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

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Nov 25, 2010

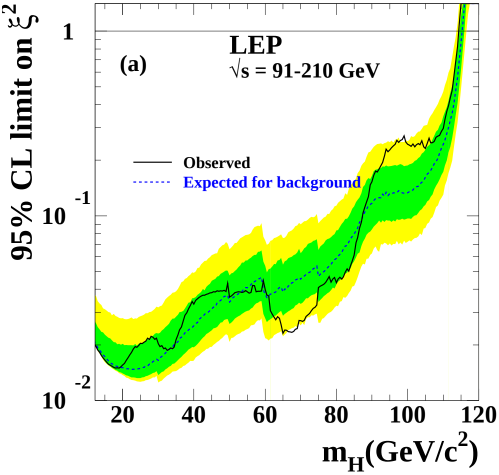
Outline

- Next to Minimal Supersymmetric Standard Model (NMSSM).
- Higgs Sector of the NMSSM.
- Tools.
- The lightest CP-odd Higgs production in association with $b\bar{b}$.
- Di-photon Decay Mode and Di-photon backgrounds.
- Di-tau Decay Mode.
- Conclusion and Outlook.

- 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 $h_1 \longrightarrow a_1 a_1$ 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

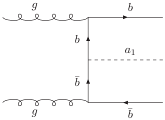
U. Ellwanger & C. Hugonie, NMSSMTools
http://www.th.u-psud.fr/NMHDECAY/nmssmtools.html

- 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 background and MadGraph for the reducible background.
- 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:

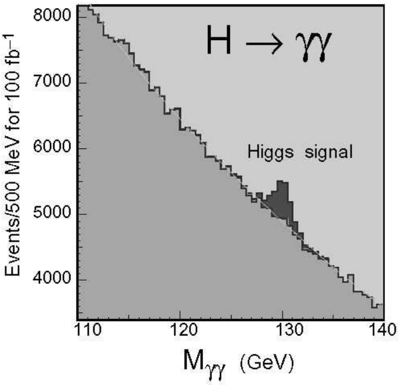


- This production mode can be dominant at large $tan\beta$. We chose $gg \longrightarrow b\bar{b}a_1$ because $gg \longrightarrow a_1$ is unfeasible due to large backgrounds.
- It gives a well studied signature by ATLAS and CMS.
- b-tagging can be used to reject light jets.

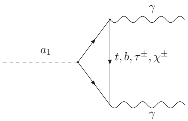
Di-Photon Decay Mode

- 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.



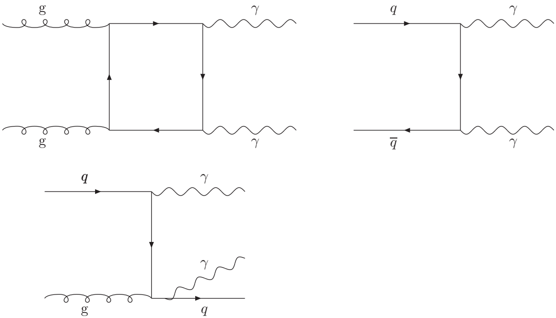
- Feynman diagram for $a_1\gamma\gamma$ is:



- 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.

Di-photon backgrounds

- Irreducible backgrounds:



- Reducible backgrounds:
  Jets (hadrons) like π^0s fake photons.

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

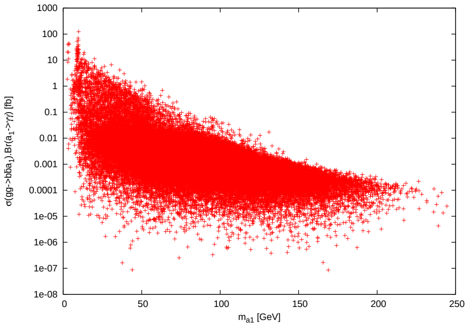
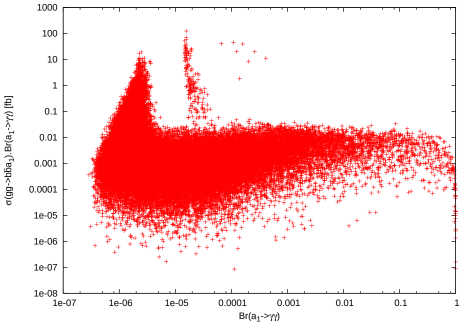


Figure: The inclusive cross section as a function of $Br(a_1 \to \gamma\gamma)$.



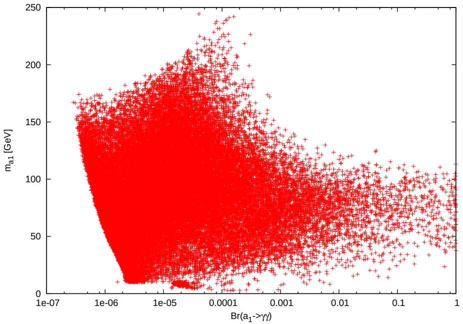


Figure: m_{a1} as a function in $Br(a_1 \to \gamma\gamma)$.

We have used the following cuts for our analysis:

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

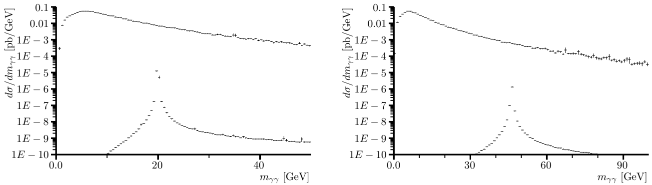


Figure: The differential cross section as a function in $m_{\gamma\gamma}$ for m_{a1} =19.98 and 46.35 GeV for the signal only and for the signal and backgrounds together.

