NMSSM Higgs Detection: LHC, LC, γC Complementarity and $h \longrightarrow aa$ decays

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Outline

- Why go beyond the MSSM?
- The CPC NMSSM and summary of no-lose theorem efforts
- Difficult NMSSM scenarios due to $h \to aa$ 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. There are significant direct lower bounds on the mass of the lightest stop.
  3. 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 appear in [3, 4, 5].

4. If the constrained MSSM (cMSSM) with universal GUT scale soft-SUSY-breaking masses is to provide adequate dark matter as well as be consistent with $b \to s\gamma$ and $g_\mu - 2$, further constraints are placed on the MSSM parameter space.
5. An early discussion of the tension between the dark matter and baryogenesis requirements appears in [6].
   Most recently, the most probable portions of parameter space consistent with Higgs mass limits, dark matter, $b \to s\gamma$ and $g_\mu - 2$ have been delineated in [7].
   These are dominated by the coannihilation, rapid-annihilation and focus regions of cMSSM parameter space with large m_0 values.
   The extent to which adequate dark matter is generated for non-universal masses (as required to be even close to getting adequate baryogenesis) is not clear.
   (Of course, you can separate the leptonic sector slepton masses crucial for dark matter from the top squark sector crucial for baryogenesis.)
6. 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.

More radical extensions, such as the recent ideas of [11], will not be discussed here.

- 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 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, $gg \to t\bar{t}h$ and $WW \to h$ with $h \to b\bar{b}$ or $h \to \tau^+\tau^-$ 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.

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The CPC NMSSM and no-lose theorem efforts

- **This summary is based on the work with Ellwanger, Hugonie and Moretti, Refs. [14, 15] and in progress.**

- **The term $\mu \widehat{H}_1 \widehat{H}_2$ in the MSSM is replaced by**

$$\lambda \widehat{H}_1 \widehat{H}_2 \widehat{S} \; + \; \frac{\kappa}{3} \widehat{S}^3 \; , \tag{1}$$

so that the superpotential is scale invariant and $\mu_{\rm eff}$ is generated when $\langle S \rangle \neq 0$.

- **We make no assumption on "universal" soft terms. Hence, the five soft supersymmetry breaking terms**

$$m_{H_1}^2 H_1^2 \; + \; m_{H_2}^2 H_2^2 \; + \; m_S^2 S^2 \; + \; \lambda A_\lambda H_1 H_2 S \; + \; \frac{\kappa}{3} A_\kappa S^3 \tag{2}$$

are considered as independent.

- **Assume the masses of sparticles are large enough to not give significant contributions to $gg \to h$ and $\gamma\gamma \to h$ couplings.**

- **In the stop sector, we chose the soft masses $m_Q = m_T \equiv M_{susy} = 1$ TeV and scan over $X_t \equiv 2 \, \frac{A_t^2}{M_{susy}^2 + m_t^2} \left(1 - \frac{A_t^2}{12(M_{susy}^2 + m_t^2)}\right)$. As in the MSSM, the value $X_t = \sqrt{6}$ – so called maximal mixing – maximizes the radiative corrections to the Higgs boson masses.**

  It leads to the most challenging points in NMSSM parameter space.

- **We require $|\mu_{\rm eff}| = \lambda \langle S \rangle \; > \; 100$ GeV; otherwise a light chargino would have been detected at LEP.**

- **We have performed a numerical scan over the free parameters.**

  We eliminated parameter choices excluded by LEP constraints on $e^+e^- \to Zh_i$ and $e^+e^- \to h_i a_j$.

  We required $m_{h^\pm} > 155$ GeV, so that $t \to h^\pm b$ would not be seen.

No SUSY or Higgs to Higgs allowed

- **We examined the "usual" LHC discovery modes:**

  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.**

Latest results for these modes were employed.

Note that the $t\bar{t}h \to t\bar{t}b\bar{b}$ mode will be quite important. We have had the experimentalists extrapolate this beyond the usual SM mass range of interest.

- Some things that have changed recently:

1. The $gg \to h_{\rm SM} \to \gamma\gamma$ N_{SD} values from CMS have gotten smaller (detector cracks ...).
2. The CMS $t\bar{t}h_{\rm SM} \to t\bar{t}b\bar{b}$ N_{SD} vales are larger than the ATLAS values.
3. The experimental evaluations of the WW fusion channels yield lower N_{SD} values than the original theoretical estimates.

- For each mode, our procedure has been to use the results for the "best detector" (e.g. CMS for the $t\bar{t}h$ channel), assuming $L = 300{\rm fb}^{-1}$ for that one detector.

The Result [14]: We can always detect at least one of the NMSSM Higgs bosons.

Higgs to Higgs Decays Allowed, but SUSY decays suppressed or absent

- **We found [15] cases for which all the modes 1) – 8) give very weak signals due to the fact that the only Higgs boson with significant WW/ZZ coupling is light and decays via $h \to aa$.**

  All such points have certain common properties.

1. **We get a SM-like CP-even Higgs boson with a mass between below 135 GeV (*i.e.* sometimes with masses below the LEP limit because LEP analysis was not sensitive to the $h \to aa$ type of decays), which can be either h_1 or h_2, with near maximal SM-like VV coupling.**
2. **This state decays dominantly to a pair of (very) light CP-odd states, $a_1 a_1$, with $m_{a_1} \lesssim 65~\mathrm{GeV}$.**
3. **Properties of 6 difficult benchmark points are displayed in Table 1.**
   - **For points 1 – 3, h_1 is the SM-like CP-even state, while for points 4 – 6 it is h_2.**
   - **Note the large $B(h \to a_1 a_1)$ of the SM-like h ($h = h_1$ for points 1 – 3 and $h = h_2$ for points 4 –6).**
   - **For points 4 – 6, with $m_{h_1} < 100~\mathrm{GeV}$, the h_1 is mainly singlet implying no LEP constraints on the h_1 and a_1 from $e^+e^- \to h_1 a_1$ production.**

- We note that in the case of the points 1 – 3, the h_2 would not be detectable either at the LHC or the LC. For points 4 – 6, the h_1, though light, is singlet in nature and would not be detectable.
- Further, the h_3 or a_2 will only be detectable for points 1 – 6 if a super high energy LC is eventually built so that $e^+e^- \to Z \to h_3 a_2$ is possible.

4. Thus, we will focus on searching for the SM-like h_1 (h_2) for points 1 – 3 (4 – 6) using the dominant $h_1(h_2) \to a_1 a_1$ decay mode.
5. In the case of points 2 and 6, it should be noted that the $a_1 \to \tau^+\tau^-$ decays are dominant, with $a_1 \to jj$ decays making up most of the rest. For points 1 and 3 – 5, for which $B(a_1 \to b\bar{b})$ is substantial, the b jets could in principal be tagged, but this will not turn out to be necessary (or desirable).
6. The list of possible SM-like masses is incomplete in that there are cases with h masses substantially below $100~\mathrm{GeV}$ that are still not ruled out by LEP. We missed these originally. We must run LHC Monte Carlos for these additional cases. For now, we will say what we can accomplish for h masses $\gtrsim 100~\mathrm{GeV}$.

   We expect there to remain NMSSM points with a SM-like h with $m_h \lesssim 60~\mathrm{GeV}$ that decays to 2 light a's that cannot be detected at the LHC. For these, the LC and/or γC will be critical.

Point Number	1	2	3	4	5	6
Bare Parameters						
λ	0.2872	0.2124	0.3373	0.3340	0.4744	0.5212
κ	0.5332	0.5647	0.5204	0.0574	0.0844	0.0010
$\tan\beta$	2.5	3.5	5.5	2.5	2.5	2.5
$\mu_{\rm eff}$ (GeV)	200	200	200	200	200	200
A_λ (GeV)	100	0	50	500	500	500
A_κ (GeV)	0	0	0	0	0	0
CP-even Higgs Boson Masses and Couplings						
m_{h_1} (GeV)	115	119	123	76	85	51
R_1	1.00	1.00	-1.00	0.08	0.10	-0.25
t_1	0.99	1.00	-1.00	0.05	0.06	-0.29
b_1	1.06	1.05	-1.03	0.27	0.37	0.01
Relative gg Production Rate	0.97	0.99	0.99	0.00	0.01	0.08
$B(h_1 \to b\bar{b})$	0.02	0.01	0.01	0.91	0.91	0.00
$B(h_1 \to \tau^+\tau^-)$	0.00	0.00	0.00	0.08	0.08	0.00
$B(h_1 \to a_1 a_1)$	0.98	0.99	0.98	0.00	0.00	1.00
m_{h_2} (GeV)	516	626	594	118	124	130
R_2	-0.03	-0.01	0.01	-1.00	-0.99	-0.97
t_2	-0.43	-0.30	-0.10	-0.99	-0.99	-0.95
b_2	2.46	-3.48	3.44	-1.03	-1.00	-1.07
Relative gg Production Rate	0.18	0.09	0.01	0.98	0.99	0.90
$B(h_2 \to b\bar{b})$	0.01	0.04	0.04	0.02	0.01	0.00
$B(h_2 \to \tau^+\tau^-)$	0.00	0.01	0.00	0.00	0.00	0.00
$B(h_2 \to a_1 a_1)$	0.04	0.02	0.83	0.97	0.98	0.96
m_{h_3} (GeV)	745	1064	653	553	554	535

Point Number	1	2	3	4	5	6
CP-odd Higgs Boson Masses and Couplings						
m_{a_1} (GeV)	56	7	35	41	59	7
t_1'	0.05	0.03	0.01	-0.03	-0.05	-0.06
b_1'	0.29	0.34	0.44	-0.20	-0.29	-0.39
Relative gg Production Rate	0.01	0.03	0.05	0.01	0.01	0.05
$B(a_1 \to b\bar{b})$	0.92	0.00	0.93	0.92	0.92	0.00
$B(a_1 \to \tau^+\tau^-)$	0.08	0.94	0.07	0.07	0.08	0.90
m_{a_2} (GeV)	528	639	643	560	563	547
Charged Higgs Mass (GeV)	528	640	643	561	559	539
Most Visible Process No.	2 (h_1)	2 (h_1)	8 (h_1)	2 (h_2)	8 (h_2)	8 (h_2)
Significance at 300 fb^{-1}	0.48	0.26	0.55	0.62	0.53	0.16

Table 1: *In the table, we give properties of selected scenarios that could escape detection at the LHC. In the table, R_i, t_i and b_i are the ratios of the h_i couplings to VV, $t\bar{t}$ and $b\bar{b}$, respectively, as compared to those of a SM Higgs boson with the same mass; t_1' and b_1' denote the magnitude of the $i\gamma_5$ couplings of a_1 to $t\bar{t}$ and $b\bar{b}$ normalized relative to the magnitude of the $t\bar{t}$ and $b\bar{b}$ SM Higgs couplings. We also give the production for $gg \to h_i$ fusion relative to the gg fusion rate for a SM Higgs boson with the same mass. Important absolute branching ratios are displayed. For points 2 and 6, $B(a_1 \to jj) \simeq 1 - B(a_1 \to \tau^+\tau^-)$. For the heavy h_3 and a_2, we give only their masses. In the case of the points 2 and 6, decays of a_1 into light quarks start to contribute. For all points 1 – 6, the statistical significances for the detection of any Higgs boson in any of the channels 1) – 8) (as listed in the introduction) are tiny; their maximum is indicated in the last row, together with the process number and the corresponding Higgs state.*

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

- To detect the $h \to aa$ decay at the LHC, we decided the best channel would be $WW \to h \to aa \to jj\tau^+\tau^-$

- The $b\bar{b}b\bar{b}$ (or $4j$) channels would have very large backgrounds.

  The 4τ channel would not allow mass reconstruction.

- 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. 1.

  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.

