MSSM Higgs in Light of LHC Higgs Discovery

Tong Li

CoEPP, Monash University

based on works:
Neil D. Christensen, Tao Han (U. of Pittsburgh), TL
Phys. Rev. D86 (2012) 074003
and
Tao Han, TL, Shufang Su (U. of Arizona), Liantao Wang (U. of Chicago)
arXiv: 1306.3229 [hep-ph]

Outline

- Impact of the Higgs Discovery on MSSM Higgs
- Indirect and Direct Constraints
- New Search Method for Light MSSM Higgs at the LHC
- Summary

Impact of the Higgs Discovery on MSSM Higgs

The discovery of the Higgs-like boson has reached impressive conclusions
Bruno Mansoulié, ATLAS Collaboration, presentation at *the Rencontres de Moriond EW,* March, 2013;

Mingshui Chen, CMS Collaboration, presentation at *the Rencontres de Moriond EW,* March, 2013.

- $m_h \approx 125$ GeV from $\gamma\gamma$ and ZZ(4l)
- spin-0 scalar boson
- overall signal strength is compatible with the SM Higgs boson: $\mu = 1.43 \pm 0.21$ (ATLAS), $\mu = 0.88 \pm 0.21$ (CMS)

Questions:

- Pure SM Higgs or SM-like Higgs in new physics?
- Can the LHC prove or disprove new physics associated with Higgs sector, like MSSM?

MSSM Higgs Sector

- Two Higgs Doublet Model
  $H_u = (H_u^+, H_u^0)^T$, $H_d = (H_d^0, H_d^-)^T$, $\langle H_u^0 \rangle = \frac{v_u}{\sqrt{2}}$, $\langle H_d^0 \rangle = \frac{v_d}{\sqrt{2}}$
  $v_u^2 + v_d^2 = v^2 = (246 \text{ GeV})^2$, $\tan\beta = v_u/v_d$

- After EWSB, five physical Higgses:
  CP-even h^0, H^0, CP-odd A^0, charged $H^\pm$

- tree level Higgs masses determined by m_A and $\tan\beta$:

$$m_{h^0,H^0}^2 = \frac{1}{2}\left((m_A^2 + m_Z^2) \mp \sqrt{(m_A^2 - m_Z^2)^2 + 4m_A^2 m_Z^2 \sin^2 2\beta}\right)$$

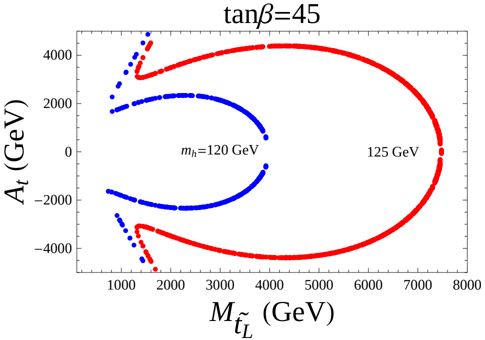
$$m_{H^\pm}^2 = m_A^2 + m_W^2, \quad \cos^2(\beta - \alpha) = \frac{m_{h^0}^2(m_Z^2 - m_{h^0}^2)}{m_A^2(m_{H^0}^2 - m_{h^0}^2)}$$

- The CP-even Higgs boson that couples to WW and ZZ more strongly is called the SM-like Higgs.

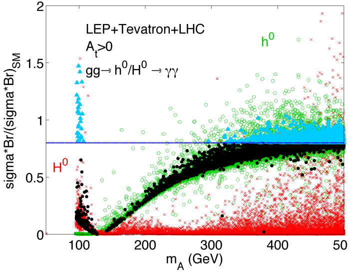
- radiative corrections:

$$\Delta m^2_{h^0} \approx \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{\tilde{A}_t^2}{M_S^2}\left(1 - \frac{\tilde{A}_t^2}{12M_S^2}\right)\right]$$

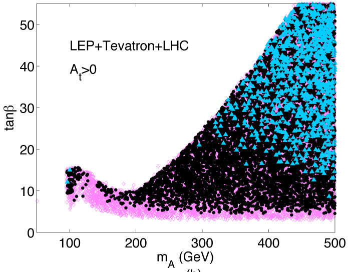
$$\tilde{A}_t = A_t - \mu\cot\beta,\;\; M_S = (m_{\tilde{t}_L} + m_{\tilde{t}_R})/2$$



