Testing the No-lose and More-to-gain Theorems of the NMSSM at the LHC

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- Di-photon Decay Mode.
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- Conclusion.

Minimal Supersymmetric Standard Model (MSSM)

- Every particle in the SM has a superpartner.
- There are five physical Higgs states (assuming CP-conservation): 2 CP-even, 1 CP-odd and a pair of charged Higgses.
- At tree level, MSSM Higgs sector can determined by two parameters: $tan\beta$ and m_A.
- By assuming R-parity is conserved, the lightest neutralino (LSP) is a good candidate for dark matter.

MSSM Shortcomings

- μ- problem:
  The presence of μ in the superpotential before Electro-Weak Symmetry Breaking (EWSB) would require μ to be 0 or M_P but for phenomenological reasons $\mu \sim$ 100-1000 GeV.

$$W_{MSSM} \ni \mu \hat{H}_u \hat{H}_d$$

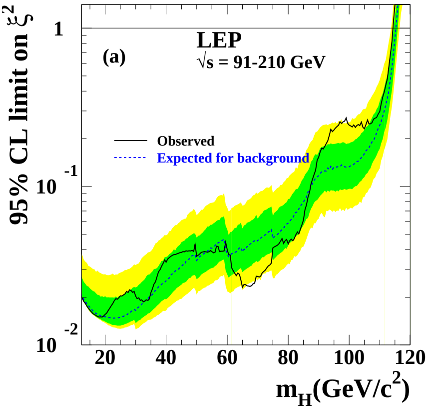
- Little hierarch problem:
  The upper limit for the lightest CP-even Higgs is $m_Z \approx 91$ GeV whereas LEP direct search excluded it with mass less than 114.4 GeV at 95% confidence level. So large quantum corrections from too heavy stop masses should be included to evade this limit.
  (Note: Other corrections from squark masses also affect the NMSSM m_{h1}).

Next to Minimal Supersymmetric Standard Model (NMSSM)

- Solves μ problem:
  In the NMSSM, the effective μ-term is generated by introducing a new singlet superfield
  $$W_{NMSSM} = W_{MSSM} + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3$$
  Once the scalar component of the singlet gets a VEV then μ automatically will be of order of electroweak scale, $\mu_{eff} = \lambda \langle S \rangle$.
- Solves little Hierarchy problem by:
  a) Pushing up the SM-like Higgs mass by an extra term proportional to λ, its lower limit at tree level becomes
  $$m_{h1} < m_Z^2 (cos^2(2\beta) + \frac{2\lambda^2 sin^2(2\beta)}{g_1^2 + g_2^2}),$$
  so the upper limit for m_{h1} can reach 140 GeV.
  b) Non standard Higgs decays are possible, e.g. h$\rightarrow$2 Higgs where LEP limit will not be applied in this case.

- Higgs singlets exist in Superstring theories.
- Richer Phenomenology than MSSM where the spectrum of NMSSM compared to MSSM contains:
  - One more scalar Higgs, $m_{h1} < m_{h2} < m_{h3}$.
  - One more pseudoscalar Higgs, $m_{a1} < m_{a2}$.
  - One more neutralino.

- it can explain a 2.3 σ event excess occurred at LEP for the process $e^+e^- \to Zb\bar{b}$ for $M_{b\bar{b}} \sim 98$ GeV by: having a reduced branching ratio to $b\bar{b}$ by enhancing the branching ratio of $h_1 \longrightarrow a_1 a_1$ ($m_{a1} < 2m_b$ or a_1 is highly singlet) or having a reduced ZZh coupling.



Higgs Sector of the NMSSM

- Six free parameters at tree level:

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

- There are two famous theorems of the NMSSM related to Higgs spectrum, need to be confirmed.
  - (No-Lose Theorem)
    At least one Higgs should be discovered at the LHC.
  - (More-to-Gain Theorem)
    More and/or different Higgs bosons of the NMSSM can be visible in some regions of parameter space compared to those available within the MSSM.