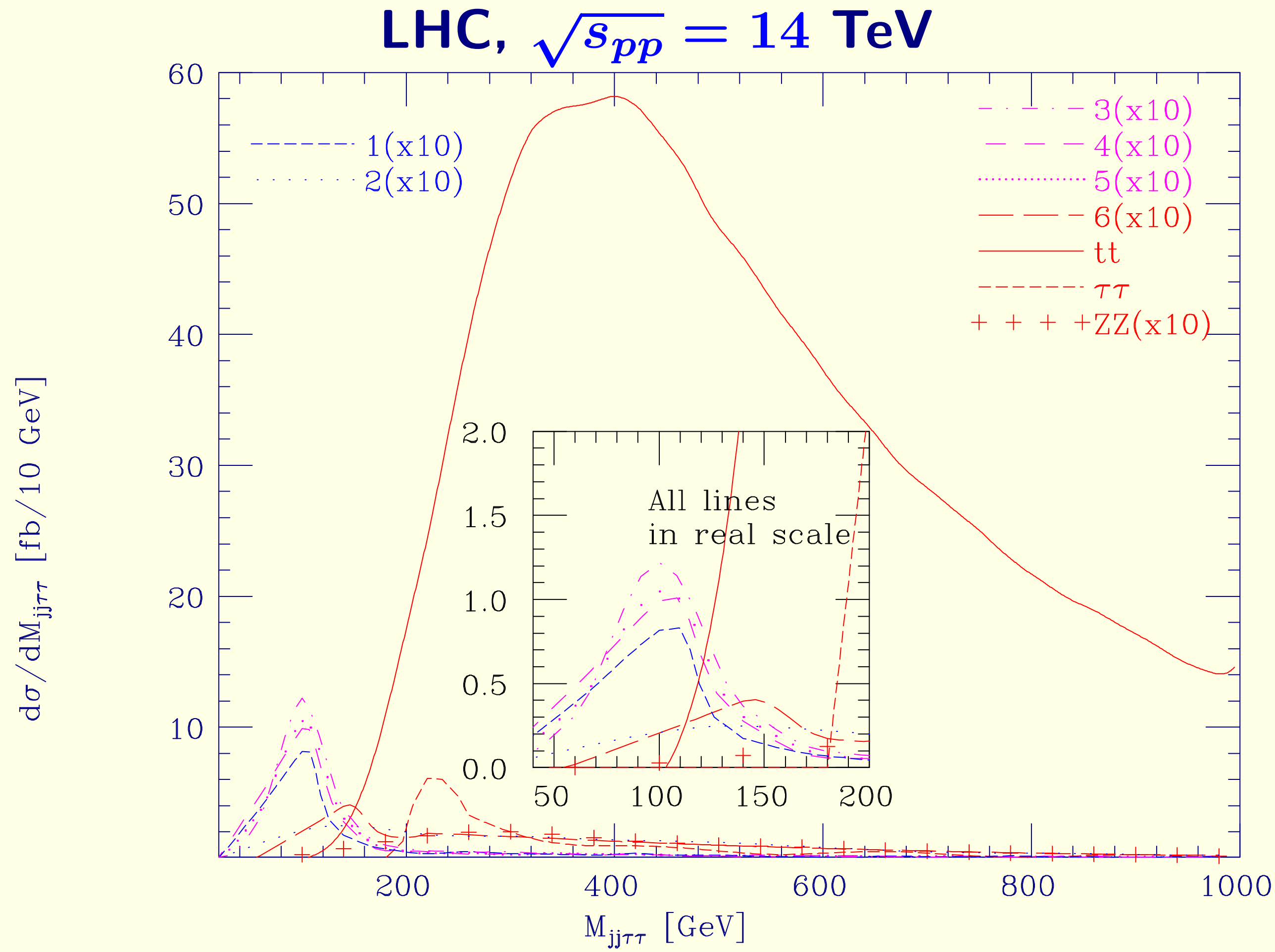

Figure 1: *Reconstructed mass of the $jj\tau^+\tau^-$ system for signals and backgrounds before b-tagging, at the LHC. We plot $d\sigma/dM_{jj\tau^+\tau^-}$ [fb/10 GeV] vs $M_{jj\tau^+\tau^-}$ [GeV]. The lines corresponding to points 4 and 5 are visually indistinguishable. No K factors are included.*

- **Remarks:**

1. For all six NMSSM setups, the Higgs resonance produces a bump at low $M_{jj\tau^+\tau^-}$.
2. The potentially large DY background has been suppressed by strong cuts requiring 2 fast forward / backward jets + 2 softer jets.
3. 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. 1.)
4. 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 $M_{jj\tau^+\tau^-}$.)
5. 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.)
6. 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.

7. Overall, these results are very encouraging.

   If we can obtain similar N_{SD} values for some of the low m_h masses not excluded by LEP, then a no-lose theorem for NMSSM Higgs detection at the LHC is close at hand.

   Note: lower masses will peak, if anything, somewhat below the peaks for the masses studied. However, there will be greater difficulty in isolating the jets. Study is in progress. We do not expect total success.

8. An open question is whether this same kind of signal could be seen for points $1, 3, 4, 5$ in the $b\bar{b}b\bar{b}$ final state (using multiple b tagging). Accurate evaluation of backgrounds in this final state is a still-unsettled issue for the CMS and ATLAS collaborations.

   However, they do claim ability in the MSSM context to extract the $H^0 \to h^0 h^0$ signal when $BR(H^0 \to h^0 h^0)$ is large.

   The importance of extracting this channel if the $jj\tau^+\tau^-$ signal is seen is that one could then check that the a couples to fermions according to their mass, the critical characteristic of a Higgs boson.

9. For the above points, $a \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$ is not allowed.

   Scanning reveals points for which $h \to aa$ is dominant and $a \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$ is

dominant.

These are a small percentage of the total $h \to aa$ dominant points, but will require special attention. The CMS estimates for the $WW \to h \to invisible$ will come into play and may allow us to close this final loop-hole for the no-lose theorem.

The LC scenario

- **Although we may 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, with energy up to 800 GeV, in the context of the difficult scenarios (such as points 1 — 6 of Table 1 and still lower m_h cases) discussed above.

  In the following, h represents the SM-like Higgs (e.g.$h = h_1$ for points 1–3 and $h = h_2$ for points 4–6 in Table 1).

- **Because the ZZh coupling is nearly full strength in all cases, and because the h mass is of order 100 GeV or less, 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 $a_1 a_1$.**

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

The next stage will be to look at rates for the various h decay final states, F, and extract $BR(h \to F) = \sigma(e^+e^- \to Zh \to ZF)/\sigma(e^+e^- \to Zh)$.

For the NMSSM points considered here, the main channels would be $F = b\bar{b}b\bar{b}$, $F = b\bar{b}\tau^+\tau^-$ and $F = \tau^+\tau^-\tau^+\tau^-$.

At the LC, a fairly accurate determination of $BR(h \to F)$ should be possible in all three cases. This would allow us to determine $BR(h \to a_1 a_1)$ independently.

- We have also shown that the $WW \to h \to aa \to jj\tau^+\tau^-$ mode always gives a good signal.

- 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.

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The study I present here is a recent effort to show the possibly special role of a γC for the 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.**

- **We will consider first a series of cases that would be typical of the NMSSM.**

- **We have also explored cases in which $h \to a_1 a_2$ with $m_{a_1} \neq m_{a_2}$ (not relevant for the difficult NMSSM cases, but possibly relevant in the context of other models, including the CPX MSSM).**

The most important signal channels

1. $\gamma\gamma \to h \to aa \to b\bar{b}b\bar{b}$, $\leftarrow$ done

2. $\gamma\gamma \to h \to aa \to b\bar{b}\tau^+\tau^-$, $\leftarrow$ done

3. $\gamma\gamma \to h \to aa \to \tau^+\tau^-\tau^+\tau^-$. $\leftarrow$ not yet done

The most important backgrounds

1. $\gamma\gamma \to b\bar{b}b\bar{b}, b\bar{b}c\bar{c}, c\bar{c}c\bar{c}$,

2. $\gamma\gamma \to b\bar{b}\tau^+\tau^-, c\bar{c}\tau^+\tau^-$,

3. $\gamma\gamma \to \tau^+\tau^-\tau^+\tau^-$.

- Scenarios presently under consideration are those in which the a's have large $b\bar{b}$ branching ratio.

- **Results presented also assume that the primary h has SM-like $\gamma\gamma$ production rate. This is typical of the NMSSM cases that would escape LHC detection in traditional modes.**

- **It is also interesting to assess $\gamma\gamma$ collider sensitivity for Higgs that decay primarily to aa but do not have SM-like $\gamma\gamma$ coupling. This is easily done by rescaling the results given.**

Tools used – signal

- **Pythia 6.158,**

- **Interfaced with CAIN for correct $\gamma\gamma$ luminosity spectra,**

- **Results will be presented for both the peaked spectrum case appropriate if m_h is up near 120 to $130~\mathrm{GeV}$, and for the case of a broad $E_{\gamma\gamma}$ spectrum, as most suitable if the Higgs mass is lower and unknown.**

  In particular, if there is very weak knowledge of the Higgs mass from LHC, the $\gamma\gamma$ collider would need to be run with both types of spectrum to ensure easy h discovery.

The broad spectrum allows good sensitivity if $m_h \leq 115\ \mathrm{GeV}$.

The peaked spectrum is needed for $m_h \gtrsim 115\ \mathrm{GeV}$.

- "NMSSM" implemented by hand by:

  1. Setting the "heavy" H mass in Pythia to m_h and A mass to m_a,
  2. Inhibiting H decays involving quarks, leptons and Z to ensure $BR(H \to AA) \simeq 1$,
  3. Overall cross section normalized to the SM process, $\sigma(\gamma\gamma \to h_{\mathrm{SM}})$.

Tools used – background

- WHIZARD 1.24,

- Cross sections for 4-fermion processes cross checked with theoretical computations for $\gamma\gamma \to e^+e^-e^+e^-, \mu^+\mu^-\mu^+\mu^-, e^+e^-\mu^+\mu^-$ (from: C. Carimalo, etal "Towards a complete $\gamma\gamma \to$ 4 leptons Monte Carlo"),

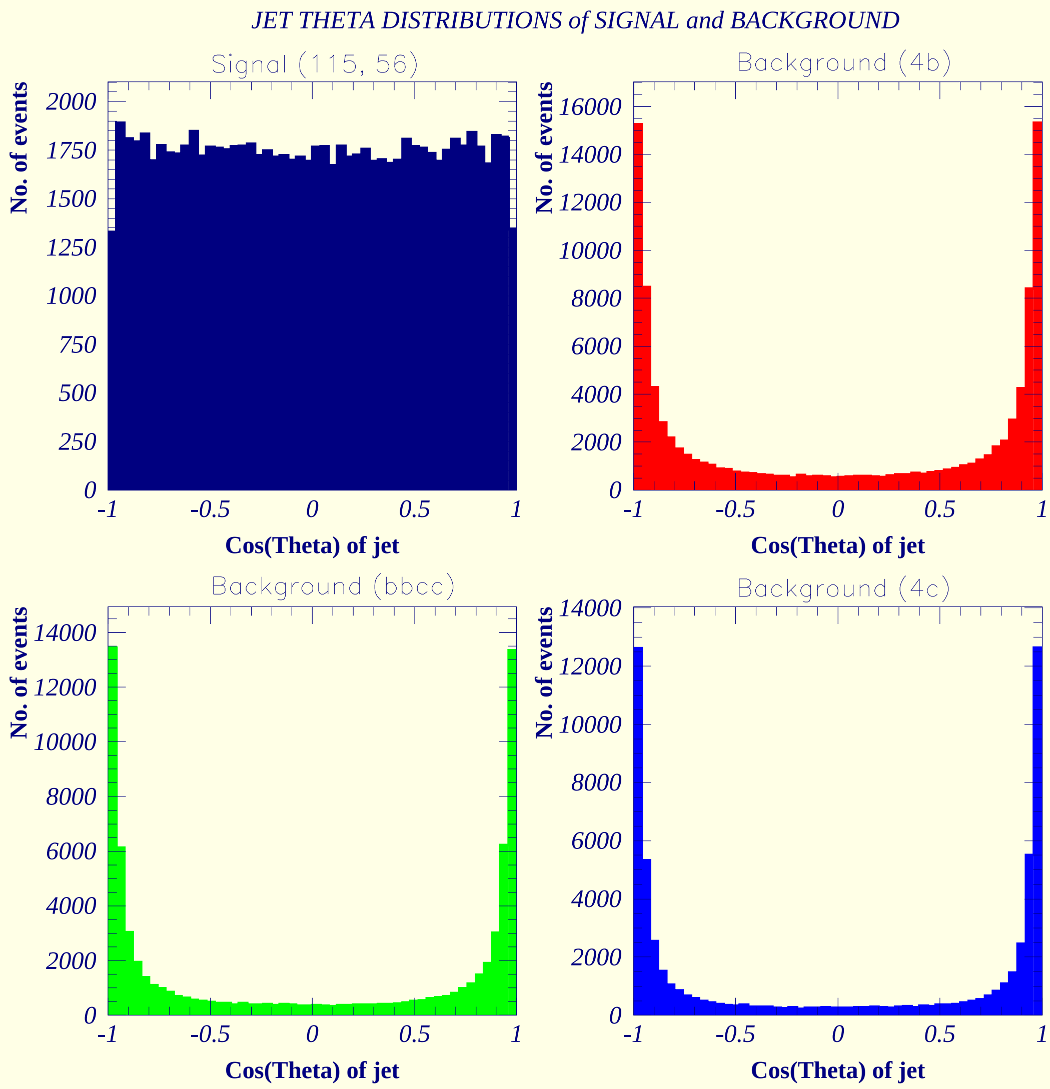
- Cross sections for $\gamma\gamma \to b\bar{b}$ and $\gamma\gamma \to c\bar{c}$ consistent with Pythia, including beam polarization effects,