Combining the existing constraints from all the current bounds of the direct searches from LEP2, the Tevatron and the LHC, the consequences of the findings on the Higgs sector were studied within the framework of the Minimal Supersymmetric Standard Model (MSSM). N. Christensen, T. Han and S. Su, Phys. Rev. D 85, 115018 (2012)



(b)



(b)

black dots: $123 < m_{h^0}$ *or* $m_{H^0} < 127$ GeV

blue dots: $\sigma x Br(gg \to h^0, H^0 \to \gamma\gamma)_{\rm MSSM} > 0.8(\sigma x Br)_{\rm SM}$

- Two distinctive scenarios are left and both incorporate a SM-like Higgs boson.

- Decoupling region with $m_A \gtrsim 300$ GeV:

$$\cos(\beta-\alpha) \xrightarrow{M_A \gg M_Z} \frac{M_Z^2}{2M_A^2}\sin 4\beta \xrightarrow{\tan\beta \gg 1} -\frac{2M_Z^2}{M_A^2\tan\beta} \to 0$$

$$\sin(\beta-\alpha) \to 1$$

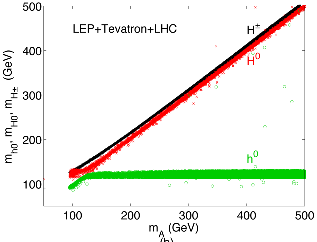
$ZZh^0, WWh^0 \propto \sin(\beta-\alpha)$, the light CP-even Higgs h^0 is SM-like, $H^0, A^0, H^\pm$ heavy and degenerate.

- Non-decoupling region with m_A around $95-110$ GeV:

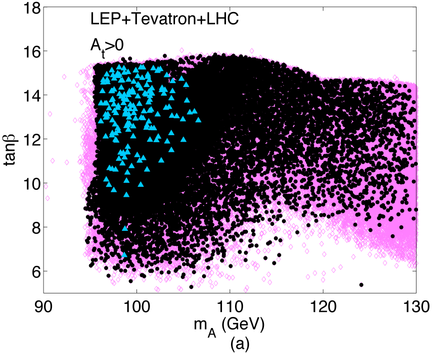
$$\cos(\beta-\alpha) \to 1, \sin(\beta-\alpha) \to 0$$

$ZZH^0, WWH^0 \propto \cos(\beta-\alpha)$, the heavy CP-even Higgs H^0 is SM-like, $h^0, H^0, A^0, H^\pm$ all light.

A. Djouadi, Phys. Rept. 459:1-241, 2008



non-decoupling region: $95 < m_A < 110$ GeV and $6 < \tan\beta < 16$



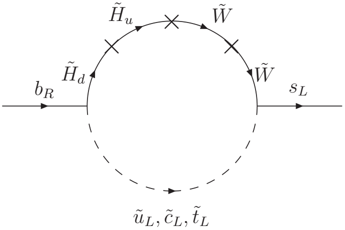
Indirect and Direct Constraints on Non-Decoupling scenario

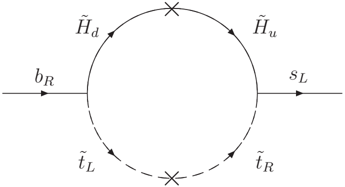
Indirect constraint: flavor physics observables

- $B \to X_s\gamma$ most stringent:
  $Br(B \to X_s\gamma)_{\rm exp} = (3.43 \pm 0.21) \times 10^{-4}$
  $Br(B \to X_s\gamma)_{\rm SM} = (3.15 \pm 0.23) \times 10^{-4}$

  Heavy Flavor Averaging Group, Y. Amhis et. al., arXiv:1207.1158 [hep-ex]
- SUSY contributions: charged Higgs-top loop, chargino-stop loops
- light charged Higgs in non-decoupling region induces large and positive contribution

- dominant chargino-stop loops:

