BR(h_1 \to \tau^+\tau^-)$ are both small when $A_\kappa \in [205~\mathrm{GeV}, 220~\mathrm{GeV}]$; in this region of parameter space, the h_1 decays mainly to $c\bar{c}$ or gg.

  Thus, for $A_\kappa \sim 215 - 220~\mathrm{GeV}$:

  - **The h_1 has a mass that lies below the mass range currently studied for Higgs detection at the LHC.**
    Further, the h_1 will be so weakly produced at the LHC (since $\xi^2 \lesssim 0.1$) that extensions to lower Higgs masses of the current LHC studies would probably conclude it was undetectable.
  - **Simultaneously, the strongly produced h_2 has decays dominated by $h_2 \to h_1 h_1$ with $h_1 \to c\bar{c}, gg$ (but not $b\bar{b}$ or $\tau^+\tau^-$).**
    As a result, the techniques for $h \to aa$ (which require a significant $a \to \tau^+\tau^-$ branching ratio) do not apply, and the h_2 would also appear to be very difficult to observe at the LHC.

How common are points that require the $aa \to jj\tau^+\tau^-$ mode at the LHC?

- **Require in the scan that all modes 1) – 9) (9 = $WW \to h \to invisible$ for $\widetilde{\chi}_1^0\widetilde{\chi}_1^0$) are very weak.**

```
Number of points:

  scanned                                          100000000
  with mh1^2 or ma1^2 or mhc^2 < 0                  86776330  ****14% ok
  with m_stop^2 or m_sbottom^2 < 0                         0
  violating LEP constraints                          1387335
  where t -> Hc b allowed                              41490
  possible Higgs -> Higgs decays                         588
  possible Higgs -> neutralinos decays                     0
  visible at LHC in 1)-9)                           11788094
  with Landau Pole below MGUT                           2313  ***not many cut
  with unphysical global minimum                         278  ***not many cut

Remaining points: aa mode needed                        3572

Parameter ranges for these points:

    lambda     0.0623     0.7235
     kappa    -0.6230     0.6331
 tan(beta)     1.6731    53.1331
        mu  -998.9511   997.5992
   Alambda  -999.6243   999.9998
    Akappa  -447.9213   374.7996
```

How many of these are not even observable in the $WW \to h \to aa$ mode?

$WW \to h \to aa \to b\bar{b}\tau^+\tau^- \to jj\tau^+\tau^-$ = mode 10)