Tools

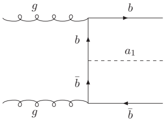
U. Ellwanger & C. Hugonie, NMSSMTools
http://www.th.u-psud.fr/NMHDECAY/nmssmtools.html

- This package is used to calculate Higgs masses, decay rates into two particle final states and SUSY spectrum, taking into account all theoretical and experimental constraints.
- We have done a random scan over 10 million points and for the successful points we have calculated the cross section by using Calchep for the signal and irreducible backgrounds and MadGraph for the reducible backgrounds.
- We have scanned over the NMSSM parameter space defined through the six following parameters:

$$\lambda : 0.0001 - 0.7, \quad \kappa : 0 - 0.65, \quad \tan\beta : 1.6 - 54,$$
$$\mu : 100 - 1000 \text{ GeV}, \quad A_\lambda : -1000 - +1000 \text{ GeV},$$
$$A_\kappa : -10 - 0.$$

The lightest CP-odd Higgs production in association with $b\bar{b}$

- One representative Feynman diagram for this production:

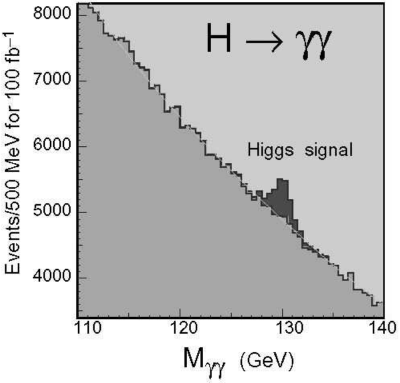


- This production mode can be dominant at large $tan\beta$. We chose $gg \longrightarrow b\bar{b}a_1$ because $gg \longrightarrow a_1$ is unfeasible due to large backgrounds.
- a1 does not couple to gauge bosons in Higgs-strahlung and VBF processes due to CP-conservation.
- It gives a well studied signature by ATLAS and CMS.
- b-tagging can be used to reject light jets.

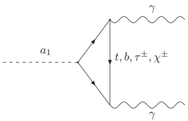
Di-Photon Decay Mode

- The most interesting mode to detect a Higgs boson below 130 GeV but quite rare in the SM and MSSM. In the NMSSM, it can reach branching ratio of O(1).
- The $h1(h2, h3)\gamma\gamma$-coupling is mediated by triangle loops of all charged particles while $a_1(a_2)$ only couples to $\gamma\gamma$ through fermions due to CP-conservation.
- Clean signature and can be resolved at the LHC.

- Look for a very narrow peak on the background distribution.



- Feynman diagram for $a_1\gamma\gamma$ is:



- If a_1 has only a singlet component, it only couples to $\gamma\gamma$ through charginos in the loop and so its branching ratio to $\gamma\gamma$ will be O(1).
- If a_1 is highly singlet it will be difficult to discover at the hadron colliders where its production will be suppressed.

Figure: The inclusive cross section as a function of m_{a1}.