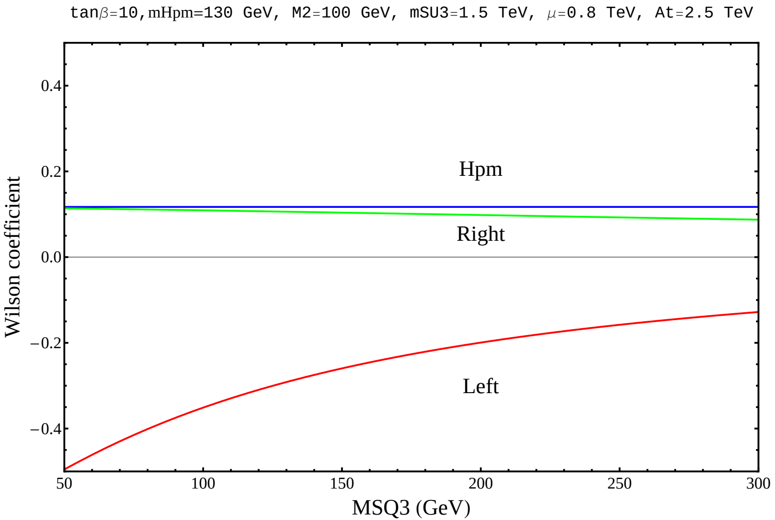




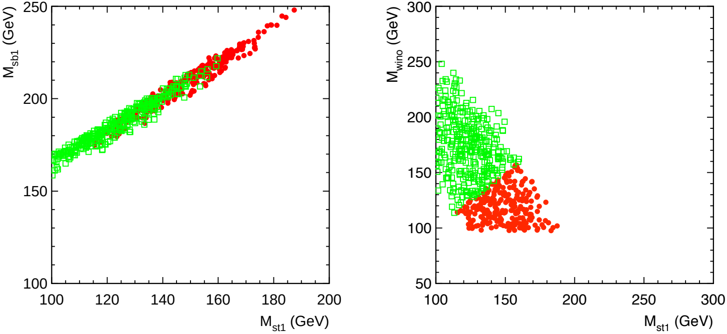
Left: $\mu M_2 \tan\beta \times \text{loop function}(M_2, \mu, M_{\tilde{Q}_3}, M_{\tilde{Q}})$,
negative for $\mu M_2 > 0$ and positive for $\mu M_2 < 0$

Right: $-\mu A_t \tan\beta \times \text{loop function}(\mu, M_{\tilde{Q}_3}, M_{\tilde{U}_3})$,
positive for $\mu A_t > 0$ and negative for $\mu A_t < 0$

- wino and stop masses, and the sign of SUSY parameters need to be tuned to cancel positive charged Higgs diagram

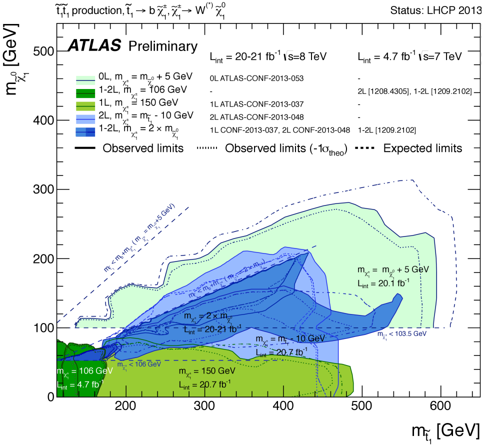


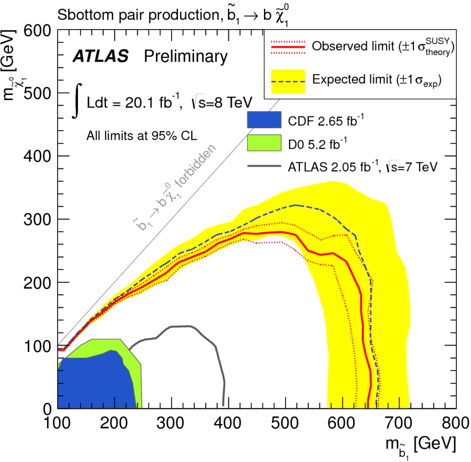
- For $\mu > 0, A_t > 0$, small M_2 and $M_{\tilde{Q}_3}$ are favored given large $|\mu|$ and $M_{\tilde{t}_R}$



- small $M_{\tilde{Q}_3}$ leads to light left-handed stop and sbottom
- spectrum case A: Wino lighter than stop (red)
  spectrum case B: Wino heavier than stop (green)

