A light pseudocalar and two scalar Higgses in the NMSSM

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SUSY around the corner?

We have been eager for new physics at the LHC, but bewildered by

endless nightmare in hep-ex arXiv

"No significant deviation from the expected backgrounds is observed, and a limit is set ..."

- Theoretically, SUSY has been the most promising candidate of new physics beyond SM since it can protect the theory from being destabilized by huge radiative corrections.
- As its minimal form, the MSSM is now undergoing severe judgment due to the experimental null result, the lower limit is well above ~ 1 TeV for $m_{\tilde{g}}$ and $m_{\tilde{q}}$.
- In addition, substantial loop corrections are required to obtain the 125 GeV Higgs, in particular, heavy top squarks and/or their maximal mixing,

$$m_h^2 \sim m_Z^2 \cos^2 2\beta + \Delta m_h^2 \left(m_t,\, m_{\tilde{t}},\, X_t\right) ,$$

which leads to $m_{\tilde{t}} \gtrsim 4$ TeV for negligible mixing, while $m_{\tilde{t}} \lesssim 1$ TeV for maximal mixing $X_t \sim \sqrt{6} m_{\tilde{t}}$. Then, the $m_{H_u}^2$ needs to be tuned $\lesssim \mathcal{O}(1\%)$ to achieve the correct EWSB scale. (Hall, *et al*, arXiv:1112.2703)

SUSY around the corner?

- In reality, the MSSM is not the end of story. There are many other theoretical possibilities, which include non-minimal extensions of the MSSM such as NMSSM that will be focused here.[1]
- Aside from the detailed discussion on the theoretical possibilities, one can ask a question in the phenomenological point of view,

"Do the searches exhaust all the possible SUSY processes?"

... *No, even the known tree-level processes.*

[1] For a simple discussion, it is assumed to be the $\mathbb{Z}_3$-invariant NMSSM.

Neutralino-chargino process

- Most of sparticle decay processes include the neutralinos ($\widetilde{\chi}^0_{2,\,3}$) and/or charginos ($\widetilde{\chi}^\pm_1$), which eventually end up with the LSP.
- Although possessing quite small cross sections in the hadron collider, the neutralinos and charginos can also be produced directly and the final states are very clean multi-lepton $+$ missing energy.

Possible decay channels with leptonic final states in the MSSM are

$$\widetilde{\chi}^0_2 \to \tilde{\ell}^{(*)}\ell,\ Z^{(*)}\widetilde{\chi}^0_1,\ h/H/A\widetilde{\chi}^0_1,\ \cdots \to \ell^+\ell^-\widetilde{\chi}^0_1,$$
$$\widetilde{\chi}^\pm_1 \to \tilde{\ell}^{(*)}\nu,\ W^{(*)}\widetilde{\chi}^0_1,\ H^\pm\widetilde{\chi}^0_1,\ \cdots \to \ell^\pm\nu\widetilde{\chi}^0_1.$$

The branching ratio of each channel depends on the model parameters, in particular, the compositions of neutralinos and charginos for M_1, M_2, and μ, as well as the the mass hierarchy. For instance, $\widetilde{\chi}^0_2 \to Z\widetilde{\chi}^0_1$ is suppressed if $\widetilde{\chi}^0_{1,\,2}$ are practically gaugino-like since the couplings of Z-$\widetilde{\chi}^0_i$-$\widetilde{\chi}^0_j$ arise only through their higgsino components. And, if $m_{\widetilde{\chi}^0_2} - m_{\widetilde{\chi}^0_1} < m_Z$, it receives the three-body suppression.

Neutralino-chargino to Higgs process

An interesting channel is $\widetilde{\chi}_2^0 \to h/H/A\widetilde{\chi}_1^0$, which has not been searched yet. If discovered, it can serve another Higgs production mode, and possibly, reveal the non-standard Higgs bosons as well as the weakly interacting sparticles.