- **No Compton spectra available yet, event generation possible only at δ-like beam energies. Need interpolation of all partial results to intermediate energies and event reweighting to obtain the correct luminosity spectrum.**

- **First results presented assume two a's of same mass.**

- **We first give results for the peaked spectrum and the LHC cases $\mathbf{1}$, $\mathbf{3}$, $\mathbf{4}$, and $\mathbf{5}$ (with $a \to b\bar{b}$ decays dominant) discussed earlier, from which the need for broad spectrum running in a general search will be clear.**

The $b\bar{b}b\bar{b}$ channel

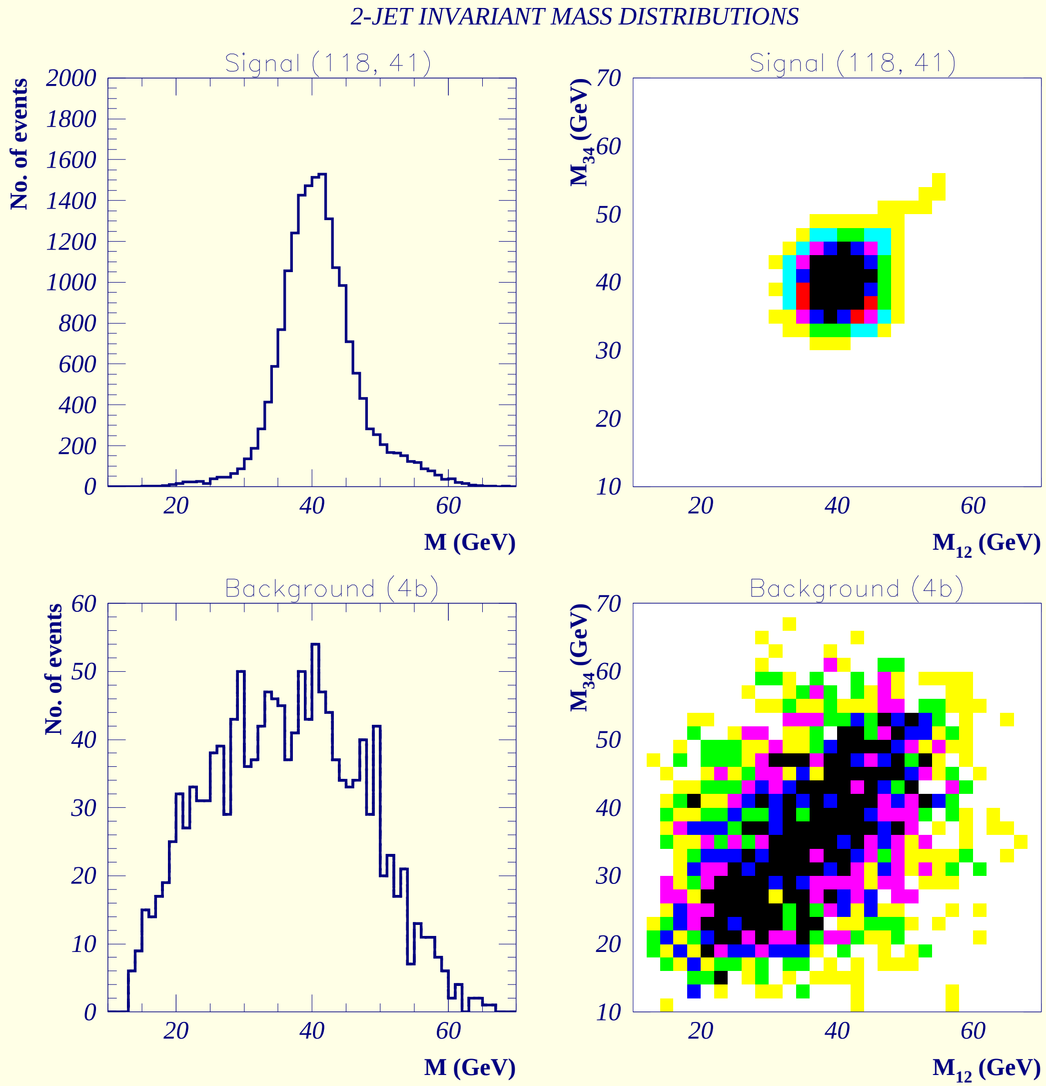


Event reconstruction: FastMC

Require:

- **Exactly 4 reconstructed jets,**
- $|\cos\theta_j| < 0.9$ **for** $j = 1, \ldots, 4$.

- **Calculate 2-jet invariant masses (3 combinations of 2 masses each), look for combination giving two values closest to each other, M_{12}, M_{34},**
- **Require $|M_{12} - M_{34}| < \mathbf{10}\ \mathrm{GeV}$.**



The $b\bar{b}b\bar{b}$ analysis

- b-tagging efficiencies assumed:

  0.5 for tagging a $b\bar{b}$ pair,

  0.035 for mistagging $c\bar{c}$ and $b\bar{b}$.

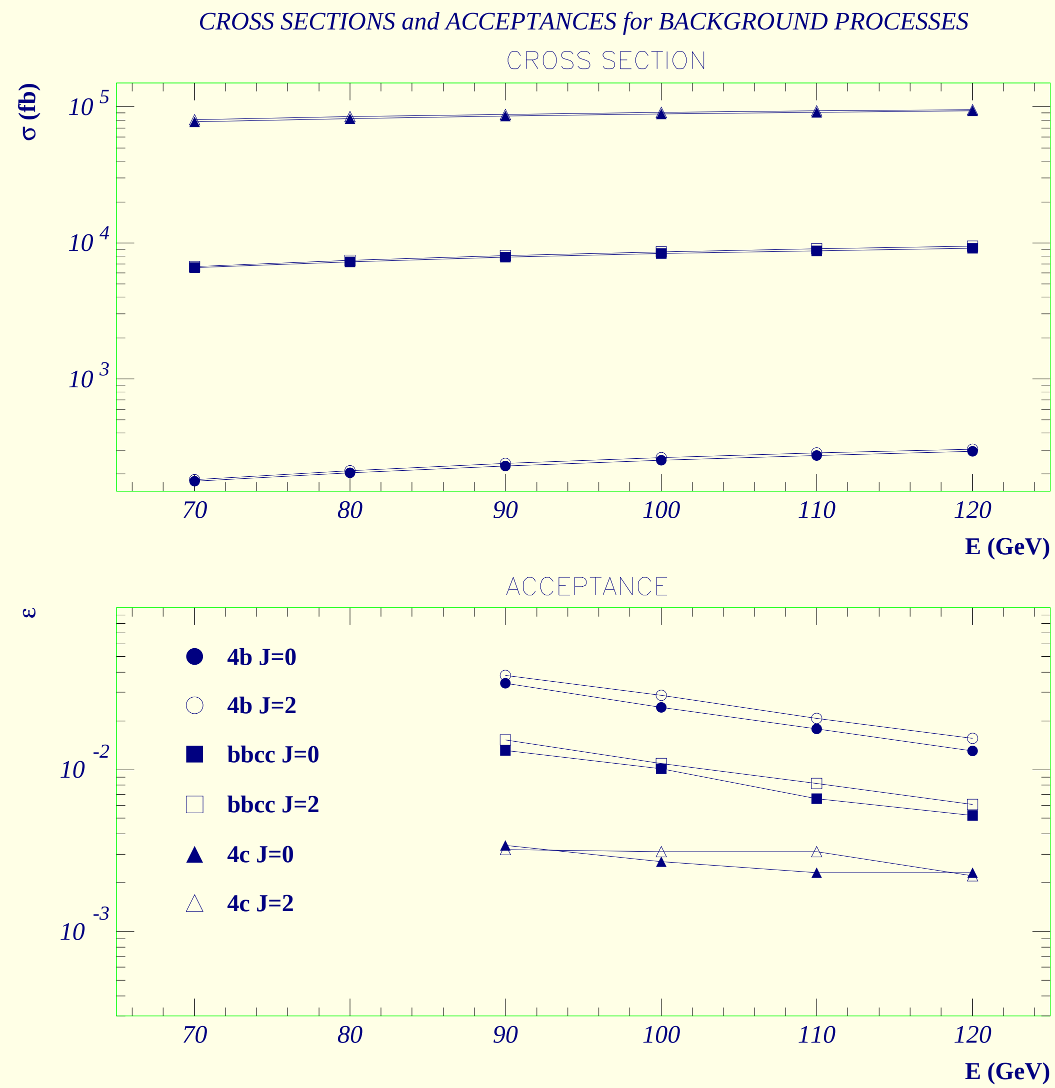
- Signal cross sections, acceptances and expected final sample:

$m_h, m_a(\text{ GeV})$	$\sigma(\gamma\gamma \to h)(\text{ fb})$	Acceptance*	No. of evts / 10^6 sec.
115, 56	112	0.26	139
123, 35	9.1	0.33	14.7
118, 41	46	0.28	63
124, 59	6.0	0.24	7.1

*) apply additional factor of 0.25 due to b tagging.

Note the small cross sections if you choose the peak in the wrong place!

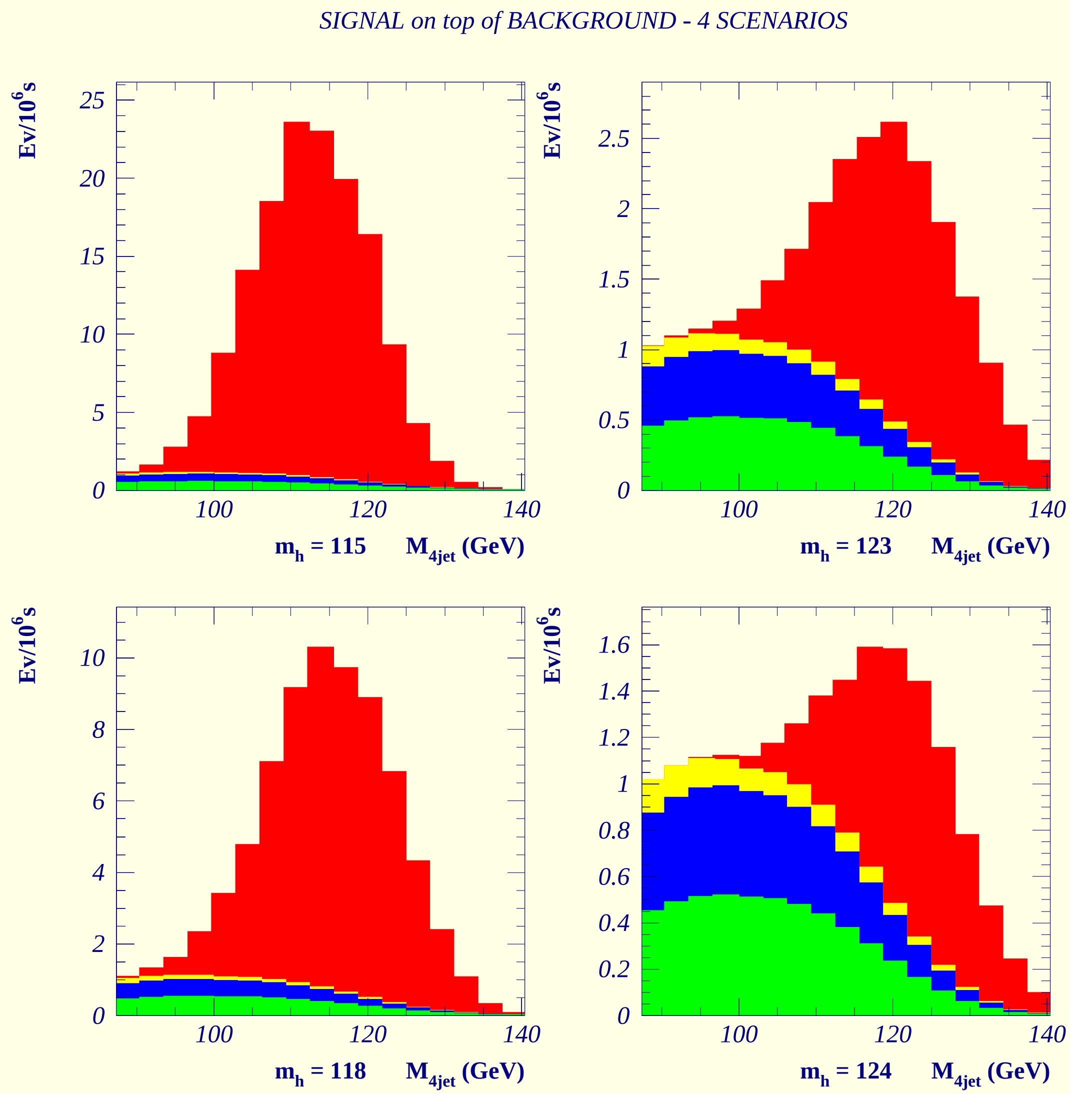
WHIZARD-calculated background cross sections and cut acceptances and their interpolation



Results for $b\bar{b}b\bar{b}$

Calculate 4-jet invariant mass:

- $\gamma\gamma \to h \to aa \to b\bar{b}b\bar{b}$,
- $\gamma\gamma \to c\bar{c}c\bar{c}$,
- $\gamma\gamma \to b\bar{b}c\bar{c}$,
- $\gamma\gamma \to b\bar{b}b\bar{b}$.