Direct constraint





- Bino mass M_1 is a free parameter
  1) $m_{\tilde b_1} > m_{\tilde t_1} > M_2 > M_1$; 2) $m_{\tilde b_1} > M_2 > m_{\tilde t_1} > M_1$
- small $m_{\tilde t_1, \tilde b_1} - M_1$ to evade stop/sbottom limits

Search for MSSM Higgs at the LHC

- HVV and VHH couplings in MSSM:

$$ZZh^0 \propto ig_Z M_Z \sin(\beta-\alpha), \;\; ZZH^0 \propto ig_Z M_Z \cos(\beta-\alpha)$$

$$WWh^0 \propto ig_W M_W \sin(\beta-\alpha), \;\; WWH^0 \propto ig_W M_W \cos(\beta-\alpha)$$

$$ZA^0h^0 \propto \frac{g_Z}{2}\cos(\beta-\alpha), \;\; ZA^0H^0 \propto -\frac{g_Z}{2}\sin(\beta-\alpha)$$

$$W^\pm H^\pm h^0 \propto \mp i\frac{g_W}{2}\cos(\beta-\alpha), \;\; W^\pm H^\pm H^0 \propto \pm i\frac{g_W}{2}\sin(\beta-\alpha)$$

$$ZH^+H^- \propto -\frac{g_Z}{2}\cos 2\theta_W, \;\; \gamma H^+H^- \propto -ie, \;\; W^\pm H^\pm A^0 \propto \frac{g_W}{2}$$

- leading pair production processes in the two regimes:

	Zh^0	ZH^0	Wh^0	WH^0
de.	$\surd$		$\surd$	
non-de.		$\surd$		$\surd$

	A^0h^0	A^0H^0	$H^\pm h^0$	$H^\pm H^0$	$H^\pm A^0$	H^+H^-
de.		$\surd$		$\surd$	$\surd$	$\surd$
non-de.	$\surd$		$\surd$		$\surd$	$\surd$

- leading channels

  $$gg \to h^0, H^0, A^0; pp \to t\bar{t} \text{ with } t \to H^{\pm} b$$

  and standard electroweak productions

  $$pp \to W^{\pm} h^0(H^0), Zh^0(H^0), q\bar{q}h^0(H^0)$$

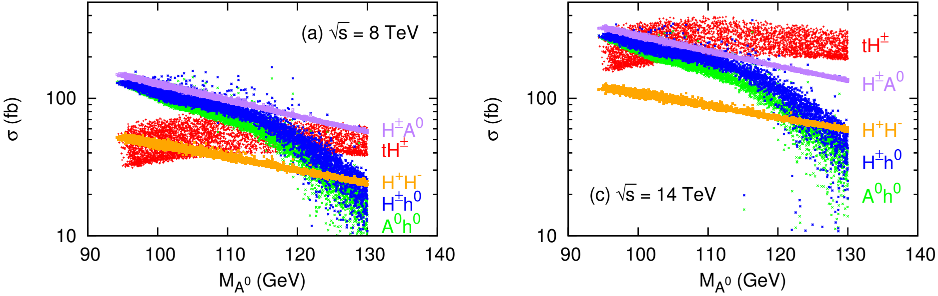
- electroweak processes via pure gauge interaction and independent of SUSY parameters except for Higgs masses

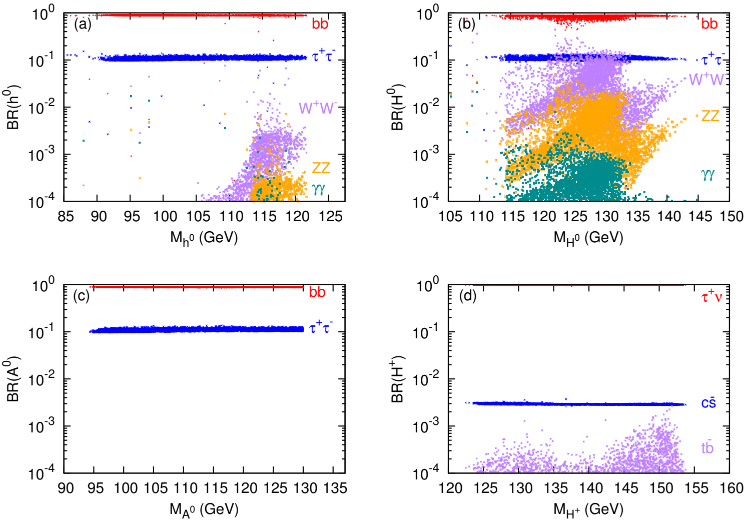
  $$pp \to W^{\pm *} \to H^{\pm} A^0, \ pp \to Z^*/\gamma^* \to H^+ H^-$$