$WW \to h \to aa \to \tau^+\tau^-\tau^+\tau^- \to jj\tau^+\tau^-$ = mode 11)

```
Number of points:

  scanned                                            100000000
  with mh1^2 or ma1^2 or mhc^2 < 0                    86776330
  with m_stop^2 or m_sbottom^2 < 0                           0
  violating LEP constraints                            1318974
  where t -> Hc b allowed                                41490
  possible Higgs -> Higgs decays                           588
  possible Higgs -> neutralinos decays                       0
  visible at LHC in 1)-11)                            11862520
  with Landau Pole below MGUT                               55
  with unphysical global minimum                            17

Remaining ``non-observable'' points                         26   ***not many, but?

Parameter ranges for these points:
    lambda     0.2656     0.6501
     kappa    -0.4523     0.4385
 tan(beta)     1.8523    21.9529
        mu  -897.8902   997.0309
   Alambda  -996.5849   995.1697
    Akappa  -209.8592   228.7437

 The most difficult point:
lambda=     0.3683
kappa=    -0.4523
tan(beta)=       2.10
mu=       176.
Al=       735.
```

```
Ak=        37.
 The most visible process at this point:
Higgs No.: 3  Channel No.: 5
Statistical significance:       0.09

mh1=        113.
 CV= -0.999E+00
 CU= -0.987E+00
 CD= -0.105E+01
 CG=  0.985E+00
 CGA=  0.102E+01
 BR(h1->gluongluon)=  0.610E-04
 BR(h1->tautau)=  0.879E-04
 BR(h1->mumu)=  0.313E-06
 BR(h1->ss)=  0.558E-06
 BR(h1->cc)=  0.446E-04
 BR(h1->bb)=  0.951E-03
 BR(h1->tt)=  0.000E+00
 BR(h1->WW)=  0.596E-04
 BR(h1->ZZ)=  0.389E-05
 BR(h1->gammagamma)=  0.219E-05
 BR(h1->Zgamma)=  0.603E-06
 BR(h1->Higgses)=  0.999E+00
 BR(h1->sparticles)=  0.000E+00
 BR(h1->a1a1)=  0.999E+00                ****************
 BR(h1->a1Z)=  0.377E-06
 BR(h1->chi1chi1)=  0.000E+00

mh2=        426.
 CV=  0.315E-01                          ********** weakly produced
 CU= -0.773E-01
 CD=  0.513E+00
 CG=  0.782E-01
 CGA=  0.211E+00
 BR(h2->gluongluon)=  0.604E-04
 BR(h2->tautau)=  0.112E-03
 BR(h2->mumu)=  0.399E-06
```

```
 BR(h2->ss)=  0.543E-06
 BR(h2->cc)=  0.101E-04
 BR(h2->bb)=  0.925E-03
 BR(h2->tt)=  0.189E-01
 BR(h2->WW)=  0.981E-02
 BR(h2->ZZ)=  0.462E-02
 BR(h2->gammagamma)=  0.111E-05
 BR(h2->Zgamma)=  0.560E-06
 BR(h2->Higgses)=  0.725E+00
 BR(h2->sparticles)=  0.240E+00
 BR(h2->a1a1)=  0.672E+00                    *******  bad decays
 BR(h2->a1Z)=  0.514E-01                     *******  bad decays
 BR(h2->h1h1)=  0.226E-02
 BR(h2->chi1chi1)=  0.703E-01

mh3=        485.
 CV= -0.324E-01                              ******* weakly produced
 CU= -0.495E+00
 CD=  0.202E+01
 CG=  0.496E+00
 CGA=  0.112E+01
 BR(h3->gluongluon)=  0.970E-03
 BR(h3->tautau)=  0.641E-03
 BR(h3->mumu)=  0.228E-05
 BR(h3->ss)=  0.303E-05
 BR(h3->cc)=  0.161E-03
 BR(h3->bb)=  0.527E-02
 BR(h3->tt)=  0.456E+00                      ******* decay ok?
 BR(h3->WW)=  0.521E-02
 BR(h3->ZZ)=  0.249E-02
 BR(h3->gammagamma)=  0.530E-05
 BR(h3->Zgamma)=  0.666E-06
 BR(h3->Higgses)=  0.489E+00                 ***** bad decay channels
 BR(h3->sparticles)=  0.411E-01
 BR(h3->chi1chi1)=  0.877E-02
```

```
ma1=         3.                    *** only jj, no tautau
 CU=  0.144E+00
 CD=  0.639E+00
 CG=  0.300E+00
 CGA=  0.264E+00
 BR(a1->gluongluon)=  0.505E+00
 BR(a1->tautau)=  0.000E+00
 BR(a1->mumu)=  0.666E-01
 BR(a1->ss)=  0.428E+00
 BR(a1->cc)=  0.000E+00
 BR(a1->bb)=  0.000E+00
 BR(a1->tt)=  0.000E+00
 BR(a1->gammagamma)=  0.117E-03
 BR(a1->Zgamma)=  0.000E+00
 BR(a1->Higgses)=  0.000E+00
 BR(a1->sparticles)=  0.000E+00
 BR(a1->chi1chi1)=  0.000E+00

ma2=       501.
 CU=  0.453E+00
 CD=  0.201E+01
 CG=  0.453E+00
 CGA=  0.616E+00
 BR(a2->gluongluon)=  0.125E-02
 BR(a2->tautau)=  0.552E-03
 BR(a2->mumu)=  0.196E-05
 BR(a2->ss)=  0.263E-05
 BR(a2->cc)=  0.201E-03
 BR(a2->bb)=  0.460E-02
 BR(a2->tt)=  0.632E+00
 BR(a2->gammagamma)=  0.100E-04
 BR(a2->Zgamma)=  0.143E-05
 BR(a2->Higgses)=  0.109E+01
 BR(a2->sparticles)=  0.224E+00
 BR(a2->chi1chi1)=  0.800E-04
```

```
mhc:       480.

neutralino1        163.
neutralino2        165.
neutralino3        445.
neutralino4        505.
neutralino5       1008.

chargino1        169.
chargino2       1008.
```