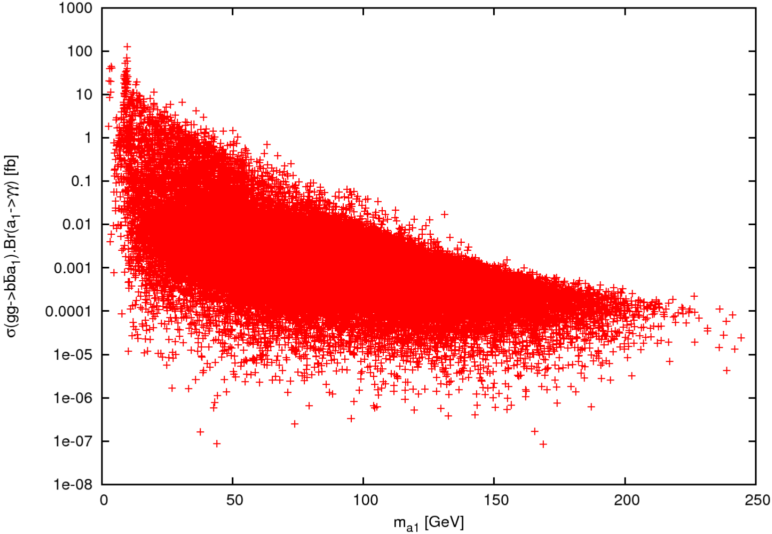
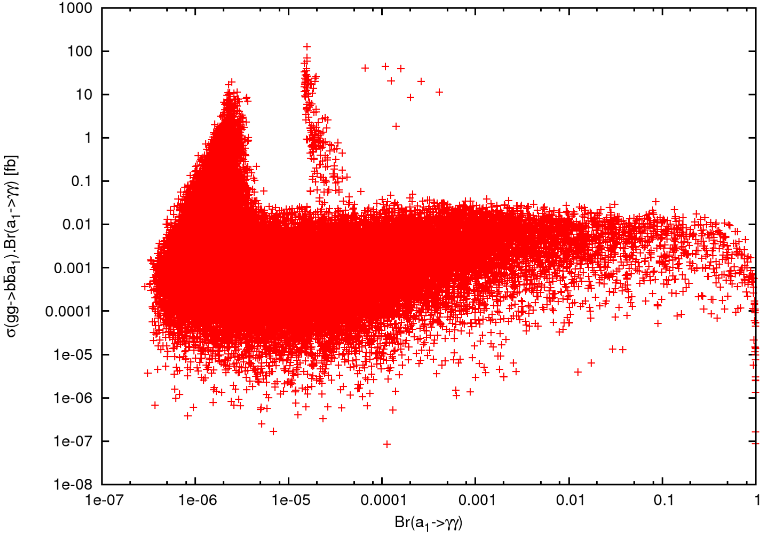


Figure: The inclusive cross section as a function of $Br(a_1 \to \gamma\gamma)$.



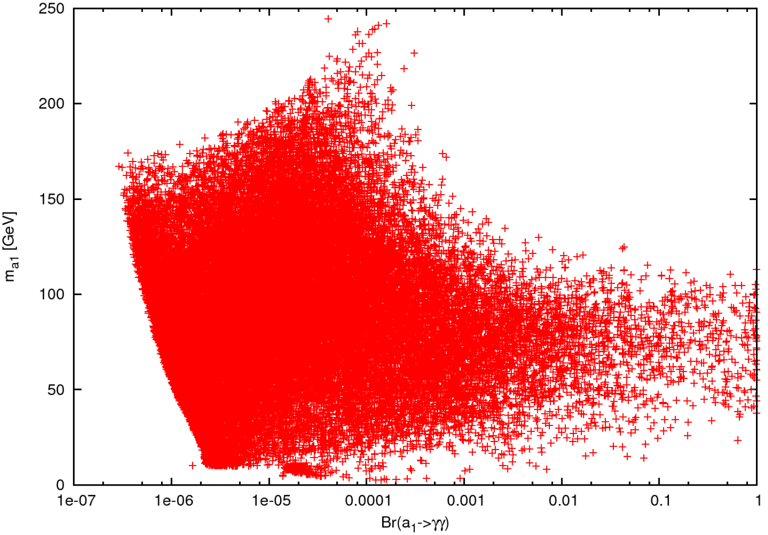


Figure: m_{a1} as a function of $Br(a_1 \to \gamma\gamma)$.