The $b\bar{b}\tau^+\tau^-$ channel

For $b\bar{b}\tau^+\tau^-$ (subdominant) final state:

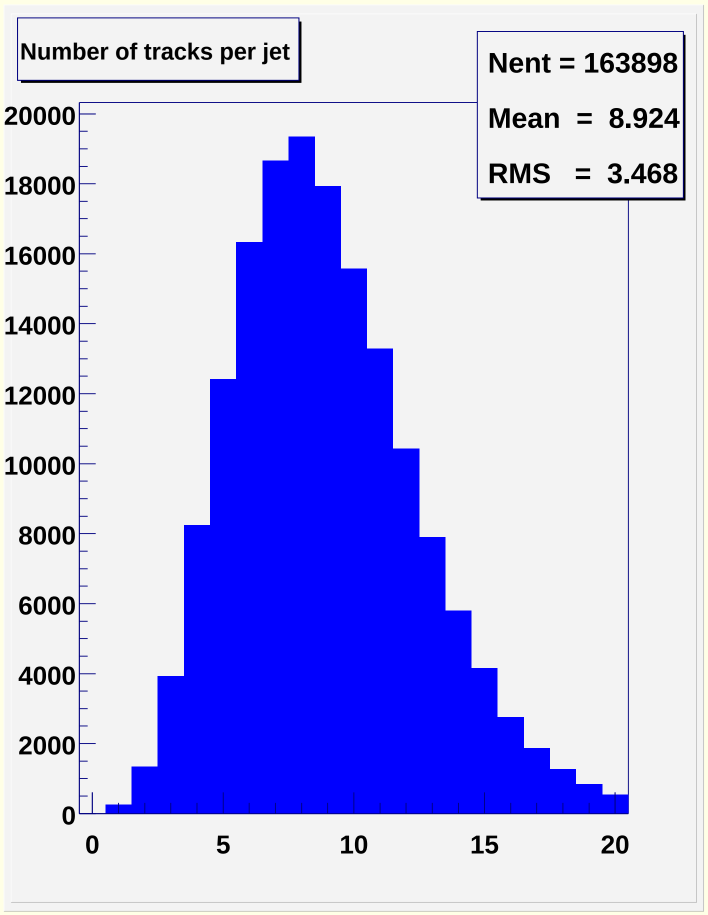
- Smaller signal than for $b\bar{b}b\bar{b}$ by $\sim 0.06/0.9$ due to BR's.
- Also, much smaller background – cross sections from WHIZARD-1.24:

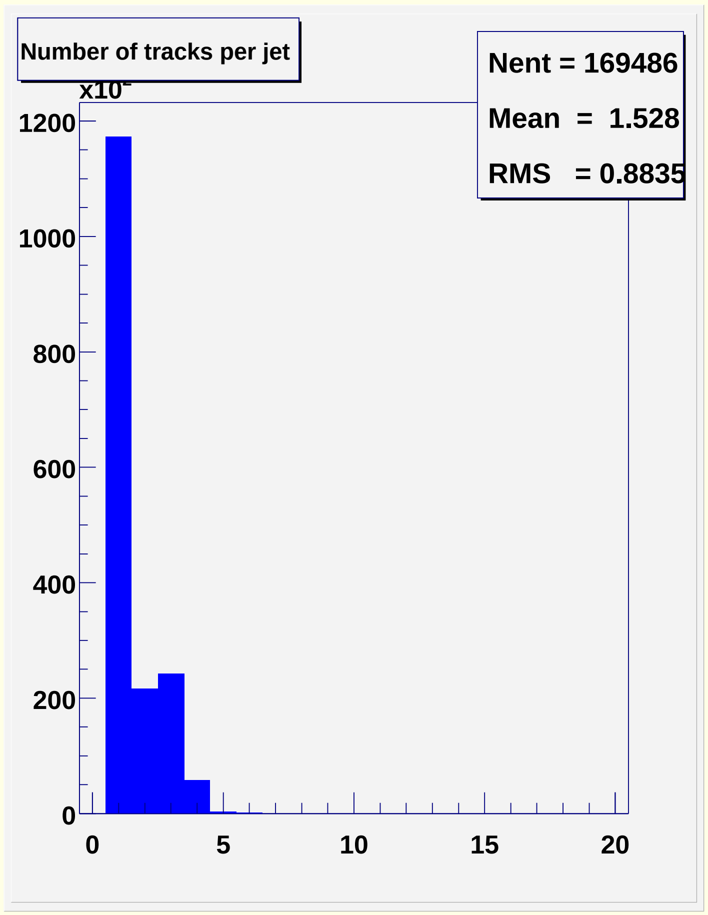
$\gamma\gamma \to$	σ (fb) $E = 110$ GeV, $J = 0$	σ (fb) $E = 110$ GeV, $J = 2$
$b\bar{b}b\bar{b}$	270	290
$b\bar{b}c\bar{c}$	8800	9100
$c\bar{c}c\bar{c}$	91000	93000
$b\bar{b}\tau^+\tau^-$	12	20
$c\bar{c}\tau^+\tau^-$	740	770
$\tau^+\tau^-\tau^+\tau^-$	410	420

- Different procedure to identify $\tau^\pm$ and $b \Rightarrow$ usually larger selection losses.
- Ultimately, much smaller statistics can be expected, but not so much different S/B.

- **Toy analysis to identify $\tau^\pm$: look at $''jets''$ (including $''j'' = e, \mu$) reconstructed from tracks ($y_{cut} = 0.004$).**
  Require 4 $''jets''$ in total, including 2 $jets$ with ≥ 4 tracks (for $b\bar{b}$) and 2 $''jets''$ with ≤ 3 tracks (for $\tau^+\tau^-$).

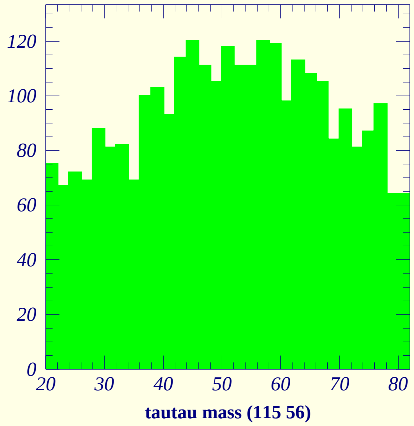
From b and $\bar{b}$ | **From τ^+ and τ^-**

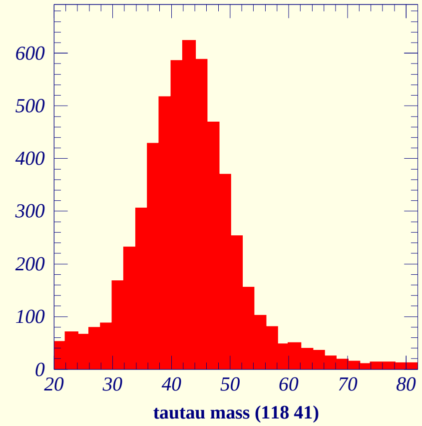


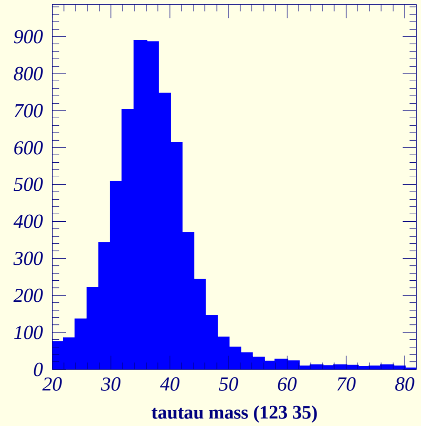


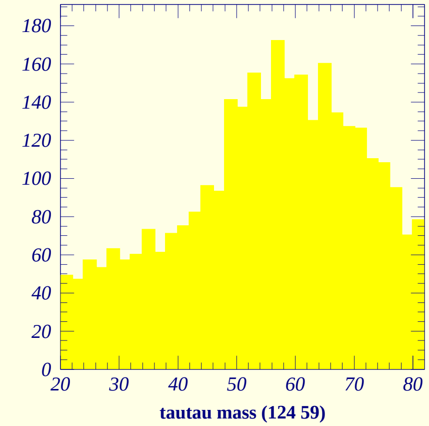
- **Only accept events with $|\cos\theta_j| < 0.9$ for $j = 1, \ldots, 4$.**

- **$\tau^\pm$ reconstruction: assume τ decays are collinear; then reconstruct the τ momenta from the $\sum p_x = 0$ and $\sum p_y = 0$ bounds.**









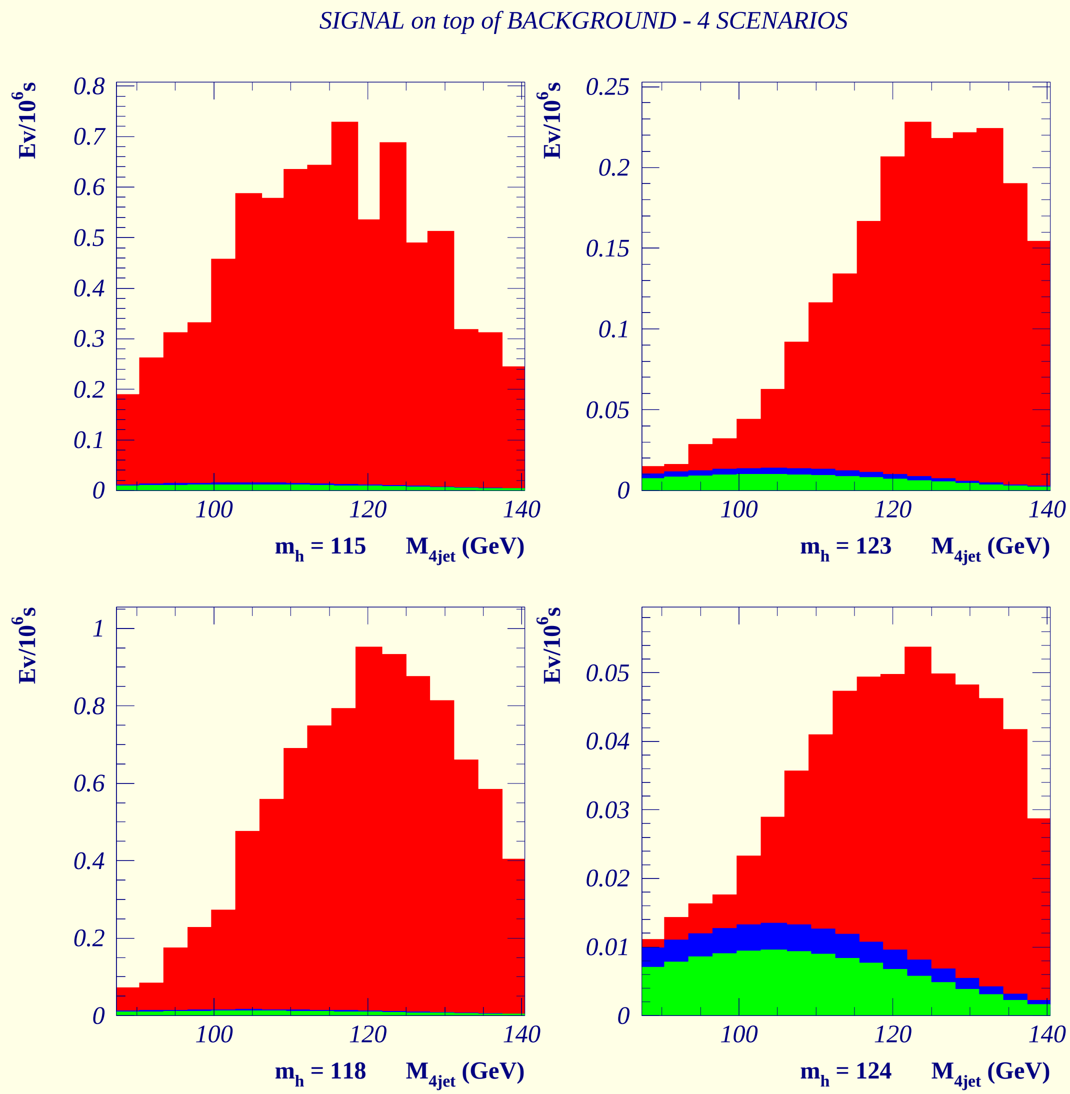
- **Require $|M_{b\bar{b}} - M_{\tau^+\tau^-}| < 15$ GeV.**

Results for $b\bar{b}\tau^+\tau^-$

Calculate $4j$ ($=2j2\tau$, with $\tau \to "j"$, including $"j" = e, \mu$) invariant mass:

- $\gamma\gamma \to h \to aa \to b\bar{b}\tau^+\tau^-$,
- $\gamma\gamma \to c\bar{c}\tau^+\tau^-$,
- $\gamma\gamma \to b\bar{b}\tau^+\tau^-$.