- non-SM-like Higgs productions in the low-mass non-decoupling region

  $$pp \to W^{\pm *} \to H^{\pm} h^0, \ pp \to Z^* \to A^0 h^0$$

- Production cross sections at 8 and 14 TeV LHC, and branching fractions for the Higgs in the non-decoupling region





- $Br(h^0/A^0 \to bb) \sim 90\%$, $Br(h^0/A^0 \to \tau\tau) \sim 10\%$, $Br(H^\pm \to \tau\nu) \sim 100\%$
- $q\bar{q}' \to W^{\pm *} \to H^\pm A^0, H^\pm h^0 \to b\bar{b}\tau^\pm\nu_\tau$ production
  $q\bar{q} \to Z^*/\gamma^* \to H^+H^- \to \tau^+\nu_\tau\tau^-\bar{\nu}_\tau$ production

- $q\bar{q}' \to W^{\pm *} \to H^{\pm}A^0 \to b\bar{b}\tau^{\pm}\nu_{\tau}$ Production

The leading SM backgrounds to this channel are

$$b\bar{b}W^{\pm} \to b\bar{b}\tau^{\pm}\nu,\ \bar{b}t(b\bar{t}) \to \bar{b}bW^{\pm} \to \bar{b}b\tau^{\pm}\nu$$

and reducible ones

$$\begin{aligned} &qg \to q'\bar{b}t(b\bar{t}) \to j\bar{b}bW^{\pm} \to j\bar{b}b\tau^{\pm}\nu, \\ &t\bar{t} \to b\bar{b}W^{+}W^{-} \to b\bar{b}\tau^{\pm}\ell^{\mp}\nu\bar{\nu}\ (\ell = e, \mu) \end{aligned}$$

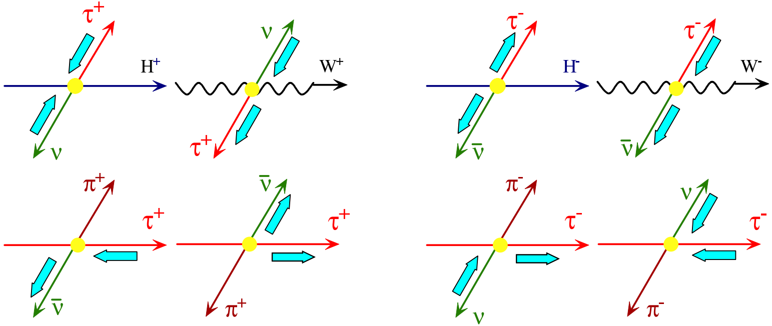
with vetoing the QCD jet j and charged lepton ℓ respectively, namely $p_T(j) > 30\ \mathrm{GeV},\ |\eta(j)| < 4.9;\ p_T(\ell) > 7\ \mathrm{GeV},\ |\eta(\ell)| < 3.5$.
We require the tau lepton hadronically decay into a charged pion and neutrino with $BR(\tau^{\pm} \to \pi^{\pm}\nu_{\tau}) = 0.11$ and employ the following basic cuts

$$p_T(\pi, b) \geq 20\ \mathrm{GeV};\ |\eta(\pi, b)| < 2.4;\ \Delta R_{\pi b}, \Delta R_{bb} \geq 0.4;\ \epsilon_b = 70\%.$$