We have used the following cuts for our analysis:

$$\Delta R(b,\bar{b}), \Delta R(b,\gamma), \Delta R(\bar{b},\gamma), \Delta R(\gamma,\gamma) > 0.4,$$
$$|\eta(b)|, |\eta(\bar{b})|, |\eta(\gamma)| < 2.5,$$
$$P_T(b), P_T(\bar{b}) > 20 \text{ GeV}, P_T(\gamma) > 2 \text{ GeV}.$$

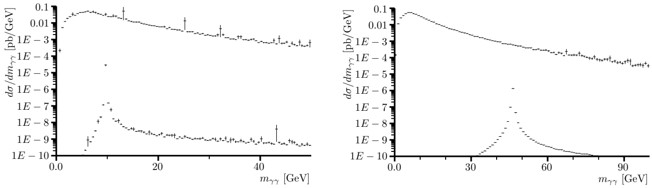


Figure: The differential cross section as a function of $m_{\gamma\gamma}$ for m_{a1} =9.76 and 46.35 GeV for the signal only and for the signal and backgrounds together.

Di-tau Decay Mode

- It is the best decay mode to discover the lightest CP-odd Higgs, a_1, at low masses for large $tan\beta$, $a_1\tau^+\tau^- \propto tan\beta$. The $b\bar{b}$ decay mode has large backgrounds.
- We need at least one tau to decay leptonically to suppress QCD backgrounds.
- The dominant backgrounds at low Higgs mass is the irreducible backgrounds, $Z, \gamma \to \tau^+\tau^-$ (Sarri, ATL-PHYS-PROC-2008).
- We have used the following cuts (we kept the tau on-shell for illustration):

$$\Delta R(b, \bar{b}), \Delta R(b, \tau^+), \Delta R(\bar{b}, \tau^+), \Delta R(b, \tau^-),$$

$$\Delta R(\bar{b}, \tau^-), \Delta R(\tau^+, \tau^-) > 0.4$$

$$|\eta(b)|, |\eta(\bar{b})|, |\eta(\tau^+)|, |\eta(\tau^-)| < 2.5$$

$$P_T(b), P_T(\bar{b}) > 20 \text{ GeV}, P_T(\tau^+), P_T(\tau^-) > 10 \text{ GeV},$$

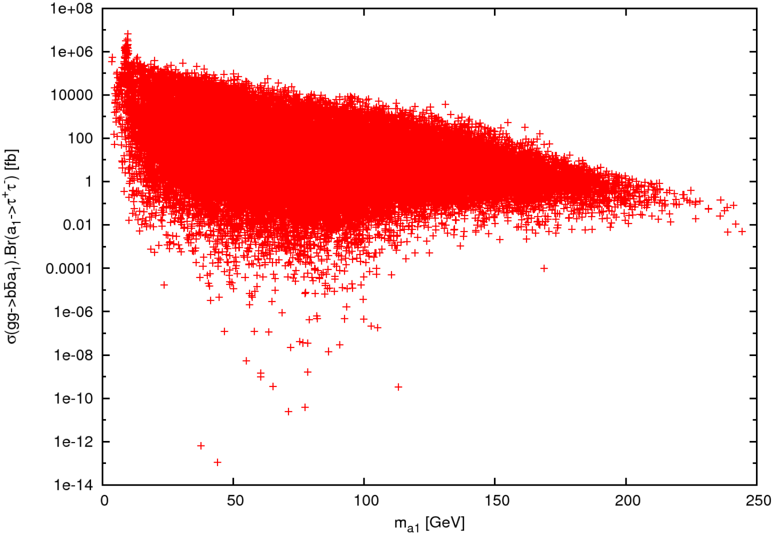


Figure: The inclusive cross section as a function of m_{a1}.

