Study of a light NMSSM CP-odd Higgs produced via bottom-quark annihilation in the di-photon channel at the LHC

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Outline

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- Supersymmetry (SUSY)
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Standard Model (SM)

- The SM gives an excellent description for particle physics phenomena and nearly all its predictions have been confirmed by experiments with high accuracy.
- The SM of particle physics is now completed but it is a low energy effective theory of certain form of more fundamental theory.

SM shortcomings

- It does not incorporate gravity.
- No good dark matter candidate.
- It can not explain massive neutrinos.
- Due to these shortcomings, we need physics beyond the SM.

Supersymmetry (SUSY)

- SUSY is an attractive framework for beyond the Standard Model physics
- The symmetry which relates bosons with fermions.
  $Q|fermion >=$ boson , $Q|boson >=$ fermion.
- Such a symmetry predicts the existence of supersymmetric particles (sleptons, squarks, charginos, neurlainos)
- Due to SUSY breaking, the supersymmetric particles have masses much greater than that of their ordinary counterparts.
- In SUSY, two Higgs doublets are required:
  1- To give masses for up-type and down type quarks as well as leptons. 2- To keep the model anomally free.
- The running coupling constants unify at Grand Unification Scale.
- No sign of SUSY yet.

Minimal Supersymmetric Standard Model (MSSM)

- To keep the elegant features of SM and solve its shortcomings: introduce 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) imposes no limits on μ but for phenomenological reasons $\mu \sim$ 100-1000 GeV.

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

- Little hierarchy problem:
  Assuming CP-conservation, the mass of the lightest CP-even Higgs boson of the MSSM at tree level

$$m_{h_1}^2 \lesssim m_Z^2 \cos^2(2\beta)$$

The upper limit for the lightest CP-even Higgs mass at the tree level is $m_Z \approx 91$ GeV. So large radiative corrections from massive superparticles (stop, gluino) should be included to lift up Higgs mass up to 125 GeV.

Next to Minimal Supersymmetric Standard Model (NMSSM)

- The NMSSM extends the MSSM by the introduction of one singlet superfield,S.

$$W_{NMSSM} = W_{MSSM} + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3$$

- Solve μ problem:
  In the NMSSM, the effective μ-term is generated by introducing a new singlet superfield.
- Once the scalar component of the singlet gets a VEV then μ autmatically will be of order of electroweak scale, $\mu_{eff} = \lambda \langle S \rangle$.

Next to Minimal Supersymmetric Standard Model

- Solve little Hierarchy problem by:
- Assuming CP-conservation in the NMSSM, the upper mass bound for the SM-like Higgs boson at tree level

$$m_h^2 \approx m_Z^2 \cos^2(2\beta) + \frac{\lambda^2 v^2}{2} \sin^2(2\beta).$$

a) Pushing up the SM-like Higgs mass by an extra term proportional to λ.
b) Non standard Higgs decays are possible, e.g. $h \rightarrow 2a$.

Next to Minimal Supersymmetric Standard Model

- Higgs singlets are existence in Superstring theories.
- Richer Phenomenology than MSSM where the spectrum of NMSSM compared to MSSM contains:
  - One more scalar Higgs.
  - One more pseudoscalar Higgs.
  - 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 which also preferred by electroweak precision data.

Higgs Sector of the NMSSM

- the Higgs sector of the NMSSM at (tree level) is described by:

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

- We use NMSSMTools to compute the masses and couplings of Higgs and sparticle states, taking into account theoretical and experimental constraints.
- We do a random scan over the following ranges:

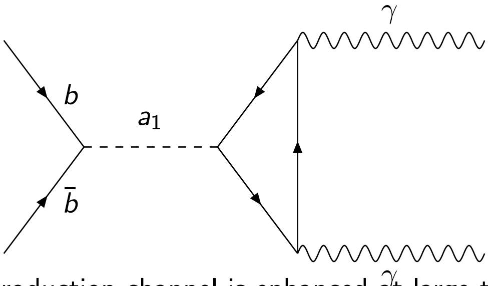
$$0.001 \le \lambda \le 0.7, \quad |A_\lambda| \le 2000 \text{ GeV}, \quad |\kappa| \le 0.65,$$
$$|A_\kappa| \le 5 \text{ GeV}, \quad 1.6 \le \tan\beta \le 60, \quad 100 \le \mu_{\rm eff} \le 1000 \text{ GeV}.$$

Higgs Sector of the NMSSM

- The soft SUSY breaking masses and couplings, to which the masses of the Higgs bosons are not so sensitive, are fixed in the scan as follows:
  Third generation squarks and sleptons = 3 TeV
  Trilinear soft SUSY breaking couplings = 3 TeV
  Gaugino masses $M_1 = 0.5$ TeV, $M_2 = 1$ TeV and $M_3 = 3$ TeV.
- For the successful points we calculate the cross section by using CalcHEP.

