A light NMSSM pseudoscalar at the LHC

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Busan particle physics workshop

5 December 2014

SUSY around the corner?

Before the LHC, we expected that SUSY would be discovered in the early stage *before finding Higgs*, *"SUSY is just around the corner,"* but

Endless nightmare in hep-ex arXiv

"No significant deviation from the expected backgrounds is observed, and a limit is set $\cdots$"

The SUSY models are now undergoing severe judgment due to the experimental null result.

- $m_{\tilde{g}} \lesssim 1.2$ TeV,
- $m_{\tilde{q}_{1,2}} \lesssim 850$ GeV,
- $m_{\tilde{t}_1}, m_{\tilde{b}_1} \lesssim 620$–$640$ GeV excluded for simplified SUSY models.
- Limits on $\tilde{\chi}^0/\tilde{\chi}^\pm$ are *model-dependent*, e.g.,
  - $m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm} \lesssim 700$ GeV for on-shell slepton-mediated channel,
  - $m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm} \lesssim 300$ GeV for W and h mediated channel are excluded.

Non-minimal SUSY?

History of `SOFTSUSY`

`SOFTSUSY` is the program to calculate the SUSY spectrum widely used by both theorists and experimentalists.

- The first version was released in the year 2000. Only MSSM included. (Allanach, hep-ph/0104145)
- From version `2.0` (2005), the accuracy upgraded by including full 2-loop MSSM RGEs.
- From version `3.0` (2009), *R*-parity violation has been included. (Allanach, *et al.*, 0903.1805)
- From version `3.4` (2013), NMSSM added. (Allanach, *et al.*, 1311.7659)

Other programs for SUSY have also included non-minimal SUSY models.

NMSSM

The NMSSM is the *simplest* extension of the MSSM with the inclusion of a gauge-singlet chiral supermultiplet S:

$$\begin{aligned} W_{\text{NMSSM}} &= W_{\text{Yukawa}} + (\mu + \lambda S) H_u \cdot H_d + \xi_F S + \frac{1}{2}\mu_S S^2 + \frac{1}{3}\kappa S^3, \\ -\mathcal{L}_{\text{soft}}^{\text{NMSSM}} &= -\mathcal{L}_{\text{soft}}^{\text{MSSM}} + m_S^2 |S|^2 + \Big(B\mu H_u \cdot H_d + \lambda A_\lambda H_u \cdot H_d S \\ &\qquad + \xi_S S + \frac{1}{2} B\mu_S S^2 + \frac{1}{3}\kappa A_\kappa S^3 + \text{c.c.} \Big). \end{aligned}$$

- The $\xi_F S$ term can be absorbed into the S^2 and S^3 terms by a shift in S.
- For phenomenological studies, we consider the simpler NMSSM with the constrained superpotential, $\mu = \mu_S = 0$, and vanishing parameters ξ_S, $B\mu$, $B\mu_S$.
- The NMSSM provides a simple solution to the μ-problem of the MSSM* by generating $\mu_{\text{eff}} = \lambda \langle S \rangle$.

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*Why $\mu \sim \mathcal{O}(m_{\text{soft}})$?

NMSSM Higgs

The Higgs sector has six parameters:

$$\lambda,\ \kappa,\ A_\lambda,\ A_\kappa,\ \tan\beta = v_u/v_d,\ \mu_{\rm eff}$$

with $5+2$ Higgs bosons, one scalar and one pseudoscalar in addition to MSSM Higgses. The tree-level mass matrix for the neutral Higgs states is

$$\begin{pmatrix} m_h^2 & (\lambda^2 v^2 - m_Z^2)\sin 2\beta\cos 2\beta & -\lambda v\left[(A_\lambda + 2\kappa v_s)\sin 2\beta - 2\mu_{\rm eff}\right] \\ & m_H^2 & -\lambda v(A_\lambda + 2\kappa v_s)\cos 2\beta \\ & & m_s^2 \end{pmatrix},$$

where

$$m_h^2 = m_Z^2\cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta, \quad m_H^2 = m_A^2 + (m_Z^2 - \lambda^2 v^2)\sin^2 2\beta$$

$$m_s^2 = \kappa v_s(A_\kappa + 4\kappa v_s) + \frac{\lambda v^2}{v_s} A_\lambda \sin\beta\cos\beta.$$