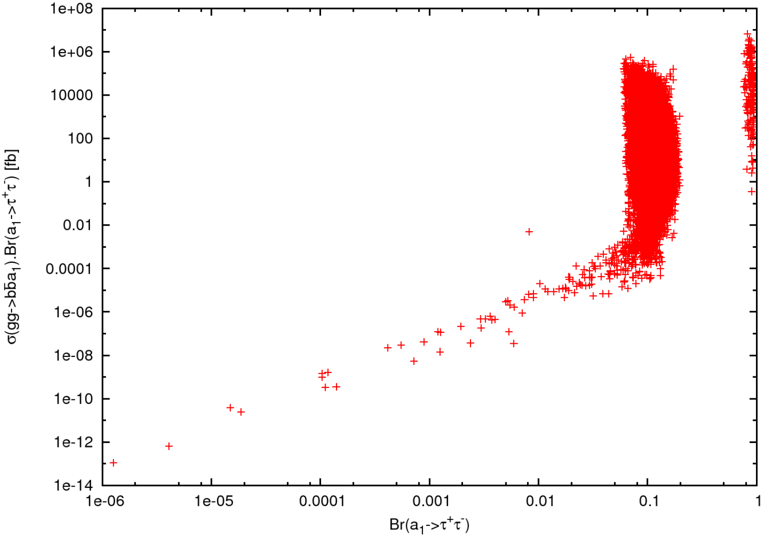


Figure: The inclusive cross section as a function of $Br(a_1 \to \tau^+\tau^-)$.

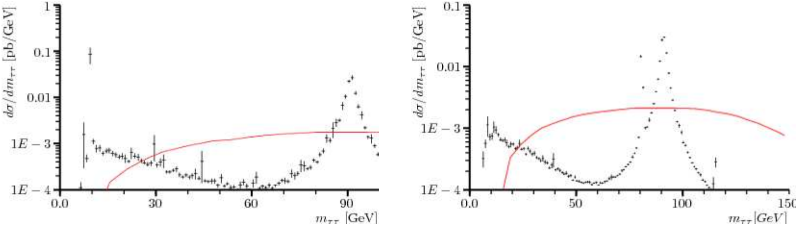


Figure: The differential cross section as a function of $m_{\tau^+\tau^-}$ for m_{a1} =9.76 GeV and 80.9 GeV for the signal and irreducible backgrounds (histogram points) and $t\bar{t}$ backgrounds (red line).

Di-muon Decay Mode

- Clean signature with excellent mass resolution.
- It has small branching ratio but it is enhanced for high $tan\beta$.
- The dominant backgrounds at low Higgs mass is the irreducible backgrounds, $Z, \gamma \rightarrow \mu^+\mu^-$ and $t\bar{t} \longrightarrow b\bar{b}\mu^+\mu^-\nu\bar{\nu}$
- We have used the following cuts:

$$\Delta R(b, \bar{b}), \Delta R(b, \mu^+), \Delta R(\bar{b}, \mu^+), \Delta R(b, \mu^-),$$

$$\Delta R(\bar{b}, \mu^-), \Delta R(\mu^+, \mu^-) > 0.4$$

$$|\eta(b)|, |\eta(\bar{b})|, |\eta(\mu^+)|, |\eta(\mu^-)| < 2.5$$

$$P_T(b), P_T(\bar{b}) > 20 \text{ GeV}, P_T(\mu^+), P_T(\mu^-) > 5 \text{ GeV},$$

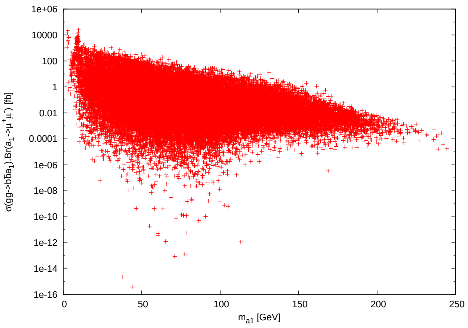


Figure: The inclusive cross section as a function of m_{a1}.

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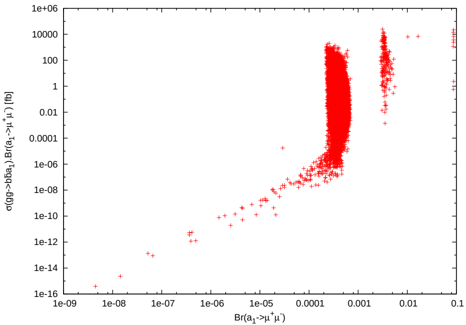

Figure: The inclusive cross section as a function of $Br(a_1 \to \mu^+\mu^-)$.