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):

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

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

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

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

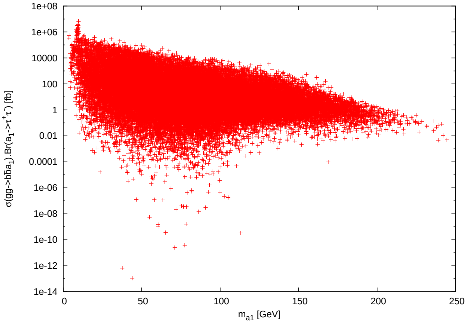


Figure: The inclusive cross section as a function of m_{a1}.

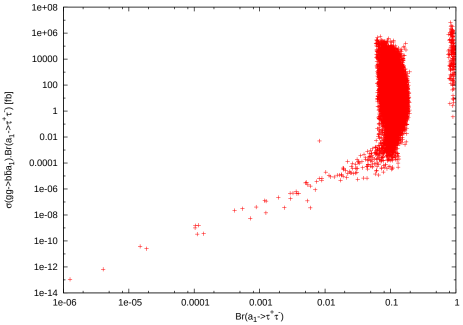


Figure: The inclusive cross section as a function in $Br(a_1 \to \tau^+\tau^-)$.

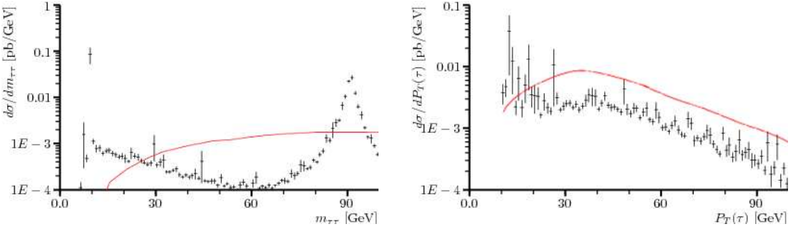


Figure: The differential cross section as a function of $m_{\tau^+\tau^-}$ for m_{a1} =9.76 GeV for the signal and irreducible and $t\bar{t}$ backgrounds (left) and as a function of the transverse momentum (right).

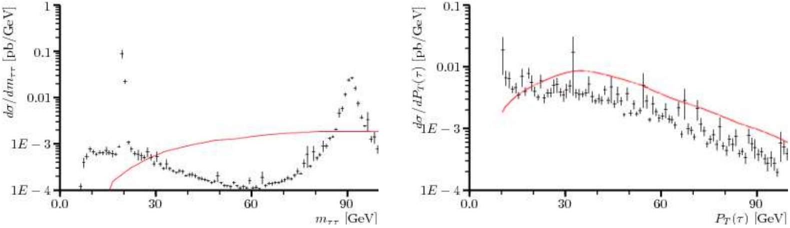


Figure: The differential cross section as a function of $m_{\tau^+\tau^-}$ for m_{a1} =19.98 GeV for the signal and irreducible and $t\bar{t}$ backgrounds (left) and as a function of the transverse momentum (right).

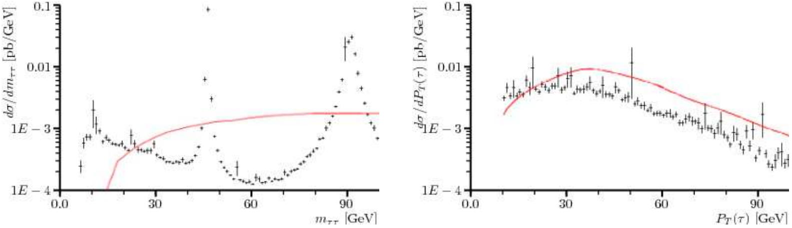


Figure: The differential cross section as a function in $m_{\tau^+\tau^-}$ for m_{a1} =46.35 GeV for the signal and irreducible and $t\bar{t}$ backgrounds (left) and as a function of the transverse momentum (right).

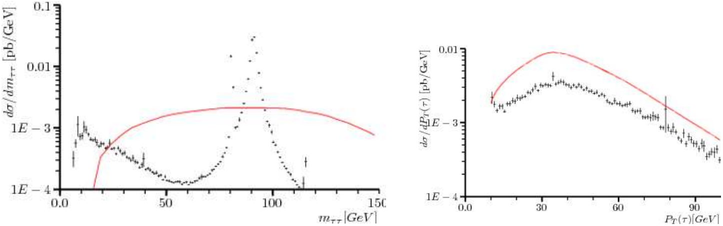


Figure: The differential cross section as a function of $m_{\tau^+\tau^-}$ for m_{a1} =80.9 GeV for the signal and irreducible and $t\bar{t}$ backgrounds (left) and as a function of the transverse momentum (right).

Conclusion and Outlook

- 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.
- The inclusive cross section of $gg \to b\bar{b}a_1.Br(a_1 \to \gamma\gamma)$ can reach 100 fb 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.
- Our result is a benchmark for:
  - Confirming physics beyond the SM.
  - Supporting the No Lose Theorem at low CP-odd Higgs mass.
  - Distinguishing between the MSSM Higgs sector and the NMSSM Higgs sector (More-to-Gain Theorem).
- $\mu^+\mu^-$ decay mode is in progress.