- This Higgs channel is assumed to have vanishing branching ratio in the recent ATLAS and CMS search results on the direct $\widetilde{\chi}_2^0\widetilde{\chi}_1^\pm$ production.

Since the Higgs boson has been found, it would be worth including the Higgs channel in the analysis. But, for the analysis to be applicable, at least one thing has to be assumed; Which Higgs?

Neutralino-chargino to Higgs process: MSSM

- In the conventional decoupling limit ($m_A \gg m_Z$) in the MSSM, the lightest Higgs is considered as SM-like one.
  - If $\widetilde{\chi}^0_{1,\,2}$ are gaugino-like and when the GUT relation for gaugino masses is assumed, $m_{\widetilde{\chi}^0_2} \gtrsim 250$ GeV to open the channel.
  - The heavy Higgses are difficult to be produced by $\widetilde{\chi}^0_2$, but can be produced by heavy neutralinos if $|\mu| \gg M_1,\ M_2$ so that $m_{\widetilde{\chi}^0_3} \gg m_{\widetilde{\chi}^0_2}$.
- It is possible to consider the heavy Higgs as SM-like. Then, all the Higgs bosons can be light since low m_A value is preferred ($110\ \mathrm{GeV} \lesssim m_A \lesssim 140\ \mathrm{GeV}$). Heinemeyer, *et al*, arXiv:1112.3026, Drees, arXiv:1210.6507, Bechtle, *et al*, arXiv:1211.1955
  - All the Higgses can appear in the light neutralino decays, and the charged Higgs can be produced by the chargino unless kinematically suppressed.

Neutralino-chargino to Higgs process: NMSSM

In the case of NMSSM, there are 5 neutralinos with the inclusion of a singlino, and 7 physical Higgs bosons, H_1, H_2, H_3, A_1, A_2, and $H^{\pm}$. The distinguishable features of NMSSM are possibility of the singlino-like LSP and the light pseudoscalar boson. The pseudoscalar is light for scenarios with either the Peccei-Quinn limit ($\kappa \to 0$) or the R-symmetry limit ($A_\kappa,\ A_\lambda \to 0$), and then the pseudoscalar is dominantly singlet-like in the parameter space where $v_s \gg v \sin 2\beta$. If $m_{A_1} < 2m_b$, $A_1 \to \tau^+\tau^-$ or $\mu^+\mu^-$ can be significantly large, often dominant. Moreover, $H_j \to A_1 A_1$ channel opens.

- According to the neutralino mass hierarchy and their compositions, $\widetilde{\chi}^0_j \to A_1 \widetilde{\chi}^0_1$ and $\widetilde{\chi}^0_j \to H_1 \widetilde{\chi}^0_1 \to A_1 A_1 \widetilde{\chi}^0_1$ will be allowed.
- If $\mu_{\rm eff} = \lambda v_s$ is small so that $\widetilde{\chi}^0_2$ and $\widetilde{\chi}^0_3$ are quite degenerate in mass, and $m_{\widetilde{\chi}^0_1}$ is a admixture of singlino-Higgsino, only $\widetilde{\chi}^0_{2,\,3} \to A_1 \widetilde{\chi}^0_1$ and $\widetilde{\chi}^0_3 \to A_1 \widetilde{\chi}^0_2$ will be allowed. Cheung, Hou, arXiv:0809.1122

Neutralino-chargino to Higgs process: NMSSM

$m_{A_1} < 2m_\tau$

When $m_{A_1} < 2m_\tau$, $A_1 \to \mu^+\mu^-$ is dominant among leptonic final states. Then, the final state will contain more muons than electrons through the processes of

$$\widetilde{\chi}_3^0 + \widetilde{\chi}_1^\pm \to 2A_1\widetilde{\chi}_2^0 + W^*\chi_1^0 \to 2\mu 2A_1^0\chi_1^0 + \ell\nu\chi_1^0 \to 4\mu + \ell + \not{E}_{\mathrm{T}},$$
$$\widetilde{\chi}_2^0 + \widetilde{\chi}_1^\pm \to 2A_1\widetilde{\chi}_1^0 + W^*\chi_1^0 \to 2\mu + \ell + \not{E}_{\mathrm{T}},$$

where $\ell = e,\ \mu$. However, this process seems to be difficult to realized because