Higgs production via bottom-quark annihilation in the di-photon channel at the LHC

- Feynman diagram for this production:

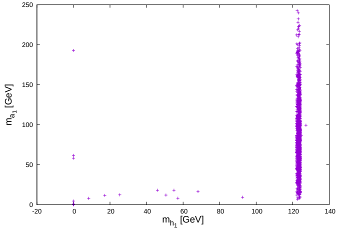


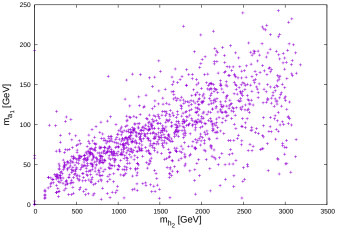
- This production channel is enhanced at large $\tan\beta$.
- The initial bottom quarks reside in the proton sea, and the bottom-quark sea is generated from the splitting of gluons into nearly-collinear bottom-antibottom pairs.

Higgs production via bottom-quark annihilation in the di-photon channel at the LHC

- Presence of the two photons in the final state provides a very clean signature for probing a_1 properties such as its mass.
- In the NMSSM it can reach branching ratio of O(1).
- The Higgs-$\gamma\gamma$-coupling is mediated by triangle loops of all charged particles. CP-odd Higgs(es) 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.

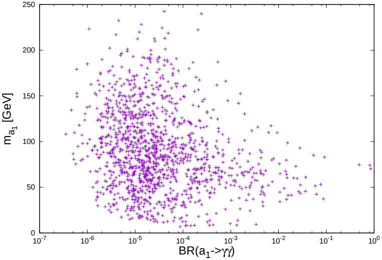
Results and Discussions





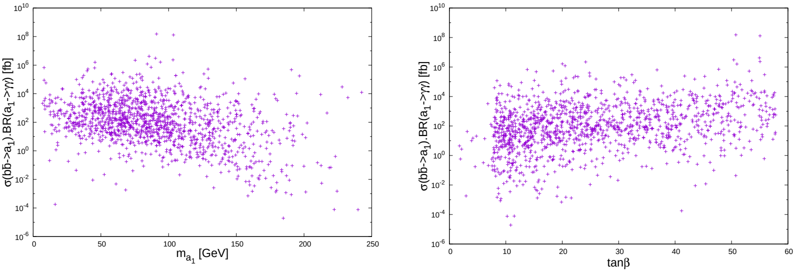
- In our parameter space the h_1 is mostly the SM-like Higgs with masses between 122 and 128 GeV.
- The h_1 can also be a singlet-like with masses less than that of the SM Higgs boson in small area of parameter space.
- The h_2 can play the role of the SM-like Higgs in a small region of the parameter space.
- The smaller m_{a_1} the smaller m_{h_2}.

Results and Discussions



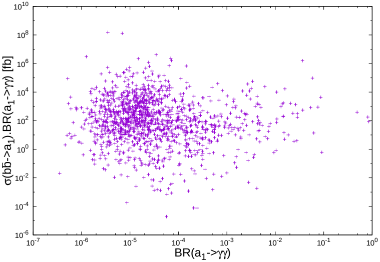
- There is a certain region of the NMSSM parameter space in which the $BR(a_1 \to \gamma\gamma)$ is dominant, reaching up to 100%.
- If a_1 has only a singlet component, it only couples to $\gamma\gamma$ through charginos in the loop and so its branching ratio to $\gamma\gamma$ will be O(1).

Results and Discussions



- The production rates decreases by increasing the a_1 mass.
- The production rates reach its maximum of 10^8 fb at large values of $\tan\beta$.

Results and Discussions



- The enhancement of the BR($a_1 \to \gamma\gamma$) is a characteristic feature of the NMSSM compared with other SUSY models.
- Unfortunately, this region does not correspond to the one that maximizes the inclusive production rates because the production channel $b\bar{b} \to a_1$ is suppressed in contrast to the decay channel $a_1 \to \gamma\gamma$ which is enhanced.

Conclusion

- The $\gamma\gamma$ decay channel of the CP-odd Higgs can be enhanced in the NMSSM, reaching up to 100%, unlike the MSSM due to introducing the singlet scalar superfield.
- The production rates of process $b\bar{b} \to a_1$ followed by the decay $a_1 \to \gamma\gamma$ are quite large, reaching up to 10^8 fb at large values of tanβ. This may help extracting the a_1 signals at least at high-Luminosities of the LHC although the details of signal-to-background analysis is required to make the final conclusion.
- The a_1 production through bottom-quark fusion in the di-photon final state is enhanced at large values of tanβ, and can be exploited to measure both the a_1-to-bottom-antibottom $a_1 b\bar{b}$ coupling and the effective a_1-to-diphoton coupling at the LHC.

Thank you