- **Could $m_{a_1} < 2m_\tau$ be eliminated by Υ, $B_{s,d}$, .. decays?**

  Not clear:

  - **theory of such decays always filled with uncertainties;**
  - **also most difficult point above has suppressed $b\bar{b}$ coupling.**

Difficult scenarios at the LC

- **Whether or not we have a good LHC signal if nature chooses a difficult point, ultimately, a means of confirmation and further study will be critical.**

  Thus, it is important to summarize the prospects at the LC.

- **For difficult scenarios, we always find that either h_1 or h_2 has reasonable WW, ZZ coupling and mass at most $\sim 140~\mathrm{GeV}$ (but possibly much lower).**

  Discovery of the h will be very straightforward via $e^+e^- \to Zh$ using the $e^+e^- \to ZX$ reconstructed M_X technique which is independent of the "unexpected" complexity of the h decay to a_1a_1 (or h_1h_1 for $h = h_2$).

  This will immediately provide a direct measurement of the ZZh coupling with very small error.

  Then, look for different final states and check for Higgs-like coupling of the a to various final state fermions.

- **The LC should find it quite easy to look for even a rather light h decaying to aa in the ZX channel.**

The role of a γC

The γC working group has been considering the role that might be played by such a facility in a variety of physics situations. Some references for our work appear below.

References

[1] D. Asner *et al.*, arXiv:hep-ph/0308103.

[2] D. Asner, B. Grzadkowski, J. F. Gunion, H. E. Logan, V. Martin, M. Schmitt and M. M. Velasco, arXiv:hep-ph/0208219.

[3] M. M. Velasco *et al.*, in *Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001)* ed. N. Graf, eConf C010630, E3005 (2001) [arXiv:hep-ex/0111055].

The γC could play a special role for NMSSM parameter cases such that the only LHC signal for Higgs bosons is the $jj\tau^+\tau^-$ low mass bump.

- If the difficult h has already been seen at an LC, the γC will allow for refined measurements, especially of the $\gamma\gamma$ coupling which will not be precisely SM-like.

- But, it is also possible that a CLIC-test module-based low-energy γC could be built before the LC.

- **We have studied the potential of such a CLICHE (CLIC Higgs Experiment) in the case of the difficult $h \to aa$ scenarios discussed previously.**