Please, notice that the mass region below the $\mu^+\mu^-$ threshold is severly constrained from meson decays, muon g-2 and so forth (S. Andreas et al, 2010).

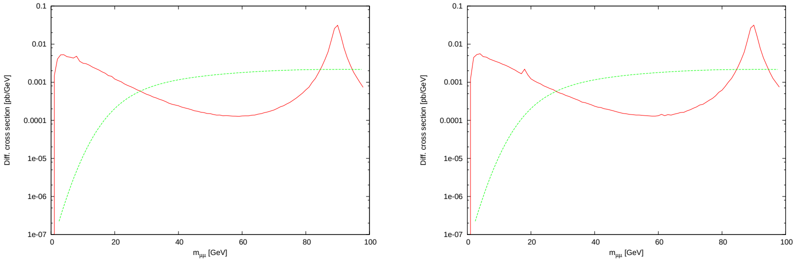

Figure: The differential cross section as a function of $m_{\mu^+\mu^-}$ for m_{a1} $=$9.76 GeV and 19.98 GeV for the signal and irreducible backgrounds (red line) and $t\bar{t}$ backgrounds (green line).

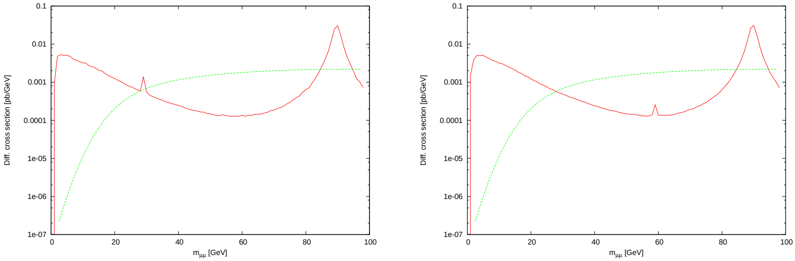

Figure: The differential cross section as a function of $m_{\mu^+\mu^-}$ for m_{a1} =30.67 GeV and 60.51 GeV for the signal and irreducible backgrounds (red line) and $t\bar{t}$ backgrounds (green line).

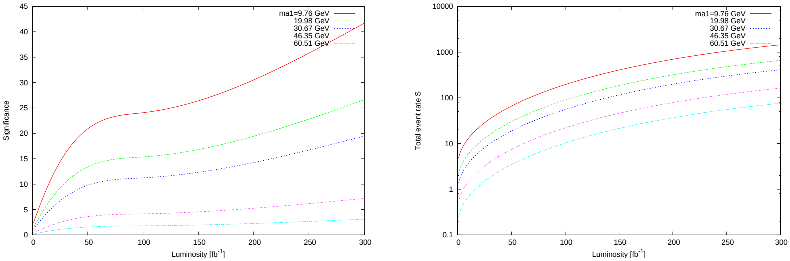

Figure: The significance $S/\sqrt{B}$ (left) and total event rate S (right) of the $q\bar{q}, gg \to b\bar{b}a_1 \to b\bar{b}\mu^+\mu^-$ signal as a function of the integrated luminosity.

Conclusion

- The $\gamma\gamma$ decay mode of the CP-odd Higgs can be dominant in the NMSSM unlike the MSSM due to introducing the singlet scalar superfield but it suffers from large irreducible backgrounds so this channel is unfeasible.
- The $\tau^+\tau^-$ decay mode of a_1 is a promising channel to discover the light CP-odd Higgs of the NMSSM at the LHC with mass $< M_Z$.
- The $\mu^+\mu^-$ decay mode has clean signature and this channel is important to detect a_1 with mass less than 60 GeV.
- Our results are a step forward in:
  - Establishing the No Lose Theorem by direct detection of a_1 rather than looking for the decay $h_{1,2} \longrightarrow a_1 a_1$.
  - Distinguishing between the MSSM Higgs sector and the NMSSM Higgs sector (More-to-Gain Theorem).