- $H \to A_1A_1 \to \mu^+\mu^-\mu^+\mu^-$ is allowed. In particular, if H is singlet-like, this is the dominant decay channel and it has very stringent upper limit set by CMS, arXiv:1210.7619, where a model-independent bound on $\sigma(pp \to H \to 2A_1 \to 4\mu)$ has been considered for $86\ \mathrm{GeV} < m_H < 150\ \mathrm{GeV}$.

Neutralino-chargino to Higgs process: NMSSM

$2m_\tau < m_{A_1} < 2m_b$

When $A_1 \to \tau^+\tau^-$ is dominant, while $A_1 \to \mu^+\mu^-$ is sub-dominant (or negligible), one has to cope with at least two things,

(I) LEP constraints, for instance, on the process $e^+e^- \to HZ \to AAZ \to 4\tau + Z$,

(II) Isolated lepton identification and tau-jet reconstruction.

The LEP constraints can be evaded if the lightest scalar boson (H_1) is predominantly singlet-like. This will be discussed later shortly. The second thing is generic problem in the collider experiment since the taus sharing the same parent pseudoscalar are nearly collinear,[2] for example,

$$\Delta R_{\tau^+\tau^-} \sim \frac{4m_{\widetilde{\chi}_2^0} m_{A_1}}{m^2_{\widetilde{\chi}_2^0} - m^2_{\widetilde{\chi}_1^0}}$$

in $\widetilde{\chi}_2^0 \to A_1 \widetilde{\chi}_1^0 \to \tau^+\tau^-\widetilde{\chi}_1^0$ process, and the visible leptons can be soft due to the energy carried away by neutrino(s) in the tau decays.

[2] The decay products of the tau are also collinear to the tau direction.

Neutralino-chargino to Higgs process: NMSSM

Lepton isolation

In the ATLAS and CMS searches, the procedure of choosing the isolated lepton is

(i) Define a cone of size R around the candidate lepton (ℓ),

(ii) Calculate $I_{\rm rel}$ defined as

$$I_{\rm rel} \equiv \frac{\sum_t p_{\rm T}^t}{p_{\rm T}^\ell},$$

where t are the tracks excluding the lepton candidate,

(iii) If $I_{\rm rel} > I_{\rm rel}^{\rm min}$, the candidate is regarded as the isolated lepton.

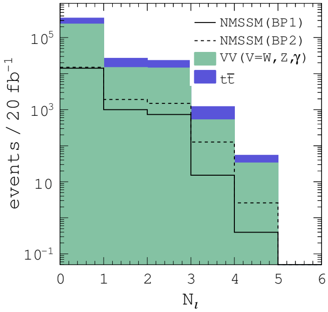
The criterion becomes tighter as R is larger and $I_{\rm rel}^{\rm max}$ is smaller (*tracker relative isolation*). For instance, the CMS analysis selected $R = 0.3$ and $I_{\rm rel}^{\rm max} = 0.15$. However, these chosen values are optimal for SM processes with W/Z (See CMS, arXiv:1206.4071), but not suitable at all for the light pseudoscalar process. Our simulation found that the SUSY signal is almost hidden in the backgrounds since the number of isolated lepton becomes small[3] when using the same criterion as that adopted by the CMS.

[3] Typically 1 or 2 since there is at least one lepton from $\widetilde{\chi}_1^\pm$.

Neutralino-chargino to Higgs process: NMSSM

Lepton isolation

One must tune the parameters or introduce a new criterion scheme for the isolated lepton to find the leptonically decaying light pseudoscalar. We choose rather loose criterion for $R = 0.1$ and $I_{\rm rel}^{\rm min} = 0.1$, while removing the fake leptons by kinematic cuts, $m_{\ell\ell}^{\rm OSSF}$ and $\Delta R_{\ell,\,\rm jet}$.