NMSSM Higgs

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

The Higgs boson can become heavier than the MSSM one. This is induced by the additional F-term contribution led by λ.

$$\begin{aligned} V_{\text{Higgs}} &= V_F + V_D + V_{\text{soft}}, \\ V_F &= V_F^{\text{MSSM}} + |\lambda(H_u^+ H_d^- - H_u^0 H_d^0)|^2, \\ V_D &= V_D^{\text{MSSM}}, \\ V_{\text{soft}} &= V_{\text{soft}}^{\text{MSSM}} + \left(\lambda A_\lambda (H_u^+ H_d^- - H_u^0 H_d^0) S + \frac{1}{3} \kappa A_\kappa S^3 + \text{c.c.} \right). \end{aligned}$$

- It can ameliorate the fine-tuning.
- The additional contribution can be large for large λ and small $\tan\beta$.
- To remain perturbative up to the GUT scale, $\lambda \lesssim 0.7$.

NMSSM Higgs

For a given mass matrix,

$$M_\phi^2 = \begin{pmatrix} M_{hh}^2 & M_{hs}^2 \\ M_{hs}^2 & M_{ss}^2 \end{pmatrix}$$

its trace equals to sum of eigenvalues, *i.e.*,

$$\mathrm{tr}\left(M_\phi^2\right) = M_{hh}^2 + M_{ss}^2 = m_h^2 + m_s^2.$$

Therefore, $s - h$ mixing can increase m_h^2 more for smaller m_s.

$$m_h = M_{hh} + \Delta_{\text{mix}}.$$

In the basis $s^M = \bar{g}_s h + \sqrt{1 - \bar{g}_s^2} s$, $M_{hh}^2 = (1 - \bar{g}_s^2) m_h^2 + \bar{g}_s^2 m_s^2$. Thus,

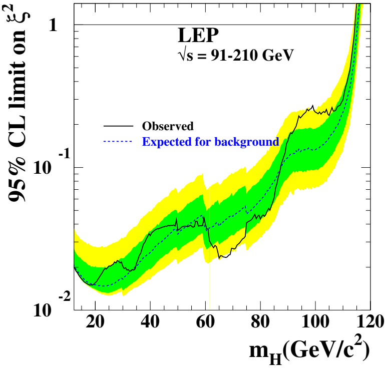
$$\Delta_{\text{mix}} = m_h - M_{hh} = m_h - \sqrt{m_h^2 - \bar{g}_s^2 (m_h^2 - m_s^2)} \approx \frac{\bar{g}_s^2}{2} \left(m_h - \frac{m_s^2}{m_h} \right) + \mathcal{O}(\bar{g}_s^4).$$

The coupling $\bar{g}_s$ can induce the process $e^+ e^- \to sZ$ (Badziak *et al.*, 1304.5437).

NMSSM Higgs

LEP bounds

The light singlet-like scalar is constrained by LEP.



LEP, hep-ex/0306033

$$\xi^2 = \bar{g}_s^2 \times \frac{\mathrm{BR}(s \to b\bar{b})}{\mathrm{BR}(h^{\mathrm{SM}} \to b\bar{b})} \sim \bar{g}_s^2.$$

- Due to a small excess ($\sim 2\sigma$), the bound on ξ^2 is weaker around $m_h = 95$–100 GeV.
- The scenario with a light singlet has been recently got attention after the Higgs discovery (Too many references, most recently, Jeong *et al.*, 1407.0955).

NMSSM Higgs

LHC bounds

The mixing of the 125 GeV Higgs boson with the light singlet-like scalar will induce different coupling strengths comparing to those in the SM.

$$k_x^2 = \frac{\sigma(xx \to h)}{\sigma(xx \to h_{\text{SM}})}, \quad k_y^2 = \frac{\Gamma(h \to yy)}{\Gamma(h_{\text{SM}} \to yy)},$$

where x: colliding partons, y: SM particles.

$$\Gamma_h^{\text{total}} = \sum_y k_y^2 \Gamma(h_{\text{SM}} \to yy) + \Gamma_h^{\text{BSM}},$$

and the signal strength is

$$\hat{\mu}_{xx \to h \to yy} = \frac{k_x^2 k_y^2 \Gamma_{h_{\text{SM}}}^{\text{total}}}{\Gamma_h^{\text{total}}},$$

where $\Gamma_{h_{\text{SM}}}^{\text{total}} \simeq 4$ MeV. Global fit of the signal strengths using k_x, k_y, and Γ_h^{BSM} sets upper limit of 20% at 95% C.L. for $\Gamma_h^{\text{total}}/\Gamma_{h_{\text{SM}}}^{\text{total}} \lesssim 1.25$.