Number of signal events/year, respectively: 78, 20, 92, 4.5.



Summary of peaked spectrum simulations

- Strong dependence on NMSSM Higgs mass (scenario) is mainly due to the luminosity spectrum being peaked at $115~\mathrm{GeV}$ — we will see that a broad spectrum will be better in general case.

- Large signal with good S/B for $b\bar{b}b\bar{b}$, even after a short time of running, especially if spectrum peaks close to m_h.

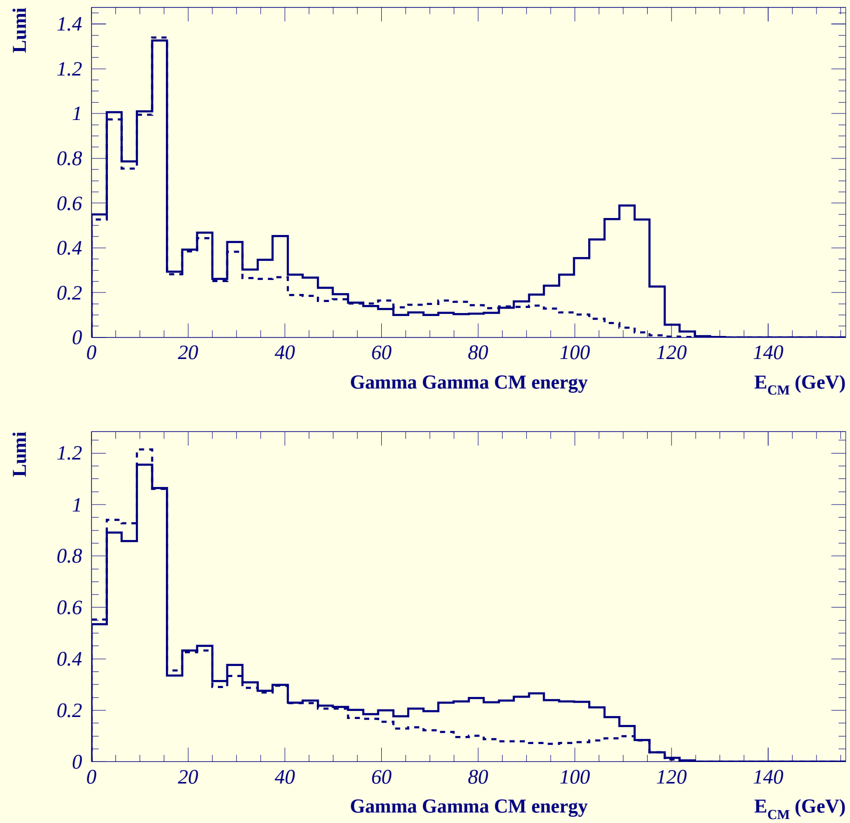
- In most cases, signal clearly visible also for $b\bar{b}\tau^+\tau^-$ after a year of running $\Rightarrow$ confirmation of $b\bar{b}b\bar{b}$ signal and check on mass dependent couplings of the a via $b\bar{b}\tau^+\tau^-/b\bar{b}b\bar{b}$ ratio.

- Overall, excellent prospects to find and study NMSSM Higgs bosons in scenarios $1, 3, 4, 5$.

- Good prospects can be expected also for $\gamma\gamma \to h \to aa \to \tau^+\tau^-\tau^+\tau^-$ in scenarios 2 and 6 [$\sigma(\gamma\gamma \to 4\tau) \sim 400~\mathrm{fb}$ and $BR(a \to \tau^+\tau^-) \simeq 0.9$], provided a suitable 4τ reconstruction algorithm is found.

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

- Up to now: used CLIC 1 spectrum peaked at 115 GeV (top). Now: broad band spectrum (bottom), but $E_e = 75$ GeV $\to$ not practical for higher m_h.



- Total cross sections for $\gamma\gamma \to h_{SM}$ from Pythia: 31.8, 40.8, 40.4, 32.2 fb for m_h= 80, 90, 100, 110 GeV, respectively.

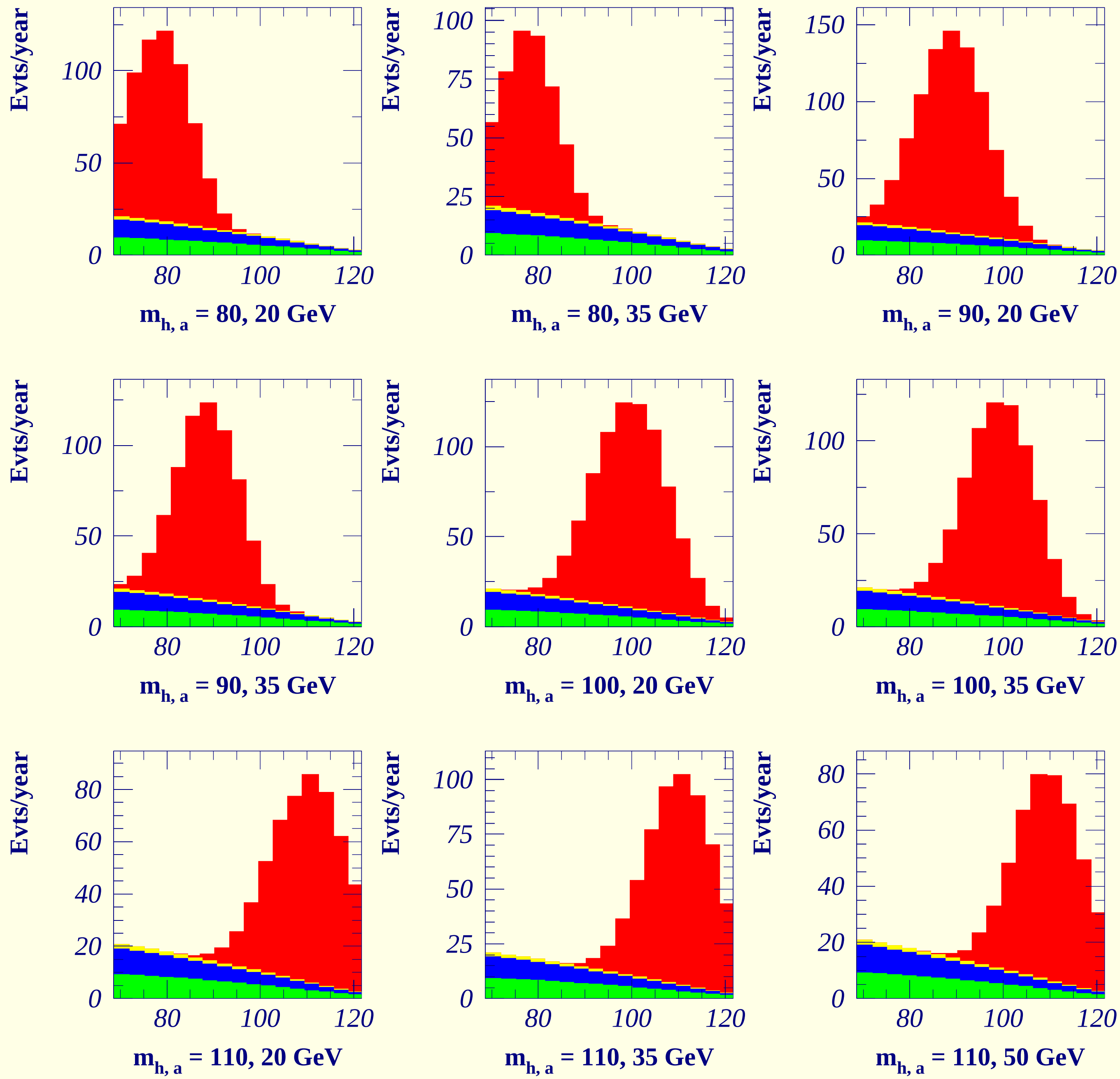
- **Look at a grid of points: $m_h = 80$, 90, 100, 110 GeV; $m_a = 20$, 35, 50. A total of 9 kinematically allowed possibilities.**

- **Same cuts and tagging (mis-tagging) efficiencies as before.**

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

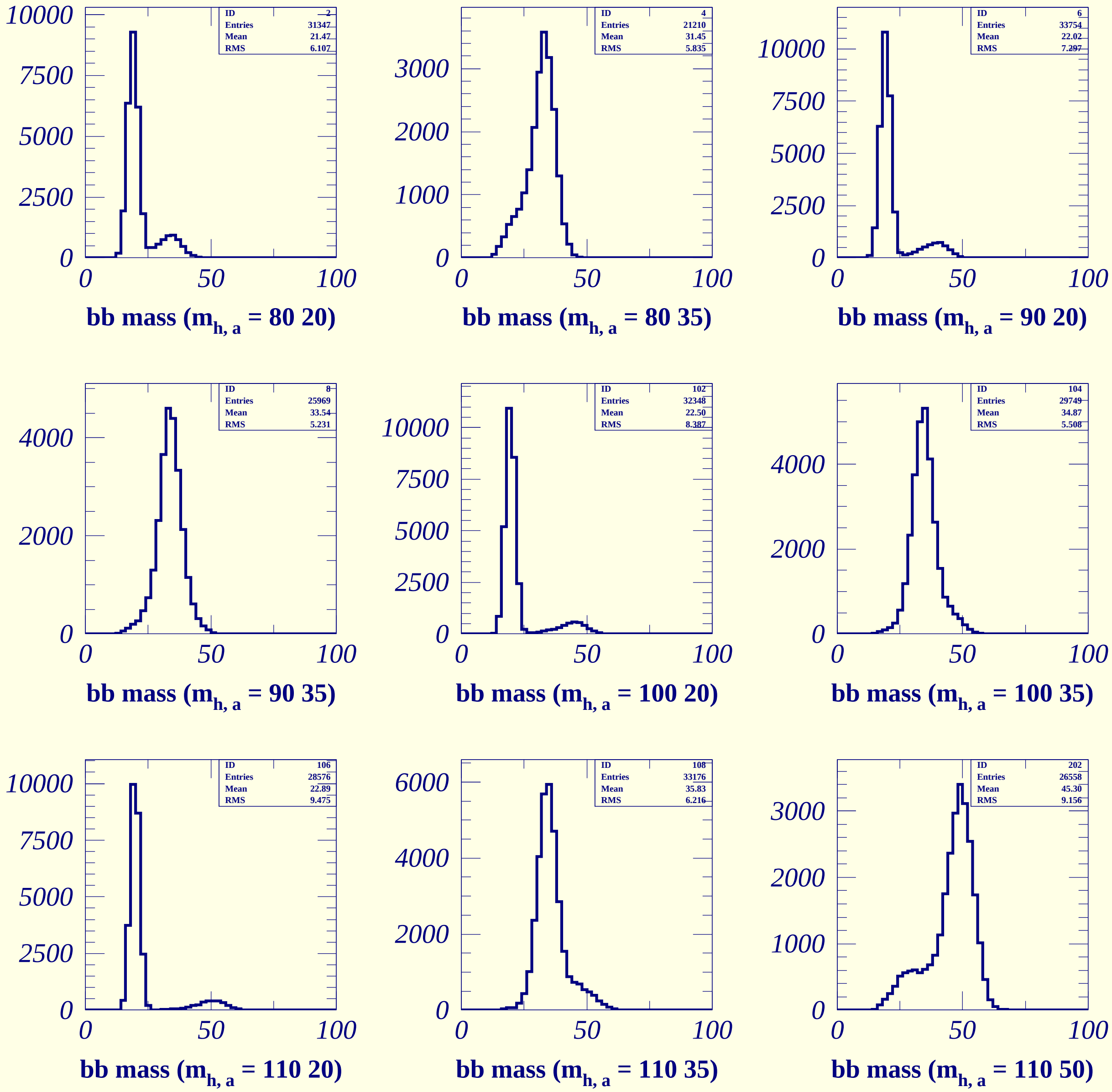
- **Excellent determination of m_a is possible — see 2nd figure.**