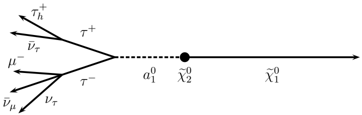


BP1: $m_{A_1} = 3.6, m_{\widetilde{\chi}_3^0} = 143, m_{\widetilde{\chi}_2^0} = 136, m_{\widetilde{\chi}_1^0} = 87$ GeV,
BP2: $m_{A_1} = 7.6, m_{\widetilde{\chi}_3^0} = 139, m_{\widetilde{\chi}_2^0} = 125, m_{\widetilde{\chi}_1^0} = 64$ GeV.
Herwig++ and Delphes used, the detail of model parameters will be given later.

Neutralino-chargino to Higgs process: NMSSM

Selection cuts

The conventional kinematic variables for finding the signal are $m_{\ell^+\ell^-}$, $M_{\rm T}$, and $\not{E}_{\rm T}$. These all are useful when $m_{\widetilde{\chi}_2^0} - m_{\widetilde{\chi}_1^0}$ is rather big, so that the leptons are hard enough, and the missing energy is large because of the LSP.

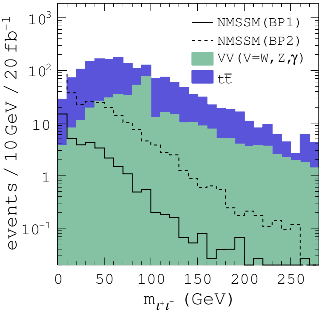


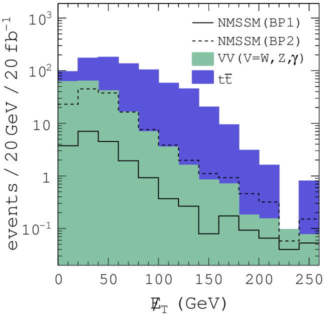
A schematic picture of the signal process

However, the leptons can be soft and the LSP momentum vector can be partially canceled by the neutrino momenta from taus in the $\widetilde{\chi} \to A_1$ process. All the kinematic variables above are likely to lose their efficiency.

Neutralino-chargino to Higgs process: NMSSM

Selection cuts



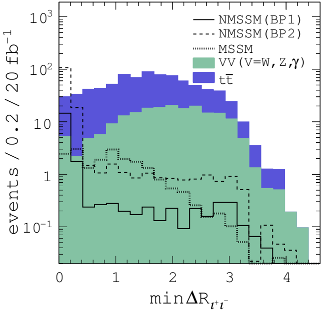


Both the $m_{\ell^+\ell^-}$ and M_T should serve upper cuts instead of lower ones and the $\not{E}_T$ cut value should be rather mild. The M_{T2} for the $\ell^+\ell^- + \not{E}_T$ system can be used since it has a definite endpoint at m_W for WW and $t\bar{t}$, while does not have any physical correlation in the signal process.

Neutralino-chargino to Higgs process: NMSSM

Selection cuts

The most important cut variables is the angular separation $\Delta R_{\ell+\ell-}$ for an OSSF lepton pair. For leptons more than two, one can choose the minimum among all possible $\Delta R_{\ell+\ell-}$ values and set an upper cut.



The MSSM signal distribution with the same final state, $\tilde{\chi}_2^0 \to \tau^\pm \tilde{\tau}^\mp \to \tau^+\tau^-\chi_1^0$ for $m_\tau \approx (m_{\tilde{\chi}_2^0} + m_{\tilde{\chi}_1^0})/2$, is shown for a comparison.