(Falkowski *et al.*, 1303.1812, Giardino *et al.*, 1303.3570, Belanger *et al.*, 1306.2941)

NMSSM Higgs

$$W_{\text{NMSSM}} = W_{\text{Yukawa}} + \lambda S H_u \cdot H_d + \frac{1}{3}\kappa S^3,$$
$$-\mathcal{L}_{\text{soft}}^{\text{NMSSM}} = -\mathcal{L}_{\text{soft}}^{\text{MSSM}} + \left(\lambda A_\lambda H_u \cdot H_d S + \frac{1}{3}\kappa A_\kappa S^3 + \text{c.c.}\right).$$

If $\kappa = 0$, the Lagrangian would be invariant under a Peccei-Quinn symmetry.

$$H_u \to e^{i\varphi_{PQ}} H_u, \quad H_d \to e^{i\varphi_{PQ}} H_d, \quad S \to e^{-2i\varphi_{PQ}} S.$$

Since the global symmetry is spontaneously broken by v_u, v_d, and v_s, a massless Goldstone boson would appear in the CP-odd scalar sector.

For small non-vanishing κ, the pseudoscalar has a small mass since PQ symmetry is explicitly broken (pseudo-Goldstone boson).

NMSSM Higgs

After dropping the Goldstone field to give a mass to the Z boson, there are two pseudoscalars in the spectrum. The lighter pseudoscalar is

$$a = \cos\theta_P A + \sin\theta_P S_I,$$

where $A = \cos\beta H_{uI} + \sin\beta H_{dI}$.

In the PQ limit ($\kappa \to 0$),

$$\cos\theta_P = \frac{v\sin 2\beta}{\sqrt{v^2\sin^2 2\beta + 4v_s^2}}, \quad \sin\theta_P = -\frac{2v_s}{\sqrt{v^2\sin^2 2\beta + 4v_s^2}}.$$

- When $v_s \gg v\sin 2\beta$, a is dominantly singlet-like.

If $m_a < 2m_b$,

- $a \to \tau^+\tau^-/\mu^+\mu^-$ are dominant decay modes.
- $h/s \to aa$ channel opens.

NMSSM neutralino

There is one additional neutralino, $\widetilde{S}$, comparing to the MSSM.

$$\mathcal{M}_{\widetilde{\psi}^0} = \begin{pmatrix} M_1 & 0 & -m_Z \cos\beta \sin\theta_W & m_Z \sin\beta \sin\theta_W & 0 \\ & M_2 & m_Z \cos\beta \cos\theta_W & -m_Z \sin\beta \cos\theta_W & 0 \\ & & 0 & -\mu_{\text{eff}} & -\lambda v \sin\beta \\ & & & 0 & -\lambda v \cos\beta \\ & & & & 2\kappa v_s \end{pmatrix}$$

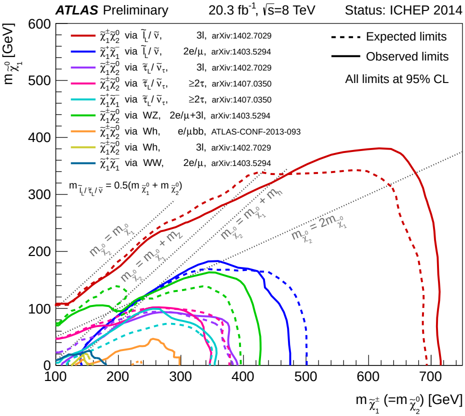
in the basis of $\widetilde{\psi}^0 = (\widetilde{B}, \widetilde{W}^3, \widetilde{H}_d^0, \widetilde{H}_u^0, \widetilde{S})$.