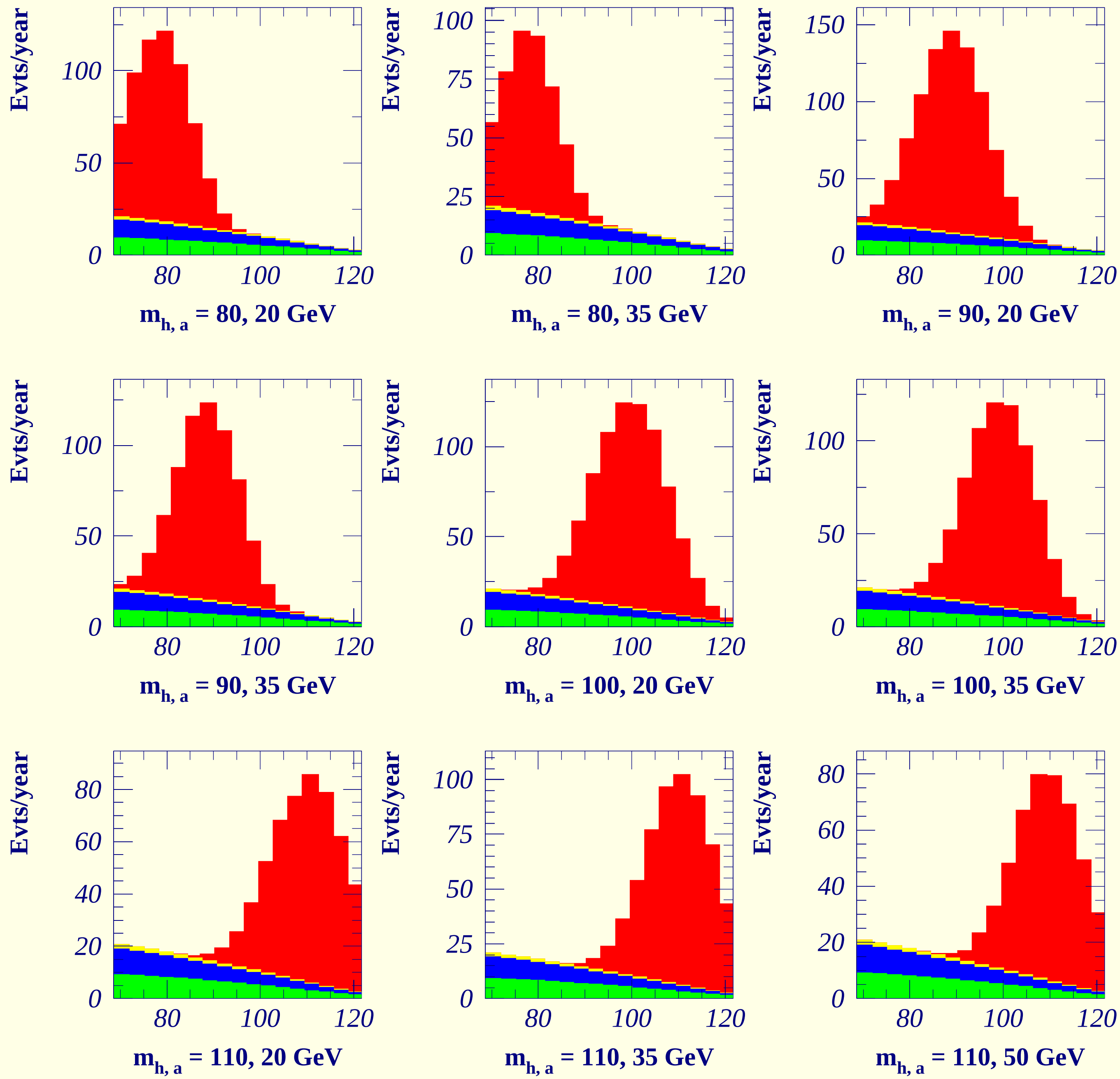
- **The hard-core simulation work has been performed by Michal Szleper.**