Singlet Higgs process in the NMSSM

The $\widetilde{\chi}^0_{2,3}\widetilde{\chi}^\pm_1$ process is not suitable for measuring the pseudoscalar mass. If there is one singlet-like scalar, $\mathcal{B}(H_i \to A_1 A_1)$ can be predominant. And because of its singlet nature, it can be even lighter than the SM-like doublet Higgs with mass of 125 GeV. For the scalar Higgses, there are important experimental constraints,

- Since H_2 is SM-like, it receives all the constraints to be compatible with the discovered 125 GeV Higgs boson. In particular, the non-standard channel $H_2 \to A_1 A_1$ should be suppressed enough.
- The main constraints on $H_1 \to A_1 A_1 \to 2\tau^+ 2\tau^-$ come from the LEP search results, in particular, the latest ALEPH analysis (arXiv:1003.0705) on $e^+e^- \to HZ \to AAZ \to 4\tau + 2\ell$.
- $H_1 \to A_1 A_1 \to 2\mu^+ 2\mu^-$ is tightly constrained by recent CMS analysis (arXiv:1210.7619).
- Tevatron search limits are not stringent for $2m_\tau < m_{A_1} < 2m_b$.

For the light pseudoscalar Higgs, there are constraints from the low-energy searches, for example, $\Upsilon(nS) \to \gamma A_1$ in BaBar, arXiv:1210.0287.

Singlet Higgs process in the NMSSM

We performed the parameter scan using NMSSMTools for finding the region survived from the constraints including $b \to s\gamma$, $B_s \to \mu^+\mu^-$, $(g-2)_\mu$, $\widetilde{\chi}_1^0$ relic abundance and spin-independent $\widetilde{\chi}_1^0 - N$ cross section limit (XENON100) as well as the collider constraints in the previous slide.

- The scan result will be appeared soon (in progress with D. G. Cerdeño and M. Peiró).

For the present collider study, we choose two benchmark points with model parameters,

- **BP1**: $\lambda = 0.285$, $\kappa = 0.1165$, $A_{\lambda,\,\kappa} = 670,\ 14$ GeV, $M_{1,\,2,\,3} = 560,\ 1200,\ 1980$ GeV, $A_t = 1.8$ TeV,
- **BP2**: $\lambda = 0.286$, $\kappa = 0.0844$, $A_{\lambda,\,\kappa} = 820,\ 14.35$ GeV, $M_{1,\,2,\,3} = 240,\ 500,\ 1380$ GeV, $A_t = 1.3$ TeV,

and $M_{\widetilde{L}} = M_{\widetilde{e}^c} = 300$ GeV, $M_{\widetilde{Q}} = M_{\widetilde{u}^c} = M_{\widetilde{d}^c} = 1$ TeV, $\mu_{\rm eff} = 123.5$ GeV, $A_{\tau,\,b} = -1.6,\ 1$ TeV for both. Then, the masses are:

- **BP1**: $m_{A_1} = 3.6$, $m_{H_1,\,H_2} = 98,\ 126$, $m_{\widetilde{\chi}_1^0,\,\widetilde{\chi}_2^0,\,\widetilde{\chi}_3^0} = 87,\ 136,\ 143$, $m_{\widetilde{\chi}_1^\pm} = 124$ GeV,
- **BP2**: $m_{A_1} = 7.6$, $m_{H_1,\,H_2} = 62,\ 126$, $m_{\widetilde{\chi}_1^0,\,\widetilde{\chi}_2^0,\,\widetilde{\chi}_3^0} = 64,\ 125,\ 139$, $m_{\widetilde{\chi}_1^\pm} = 118$ GeV.