- When κ is small, $\widetilde{S}$ can be light.
- Higgsinos would also be light as small μ_{eff} value is favored by low fine-tuning.
- The LSP will be mostly singlino-like or mixed Higgsino-singlino state.

MSSM neutralino

- The decay modes of neutralino/chargino are model-dependent and more complex than gluino/squarks.
- Possible decay modes with in the MSSM are

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



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$$\widetilde{\chi}_1^\pm \to \widetilde{\ell}\nu,\, W\widetilde{\chi}_1^0,\, H^\pm\widetilde{\chi}_1^0, \cdots \to \ell^\pm\nu\widetilde{\chi}_1^0, \cdots .$$

  - $\widetilde{\chi}_2^0 \to Z\widetilde{\chi}_1^0$ is suppressed if $\widetilde{\chi}_{1,2}^0$ are practically gaugino-like since the couplings of $Z - \widetilde{\chi}_i^0 - \widetilde{\chi}_j^0$ arise only through higgsino components.
    - If $m_{\widetilde{\chi}_2^0} - m_{\widetilde{\chi}_1^0} < m_Z$, it receives three-body suppression.
  - All the Higges, $h/H/A$, can appear in the neutralino decays, and the charged Higgs, $H^\pm$, can be produced by the chargino unless kinematic suppressed.

NMSSM neutralino-chargino-to-Higgs process

The most distinct decay modes in the NMSSM are

$$\begin{aligned} &\widetilde{\chi}_j^0 \to s\widetilde{\chi}_1^0 \to aa\widetilde{\chi}_1^0, \\ &\widetilde{\chi}_j^0 \to a\widetilde{\chi}_i^0. \end{aligned}$$

- Small $\mu_{\text{eff}} \Rightarrow \widetilde{\chi}_2^0, \widetilde{\chi}_3^0$ are degenerate in mass.
- $\widetilde{\chi}_1^0$ is an admixture of Higgsino-singlino.
- The sinlget-like pseudoscalar can be very light.

Then, the kinematically-allowed two-body decays are

$$\begin{aligned} &\widetilde{\chi}_3^0 \to a\widetilde{\chi}_2^0, \quad \widetilde{\chi}_3^0 \to a\widetilde{\chi}_1^0, \\ &\widetilde{\chi}_2^0 \to a\widetilde{\chi}_1^0. \end{aligned}$$

NMSSM neutralino-chargino-to-Higgs process

When $m_a < 2m_\tau$, $a \to \mu^+\mu^-$ is dominant.[†] Then, the final states will consist of more muons than electrons.

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

However, it seems to be difficult to be realized because

- $s \to aa \to \mu^+\mu^-\mu^+\mu^-$ is allowed.
- For singlet-like s, this is the dominant decay channel.
- Very stringent upper limit by CMS (1210.7619), where a *model-independent* bound on $\sigma(pp \to s \to 2a \to 4\mu)$ has been set for 86 GeV $< m_s <$ 150 GeV and 0.25 GeV $< m_a <$ 3.55 GeV,

$$\sigma(pp \to 2a + X) \times \mathrm{BR}^2(a \to 2\mu) \times \alpha_\mathrm{gen} < 0.86 \pm 0.06 \text{ fb}.$$

($\alpha_\mathrm{gen} = 10.1(3.6)\%$ for $m_h = 125$ (90) GeV: kinematic acceptance)

[†] Subdominant decays include $a \to gg$ and $a \to s\bar{s}$.

NMSSM neutralino-chargino-to-Higgs process

When $2m_\tau < m_a < 2m_b$, $a \to \tau^+\tau^-$ is dominant while $a \to \mu^+\mu^-$ is sub-dominant.

1. LEP constraints on the process $e^+e^- \to sZ \to aaZ \to 4\tau + Z$,
2. Isolated lepton identification and tau-jet reconstruction.

- The LEP constraints can be evaded if s is dominantly sinlget-like.
- The lepton identification is generic problem in the collider experiment since taus sharing the same parent pseudoscalar are nearly collinear.[‡]

$$\Delta R_{\tau^+\tau^-} \sim \frac{4m_{\widetilde{\chi}_2^0} m_a}{m_{\widetilde{\chi}_2^0}^2 - m_{\widetilde{\chi}_1^0}^2} \quad \text{for } \widetilde{\chi}_2^0 \to a\widetilde{\chi}_1^0 \to \tau^+\tau^-\widetilde{\chi}_1^0.$$

  - The visible leptons can be soft due to the energy carried away by neutrinos in the tau decays.