Results for broad spectrum, assuming $h \to aa$, with $a \to b\bar{b}$

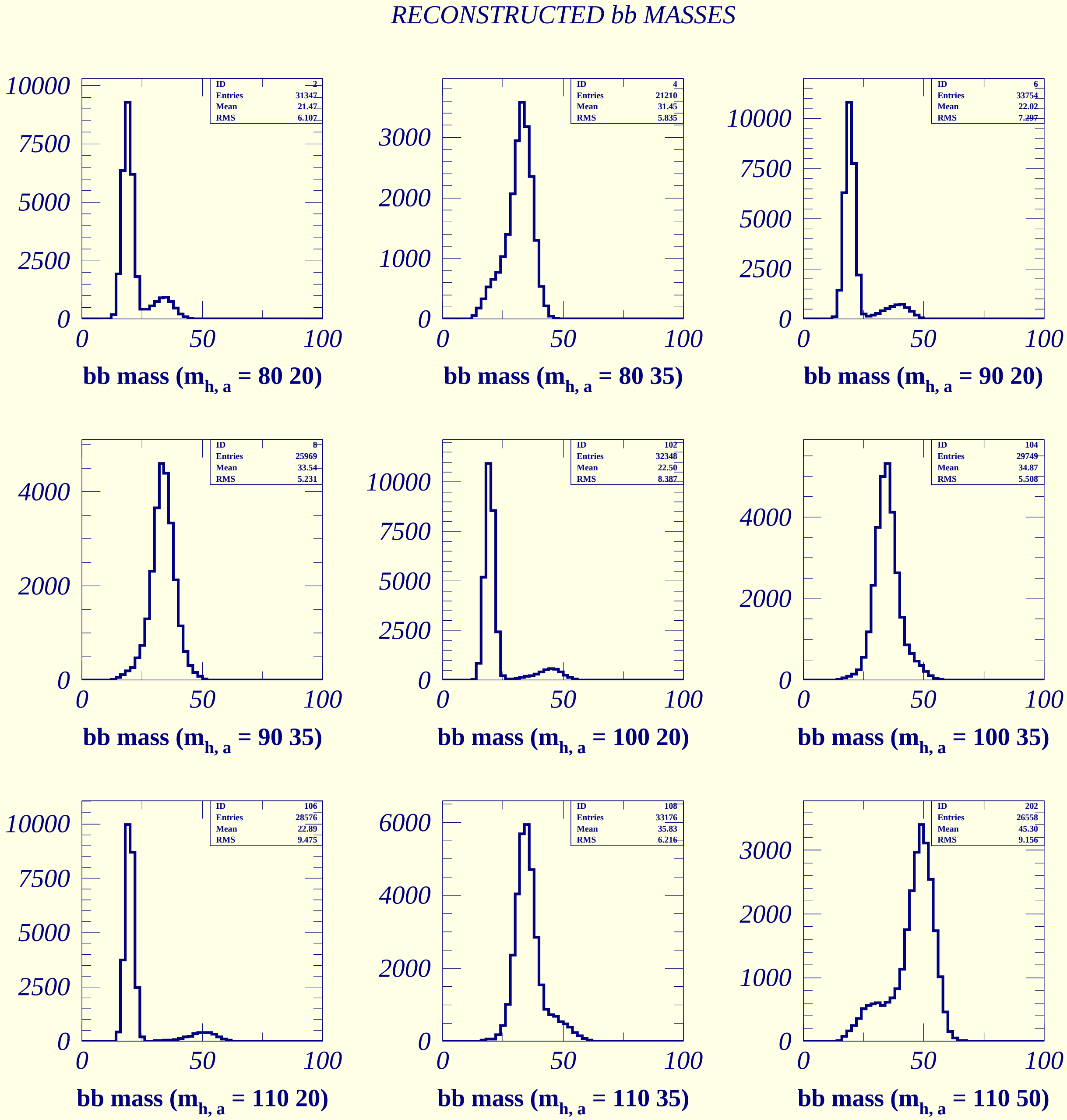
- **Result is excellent signals and small backgrounds in all cases — see 1st figure.**

- **Excellent determination of m_a is possible — see 2nd figure.**

4-JET INV. MASS - SIGNAL on top of BACKGROUND



How well can we determine the a mass?



Conclusions

- **We are whittling down to a very select type of situation for which NMSSM Higgs detection might not be possible at the LHC.**

  We are basically left with cases where the SM-like $h \to aa$ and $m_a < 2m_\tau$.

  Such cases are very rare in parameter space.

- **Clearly, if SUSY is discovered at the LHC and no Higgs bosons are detected in the standard MSSM modes, a careful search for the $WW \to h \to aa \to jj\tau^+\tau^-$ signal we have considered should have a high priority.**

  There are a reasonable number of cases where this signal *and no other* **would be visible.**

- **The same conclusion applies if the LHC observes that $WW \to WW$ scattering is perturbative, implying light Higgs bosons or similar and yet none are seen in standard modes.**

- **At the LC, discovery of a light SM-like h is guaranteed to be possible in the Zh final state using the recoil mass technique, regardless of how the h decays.**

- **If there is no LC, a CLIC-module-based γC would be a strong candidate for clarifying the Higgs nature of any $jj\tau^+\tau^-$ signal seen at the LHC, and finding signals at lower h mass that might be difficult at the LHC (we need to do the LHC studies of cases that LEP would have missed to see exactly where we stand).**

- **Eventually we will need to consider the CP-violating NMSSM Higgs sector with five mixed Higgs!**