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



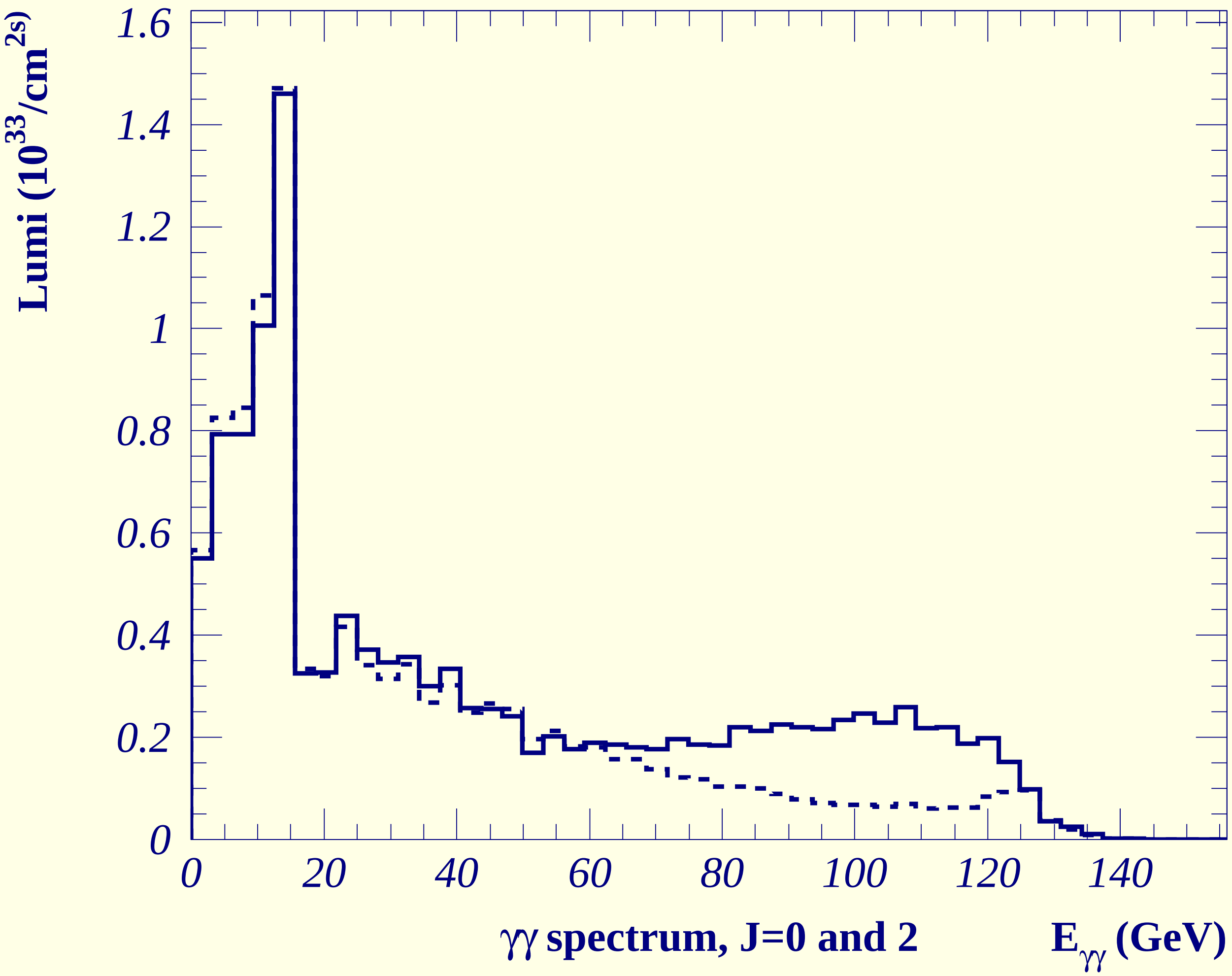
How well can we determine the a mass?

RECONSTRUCTED bb MASSES



Allowing for unequal a_1, a_2 masses; broad spectrum

For maximum reach increase E_e from 75 to 82 GeV.



- **Study $h \to a_1 a_2 \to b\bar{b}b\bar{b}$ with $(m_h, m_{a_1}, m_{a_2}) = (90, 20, 40)$, $(110, 25, 75)$, $(130, 30, 60)$ and $(130, 20, 85)$ GeV.**

- **Cross section for SM-like H are 29.5, 43.3 and 12.7 fb for $m_h = 90, 110, 130$ GeV, respectively.**

- **Analysis requires checking all 4 jets $\to$ 3 possible 2-jet combination possibilities.**

  Can't look for equal masses.

  Must assume some arbirary values for m_{a_1} and m_{a_2} in the $10 - 90$ GeV (if kinematically allowed) range. Select jet combination which fits best this combination.

- **Require $\sqrt{(M_{12} - m_{a_1})^2 + (M_{34} - m_{a_2}^2)^2} < 10$ GeV and look at the number of successfully reconstructed events.**

- **Repeat the above steps for all kinematically allowed m_{a_1}, m_{a_2} combinations.**

- **Select m_{a_1}, m_{a_2} which maximize the number of reconstructed events.**

- As we get closer to the true mass values, nice Gaussian mass peaks should appear and the actual a_1 and a_2 masses will be determined with some error.

- The first set of figures shows the a_1 and a_2 mass peaks for incorrect vs. correct choices of the a_1 and a_2 masses.

  A brief study will convince you that the mass resolution on the a_1 and a_2 masses might approach $5~\mathrm{GeV}$ in some cases, but will probably be a bit worse than this in general. A careful statistical study is need, but has not yet been performed.

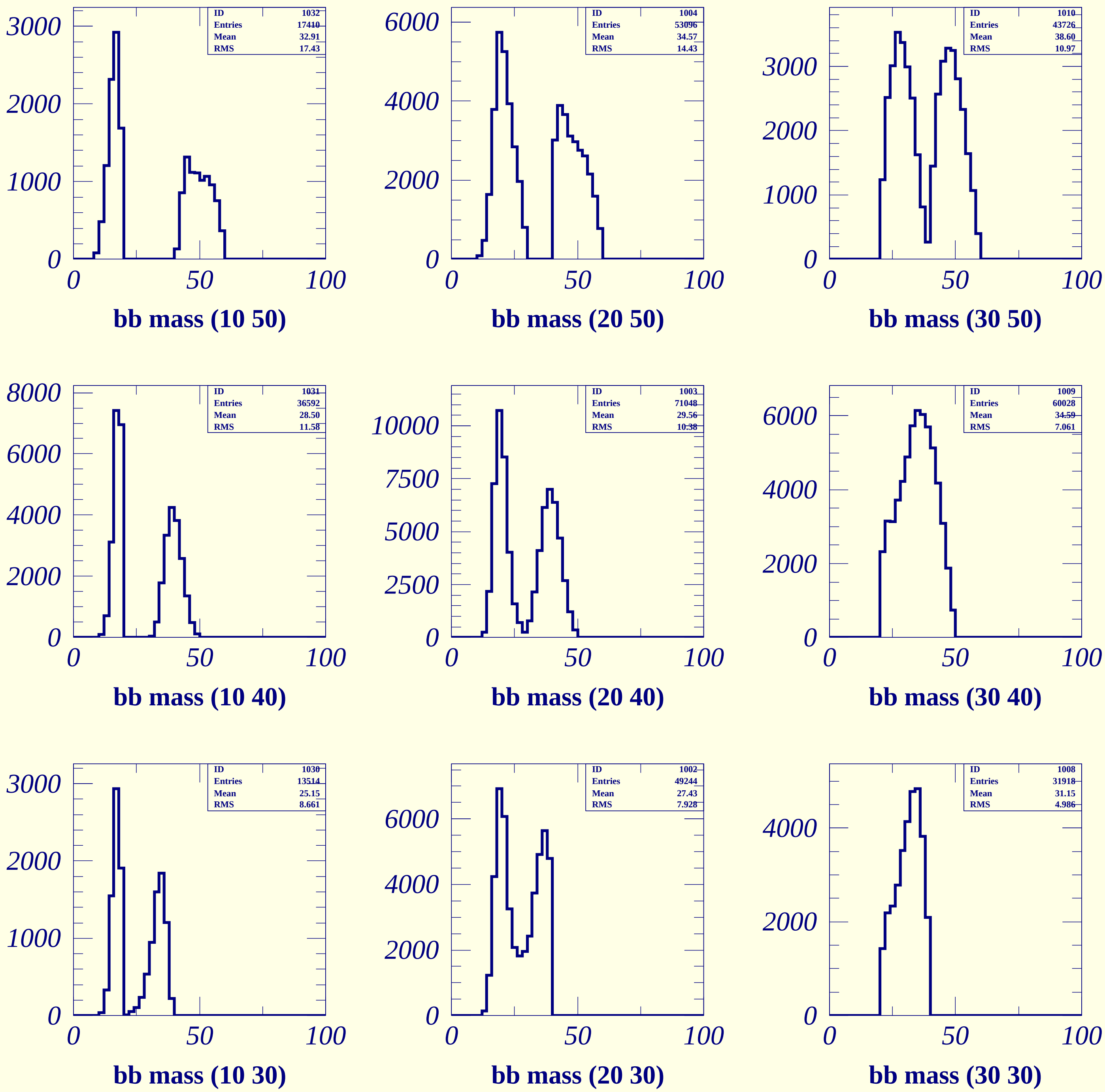
- The second set of figures shows the full reconstructed $b\bar{b}b\bar{b}~h$ mass peak for the best choice case as compared to wrong choices.

  These signal will be hard to miss, and if the h has something like SM $\gamma\gamma$ coupling, the precise value will be pretty well measured.

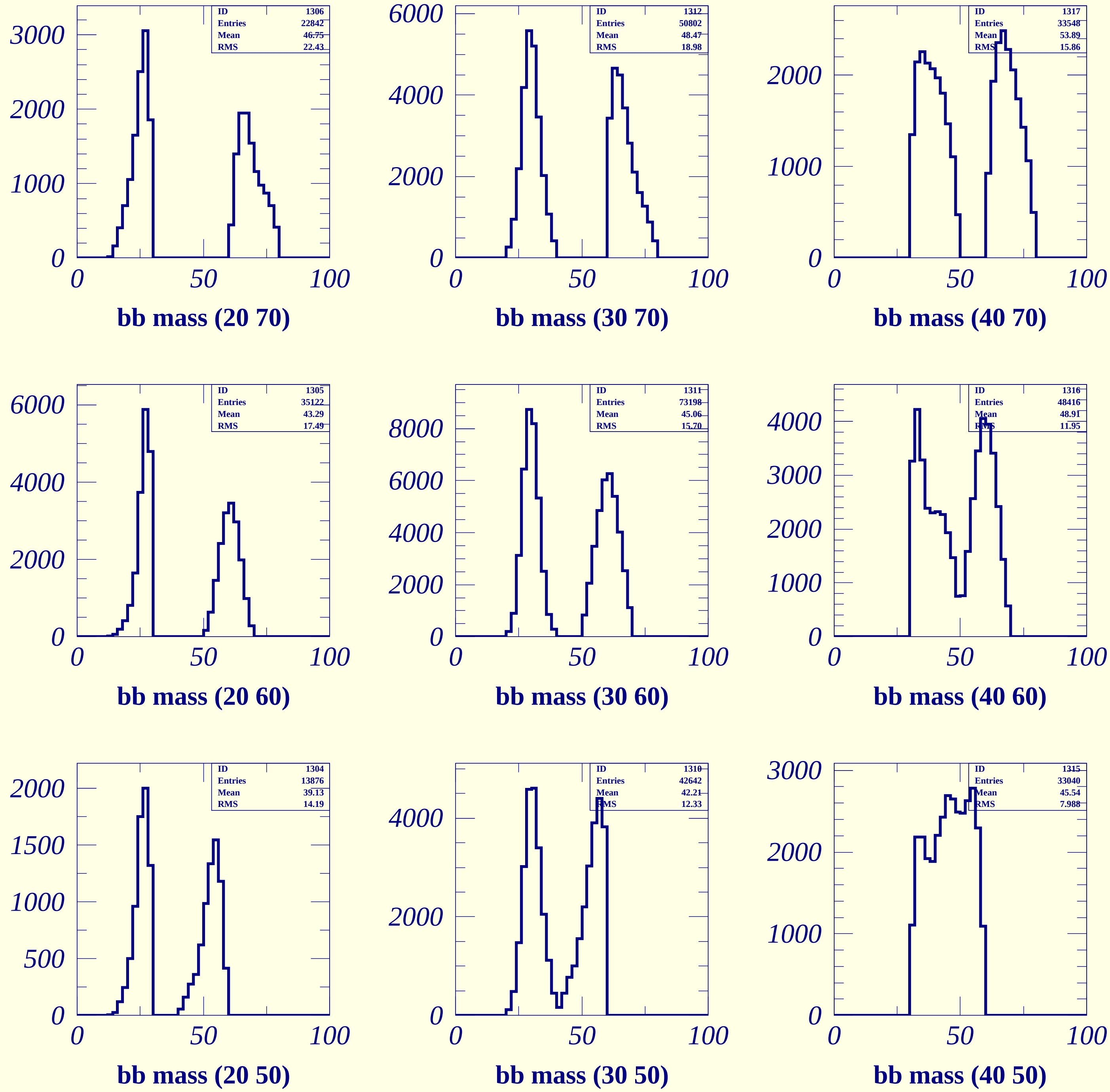
  Again, a careful statistical study is needed to determine the error on $\Gamma(h \to \gamma\gamma)$ as a function of the $\gamma\gamma \to h$ coupling relative to the $\gamma\gamma \to h_{\rm SM}$ couplings.