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

NMSSM neutralino-chargino-to-Higgs process

Lepton isolation

The procedure of choosing the isolated lepton is

Tracker relative isolation

1. Define a cone of size R around the candidate lepton (ℓ),
2. Calculate I_{rel},

$$I_{\text{rel}} = \frac{\sum_t p_{\text{T}}^t}{p_{\text{T}}^{\ell}},$$

   where t are tracks excluding the lepton candidate,
3. If $I_{\text{rel}} > I_{\text{rel}}^{\text{min}}$, the candidate is regarded as the isolated lepton.

For instance, the CMS analysis chose $R = 0.3$ and $I_{\text{rel}}^{\text{min}} = 0.15$.

- The chosen values are optimal for SM processes with W/Z.
  - They are not suitable at all for the light pseudoscalar process.
- Our simulation found that the SUSY signal is almost hidden in the backgrounds since # of isolated leptons becomes small.[§]

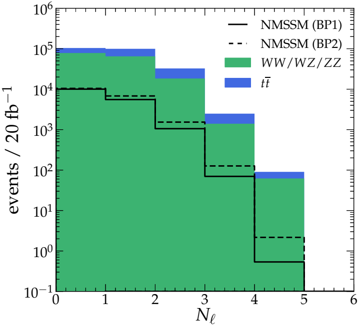
[§] Typically, 1 or 2 since there is at least one lepton from $\widetilde{\chi}_1^{\pm}$.

NMSSM neutralino-chargino-to-Higgs process

Lepton isolation

One must tune the parameters or introduce a new criterion scheme.

- We choose $R = 0.1$ and $I_{\text{rel}}^{\text{min}} = 0.1$ while removing fake leptons by kinematic cuts, $m_{\ell\ell}^{\text{OSOF}}$ and $\Delta R_{\ell,\text{jet}}$.



BP1: $m_a = 3.6$, $m_{\tilde{\chi}_3^0} = 143$, $m_{\tilde{\chi}_2^0} = 136$, $m_{\tilde{\chi}_1^0} = 87$ GeV,
BP2: $m_a = 7.6$, $m_{\tilde{\chi}_3^0} = 139$, $m_{\tilde{\chi}_2^0} = 125$, $m_{\tilde{\chi}_1^0} = 64$ GeV (HERWIG++ and DELPHES used).

NMSSM neutralino-chargino-to-Higgs process

Selection cuts

Reconstructed objects

- $p_{\mathrm{T}}^{e} > 12$ GeV and $p_{\mathrm{T}}^{\mu} > 8$ GeV, $p_{\mathrm{T}}^{\tau_h} > 15$ GeV for $|\eta| < 2.4$.
- The lepton is discarded if its angular separation to the adjacent jet with $p_{\mathrm{T}} > 20$ GeV is within a range of $\Delta R < 0.4$.
- Events with $m_{\ell^+\ell^-}^{\mathrm{OSSF}} < 12$ GeV is rejected to suppress the low-mass continuum backgrounds.
- b-tagging efficiency is set to be 70% for a jet with $p_{\mathrm{T}} > 30$ GeV, while the missing-tagging rates are assumed to be 10% and 1% for the c-jets and the light-flavor jets, respectively.

Basic selection cuts

- At least three leptons, $\ell = e$, μ, τ_h (τ_h: τ-jet), and at least one of them is required to have $p_{\mathrm{T}} > 20$ GeV.
- No b-tagged jet.
- $|m_{\ell^+\ell^-}^{\mathrm{OSSF}} - m_Z| > 15$ GeV ($\ell = e$, μ) to exclude the backgrounds associated with the leptonically decaying Z boson.

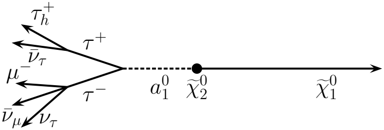
NMSSM neutralino-chargino-to-Higgs process

Selection cuts

The conventional kinematic variables for finding the signal are

$$m_{\ell^+\ell^-},\ M_{\mathrm{T}},\ \not{E}_{\mathrm{T}}$$

These all are useful when $m_{\widetilde{\chi}_2^0} - m_{\widetilde{\chi}_1^0}$ is big, so that the leptons are hard enough, and the missing energy is large because of the LSP.