Singlet Higgs process in the NMSSM

The search strategy for the light pseudoscalar and the singlet-like Higgs is the similar as that for the $\widetilde{\chi}_{2,\,3}\widetilde{\chi}_1^{\pm}$ process. The search channel of interest is

$$H_{1,\,2} \to A_1 A_1 \to \tau^+\tau^-\tau^+\tau^- \to 2\ell^+ + 2\ell^- + \not{E}_{\mathrm{T}},$$

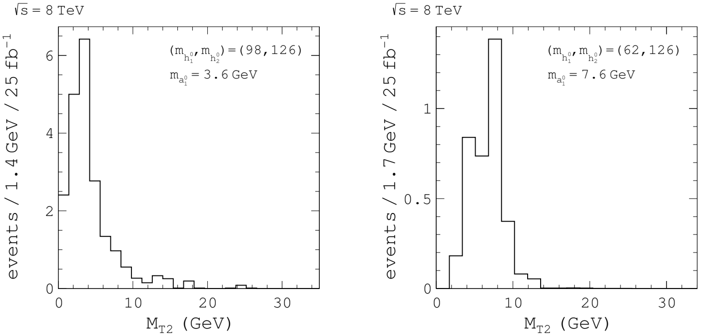
where $\ell = e$, μ, τ_h. Now the angular separation is

$$\Delta R_{\tau^+\tau^-} \sim \frac{4m_{A_1}}{m_H}.$$

Direct mass reconstruction for A_1 is not available, but one can employ the M_{T2} since

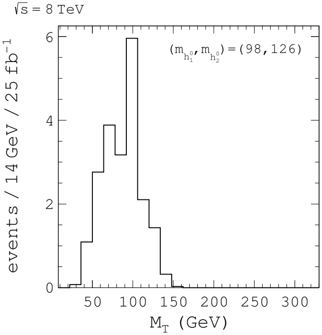
- The leptons sharing the same parent A_1 are nearly collinear. Then, the two leptons can be regarded as one visible particle system.
- The neutrinos are the same as above and their invariant mass is ~ 0.
- The decay system is now depicted as two visible $+$ two invisible particles, then the M_{T2} is calculable.
- The M_{T2} distribution is bounded above by the parent particle mass, in this case, m_{A_1}.

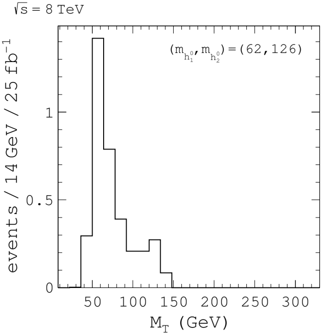
Singlet Higgs process in the NMSSM



The edge structure is slightly spoiled by the incorrect lepton identification and the detector resolution *etc*, but the peak position clearly points to m_{A_1}. This also can be used for an useful event selection cut for the search.

Singlet Higgs process in the NMSSM





The light singlet-like Higgs boson mass m_{H_1} can be estimated by the transverse mass of total system,

$$M_{\mathrm{T}}^2 = \left(\sqrt{m_{\mathcal{V}}^2 + |\mathbf{p}_{\mathrm{T}}^{\mathcal{V}}|^2} + \not{E}_{\mathrm{T}} \right)^2 - |\mathbf{p}_{\mathrm{T}}^{\mathcal{V}} + \not{\mathbf{p}}_{\mathrm{T}}|^2,$$

where $\mathcal{V} = \ell^+\ell^-\ell^+\ell^-$ system. There is a small contribution from $H_2 \to A_1 A_1$.

Conclusions

- We can say that SUSY is around the corner only when great efforts have been paid to search and analyze all the possible signal channels.
- Since at least one Higgs boson is no more hypothetical but real, it is reasonable to consider the SUSY processes involving the Higgs bosons, and it might lead us to discover non-standard new bosons such as a light pseudoscalar.
- A good example is the decay process of neutralinos, which are sensitive to the model parameters but has been conventionally assumed to be predominantly EW gauginos in the ATLAS and CMS analyses. The light pseudoscalar can be produced by the process and needs a dedicated study including the parameter tunes for reconstructed collider objects.
- Measuring the light pseudoscalar can be performed in the Higgs process using the M_{T2}, and the light singlet scalar can be studied through the decay process into the light pseudoscalar in the present and the future LHC experiments.