  In what follows, the central figure is always that for the correct choice of test m_{a_1} and m_{a_2} values.

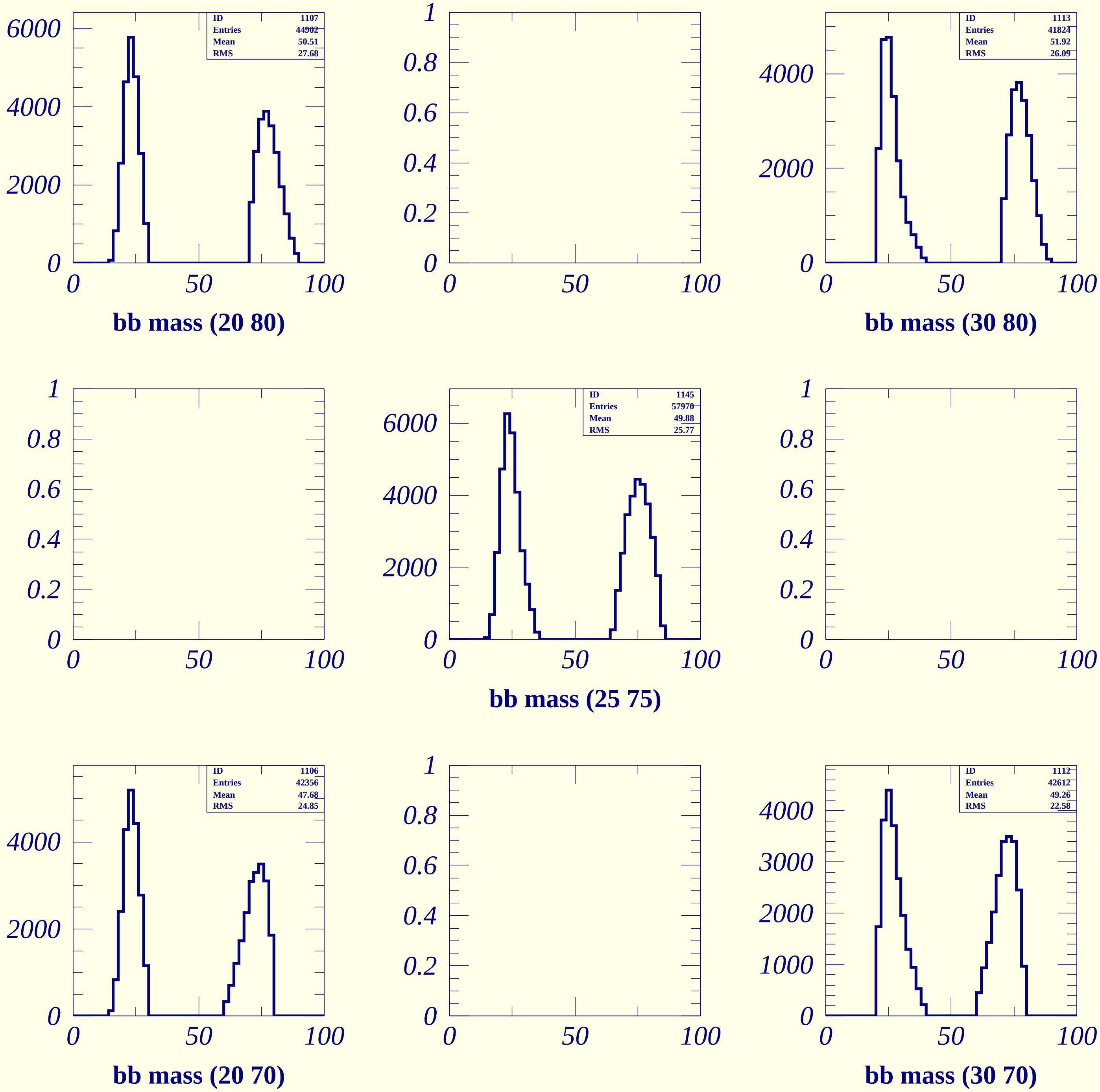
$m_{h,\,a1,\,a2}$ = 90, 20, 40 GeV



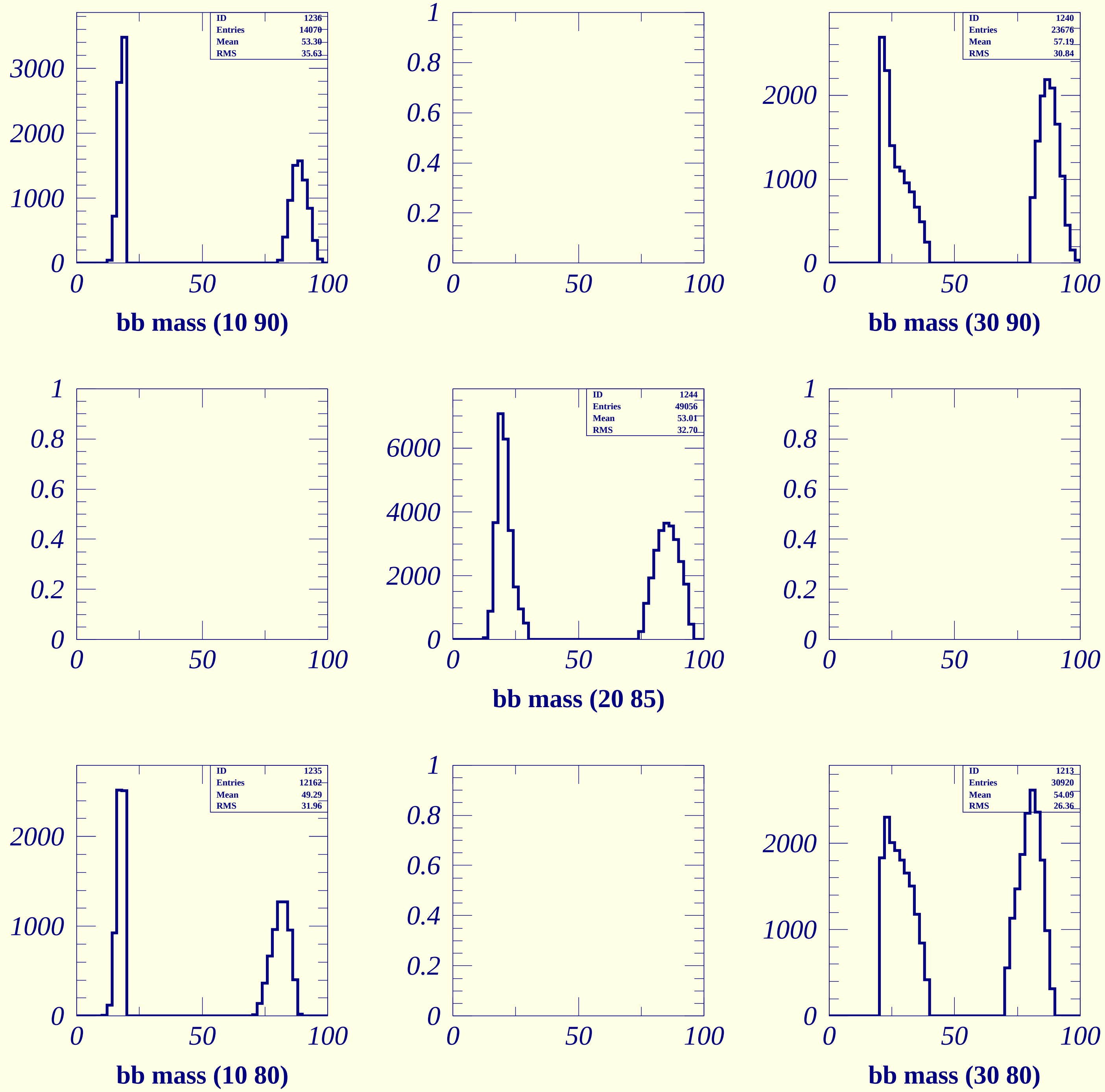
$m_{h,\,a1,\,a2}$ = 130, 30, 60 GeV



$m_{h,\,a1,\,a2} = 110, 25, 75$ GeV

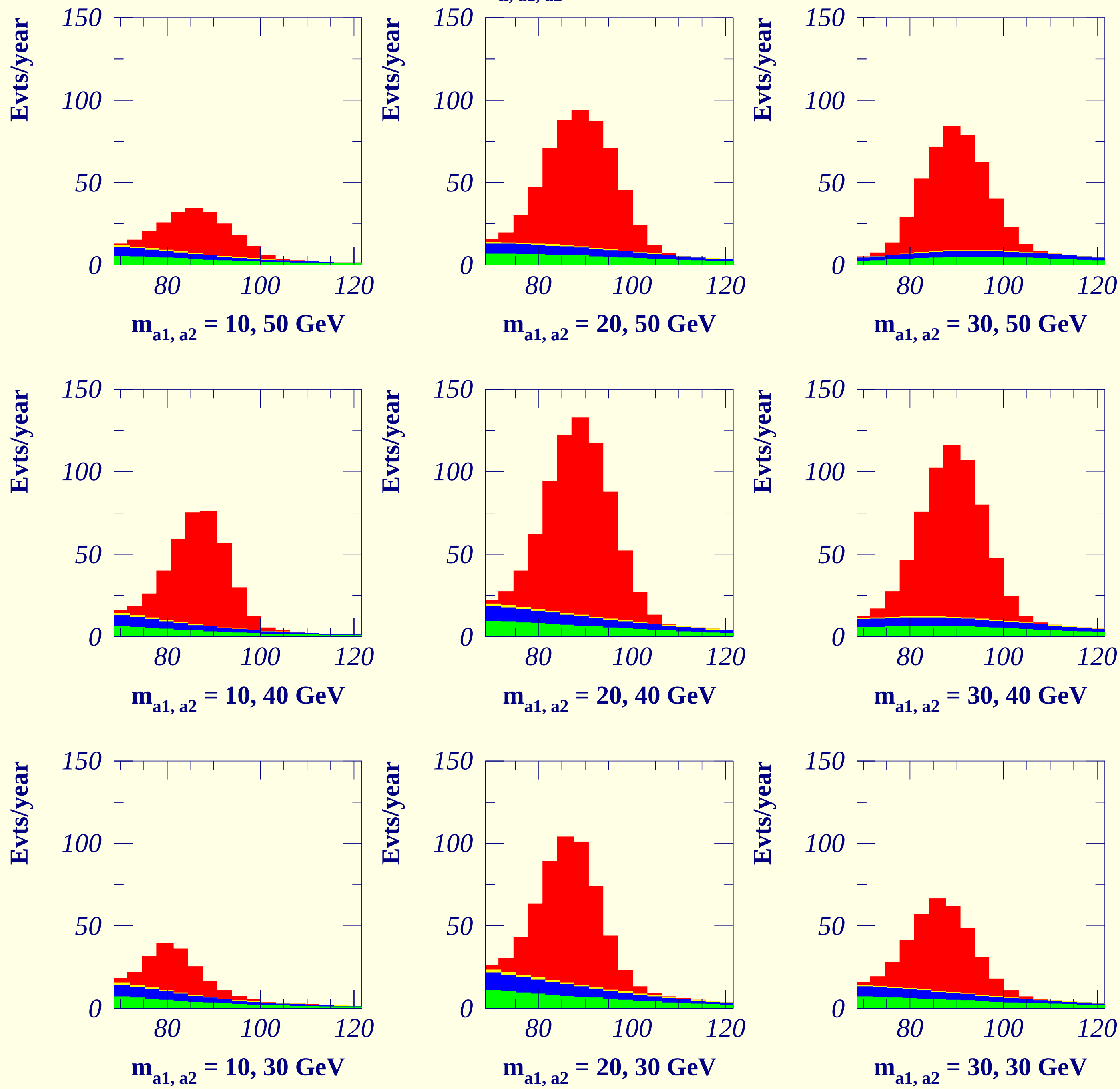


$m_{h,\,a1,\,a2} = 130, 20, 85\ GeV$



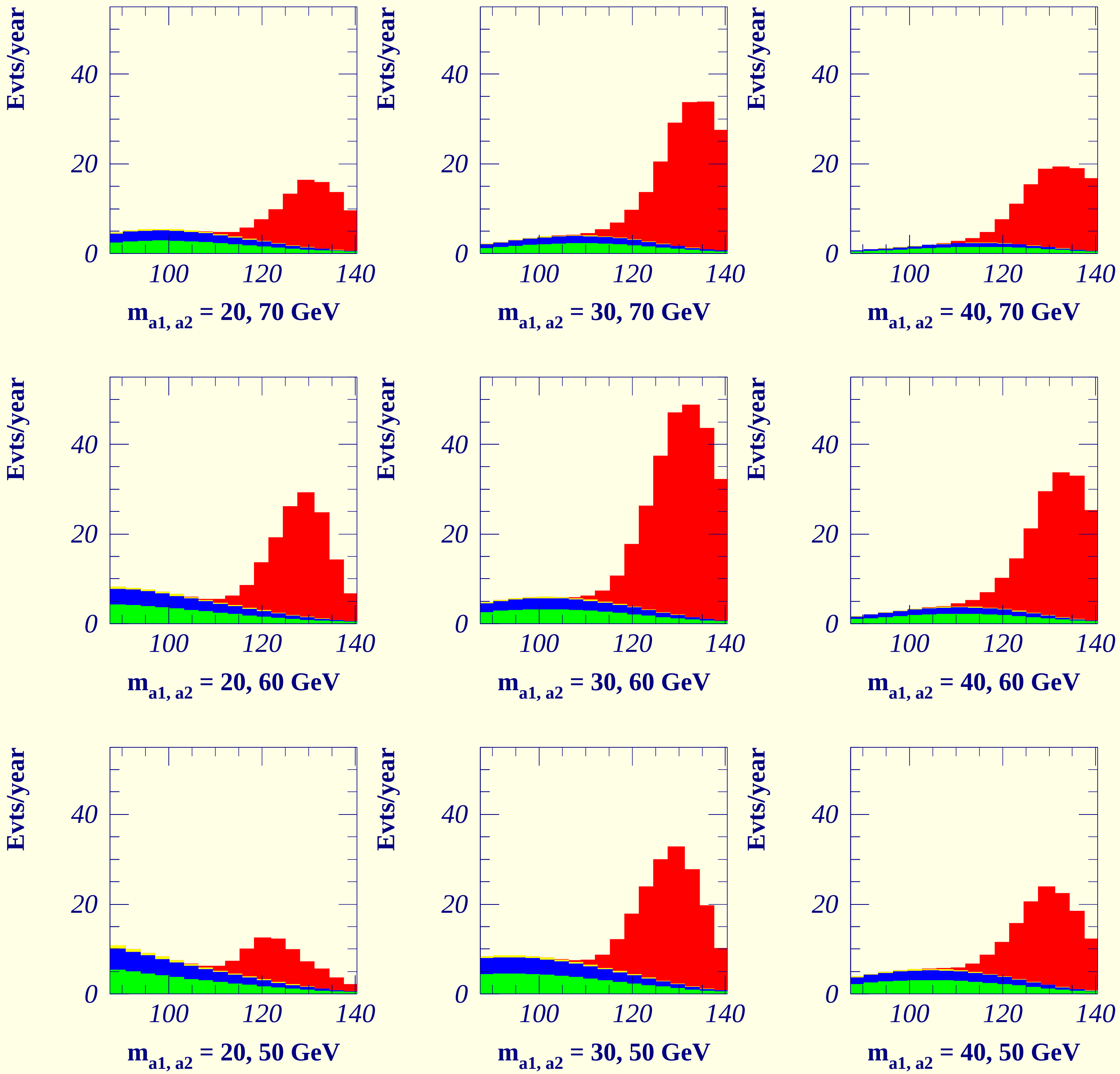
4-JET INV. MASS - SIGNAL on top of BACKGROUND

$m_{h,\,a1,\,a2}$ = 90, 20, 40 GeV