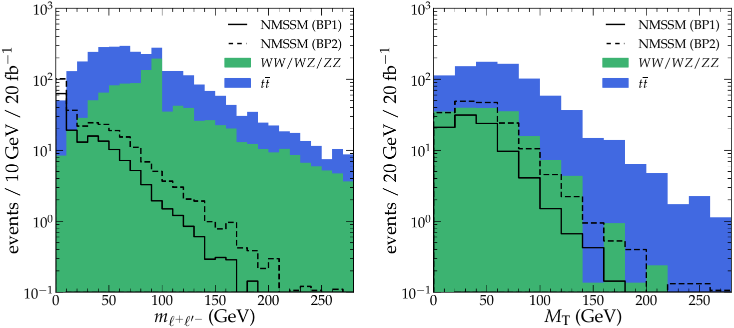


However, the leptons can be soft and the LSP momentum vector can be partially canceled by the neutrino momenta from taus in the $\widetilde{\chi} \to a$ process.

All the kinematic variables above are likely to lose their efficiency.

NMSSM neutralino-chargino-to-Higgs process

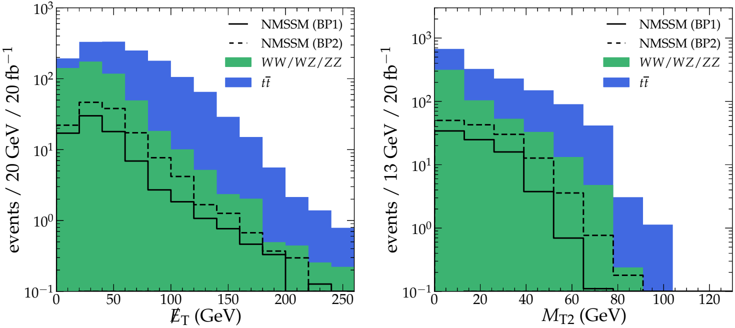
Selection cuts



Both $m_{\ell^+\ell^-}$ and M_{T} should serve upper cuts instead of lower ones.

NMSSM neutralino-chargino-to-Higgs process

Selection cuts



- $\not{E}_T$ cut should be rather mild.
- For WW and $t\bar{t}$,

$$M_{T2} \leq m_W,$$

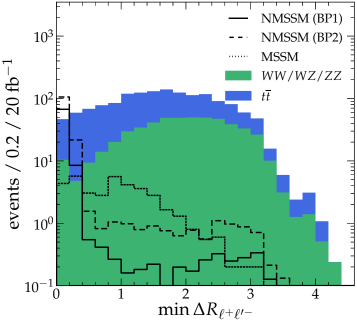
while it does not have any physical correlation in the signal process.

NMSSM neutralino-chargino-to-Higgs process

Selection cuts

The most important cut variable is the angular separation $\Delta R_{\ell^+\ell^-}$.

- 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, $\widetilde{\chi}_2^0 \to \tau^{\pm}\widetilde{\tau}^{\mp} \to \tau^+\tau^-\chi_1^0$ for $m_\tau \approx (m_{\widetilde{\chi}_2^0} + m_{\widetilde{\chi}_1^0})/2$, is shown for a comparison.

NMSSM neutralino-chargino-to-Higgs process

Cut flow

Selection cuts	BP1	BP2	Diboson	Triboson	$t\bar{t}$	$t\bar{t}W/Z$	DY	$Z+$jet
Basic cuts	79.5	140.2	523.6	2.1	991.4	3.0	4966.9	885.6
$\not{E}_{\mathrm{T}} > 30$ GeV	47.2	96.0	302.2	1.8	870.7	2.7	292.7	123.5
$\min \Delta R_{\ell^+\ell'^-} < 0.45$	45.0	86.8	9.5	0.2	86.7	0.2	16.7	7.7
$m_{\ell^+\ell'^-}$ cuts	30.9	55.1	3.1	0.04	25.5	0.03	0.0	0.0
$M_T < 60$ GeV	27.9	47.2	2.2	0.02	17.0	0.03	–	–
$M_{\mathrm{T2}} < 35$ GeV	24.6	37.3	1.5	0.01	6.2	0.02	–	–
Jet-veto	16.4	25.7	1.4	0.01	1.7	–	–	–

Table: Number of events passed the event selection cuts at 20 fb^{-1} integrated luminosity.