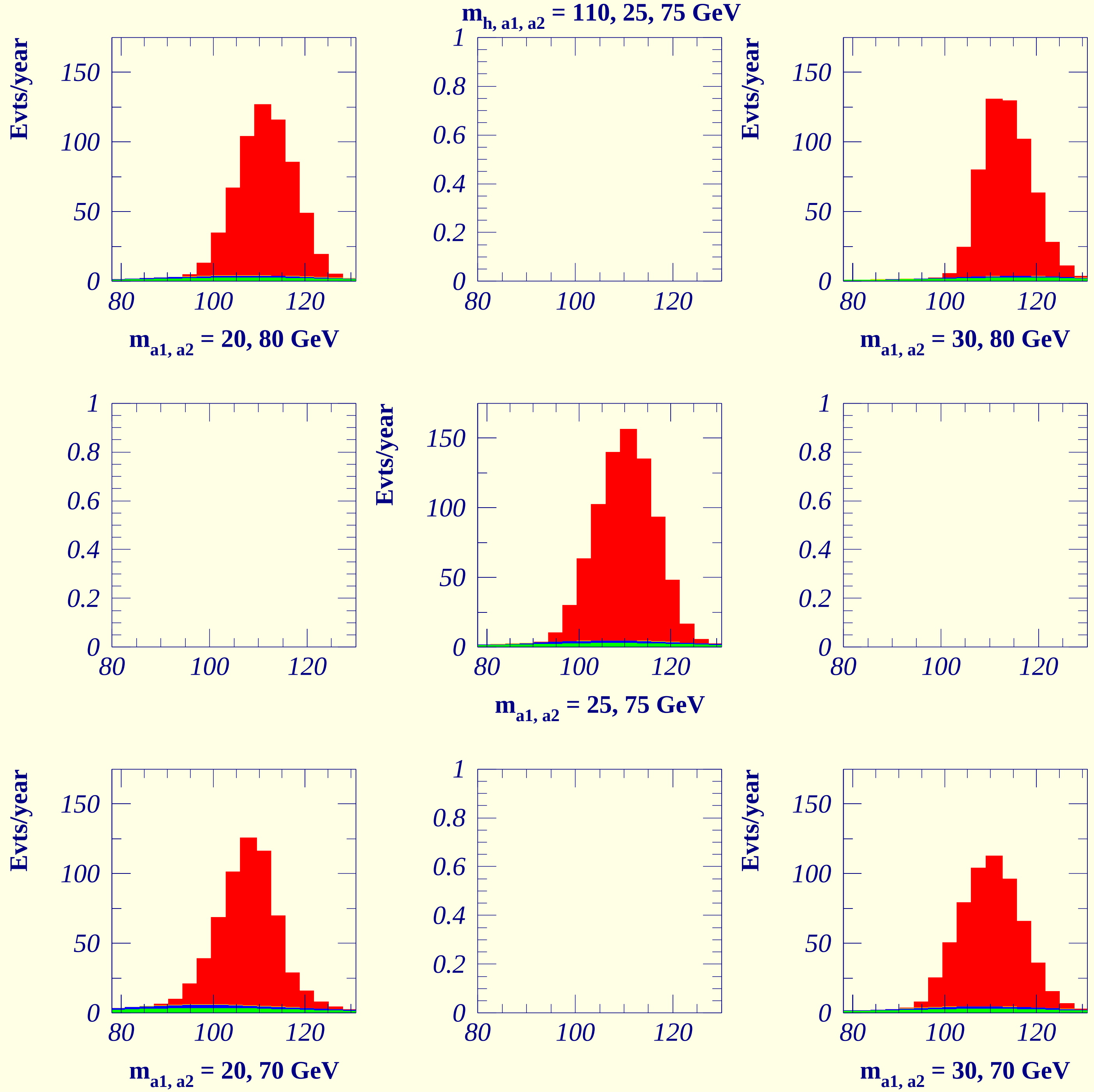


4-JET INV. MASS - SIGNAL on top of BACKGROUND

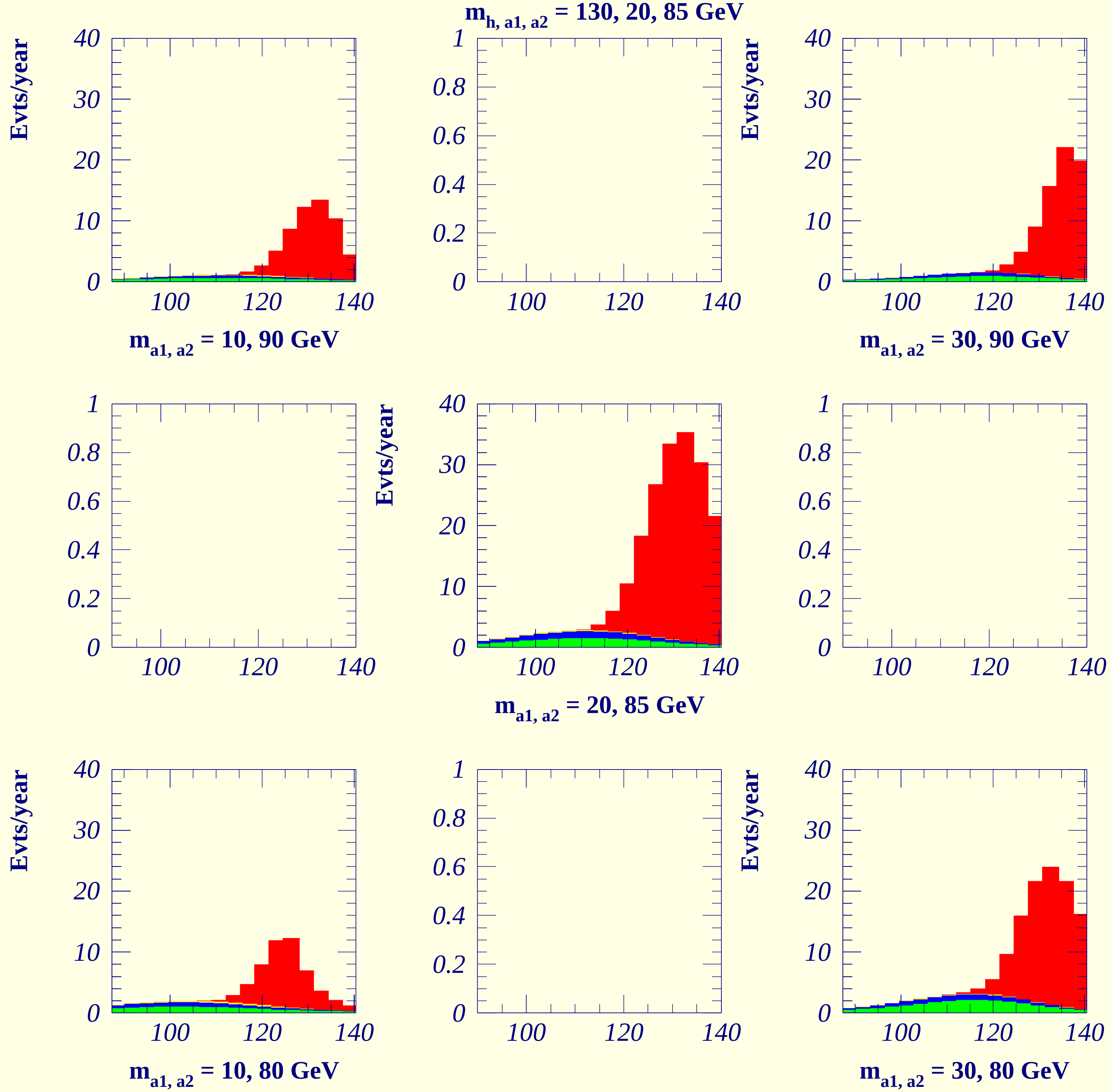
$m_{h,\,a1,\,a2}$ = 130, 30, 60 GeV



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



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



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 will probably be left with cases where $m_h \lesssim 60~\mathrm{GeV}$, $h \to aa$ and $m_a < 2m_\tau$.

- 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.

- 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!