Light singlet Higgs in the NMSSM

For the singlet-like scalar, $s \to aa$ can be predominant.

Experimental constraints

- Since h is SM-like, it receives constraints to be compatible with the discovered 125 GeV Higgs boson.
  - Non-standard channel $h \to aa$ should be suppressed enough.
- The main constraints on $s \to aa \to 4\tau$ come from the LEP results.
  - ALEPH analysis (1003.0705) on $e^+e^- \to sZ \to aaZ \to 4\tau + 2\ell$.
- $s \to aa \to 2\mu^+ 2\mu^-$ is tightly constrained by CMS (1210.7619).
- Tevatron search limits are not stringent for $2m_\tau < m_a < 2m_b$.
- For the light pseudoscalar, there are constraints from the low-energy searches, *e.g.*, $\Upsilon(nS) \to \gamma a$ at BaBar, 1210.0287.

Light singlet Higgs 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.

$$h/s \to aa \to \tau^+\tau^-\tau^+\tau^- \to 2\ell^+ + 2\ell^- + \not{E}_{\mathrm{T}} \quad (\ell = e,\, \mu,\, \tau_h),$$

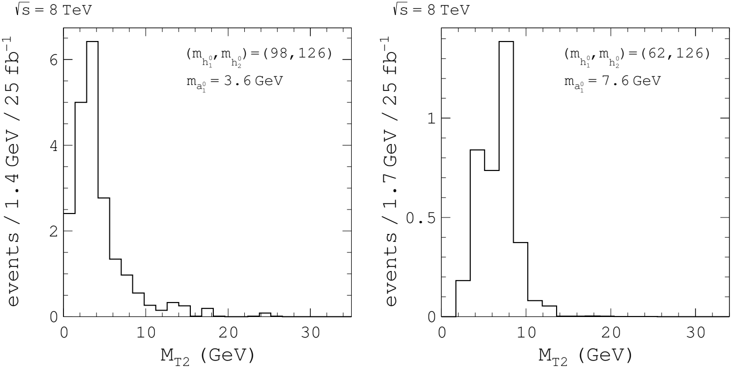
The angular separation is given by

$$\Delta R_{\tau^+\tau^-} \sim \frac{4m_a}{m_{h/s}}.$$

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

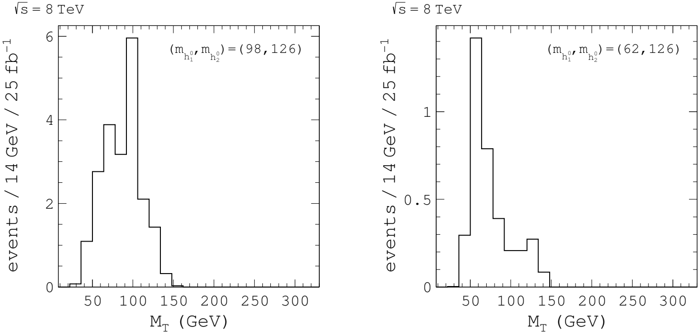
- The leptons sharing the same parent a are nearly collinear. Then, the two leptons can be regarded as one visible particle system.
- The neutrinos are the same as above and their invariant mass is ~ 0.
- The decay system is now depicted as two visible + two invisible particles, then the M_{T2} is calculable.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

Light singlet Higgs 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.

Light singlet Higgs in the NMSSM



The light singlet-like Higgs mass can be estimated by the transverse mass,

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

- There is a small contribution from $h \to aa$.

Conclusions

- At least one Higgs is *no more hypothetical but real*. It is reasonable to consider the SUSY processes involving the Higgs bosons.
  - It might lead us to discover non-standard new bosons such as a light pseudoscalar.
- The decay processes of neutralinos, which are sensitive to the model parameters, but have been conventionally assumed to be practically EW gauginos in the ATLAS and CMS analyses.
- The light NMSSM pseudoscalar can be produced by the neutralino process and needs a dedicated collider 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.