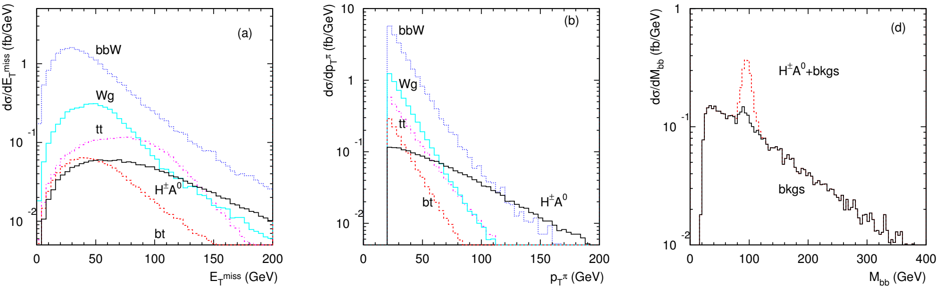
Note that the $H^-\tau^+\nu_\tau$ coupling is purely left-handed,

$$H^-\tau^+\nu_\tau \propto m_\tau \tan\beta(1-\gamma_5),$$

such that the τ^+ from H^+ decay is dominantly left-handed. However, the antifermion τ^+ from W^+ decay in background events is right-handedly polarized, same for the $\bar{\nu}$ from τ^+ decay. Thus, the π^+ tends to move along the direction of τ^+ in H^+ decay, but away the direction of τ^+ in W^+ decay. B. K. Bullock, K. Hagiwara and A. D. Martin, Nucl. Phys. **B395** (1993) 499; Q. H. Cao, S. Kanemura and C.-P. Yuan, Phys. Rev. **D69** (2004) 075008.



The differential cross section distributions of the signal $H^{\pm}A^{0}$ and backgrounds after basic cuts at 14 TeV LHC.



- The production rate of $H^{\pm}h^{0}$ is comparable with $H^{\pm}A^{0}$'s and their signals are exactly the same in this scenario. We apply the same kinematic cuts on the $H^{\pm}h^{0} \to b\bar{b}\tau^{\pm}\nu_{\tau}$ production.
- rho mode of tau lepton decay $BR(\tau^{\pm} \to \rho^{\pm}\nu_{\tau}) = 0.25$
- The log likelihood method for significance

$$LL(B,S) = 2\left[(B+S)\ln\left(\frac{B+S}{B}\right) - S\right]$$

15 fb^{-1}

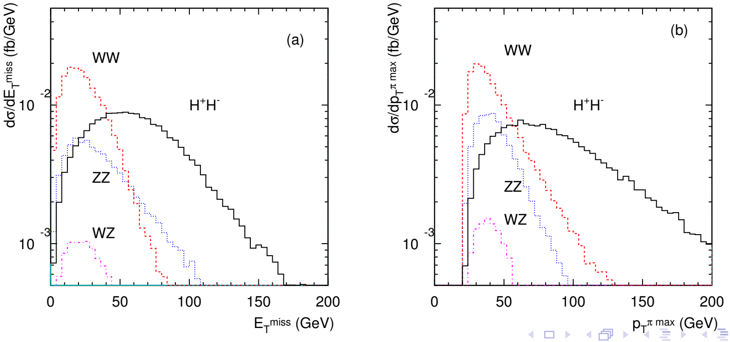
events with 8 (14) TeV	basic cuts+$\not{E}_T > 40$ GeV	$p_T(\pi/\rho) > 40$ GeV	$80 < M_{b\bar{b}} < 110$ GeV
$H^\pm A^0$ (π)	47 (96)	31 (66)	29 (61)
$H^\pm A^0$ (ρ)	110 (225)	70 (150)	65 (140)
$H^\pm h^0$ (π)	44 (90)	28 (63)	26 (60)
$H^\pm h^0$ (ρ)	105 (210)	65 (140)	62 (135)
$b\bar{b}W^\pm$ (π)	290 (760)	75 (210)	14 (37)
$b\bar{b}W^\pm$ (ρ)	1150 (2900)	340 (920)	66 (165)
bt (π)	25 (49)	6.1 (12)	0.8 (1.5)
bt (ρ)	100 (190)	29 (60)	4.2 (7.5)
Wg (π)	77 (220)	18 (55)	2.6 (8.3)
Wg (ρ)	300 (850)	88 (270)	15 (43)
$t\bar{t}$ (π)	30 (140)	9.6 (48)	1.6 (7.9)
$t\bar{t}$ (ρ)	117 (550)	47 (230)	7.9 (38)
S/B $(H^\pm A^0, \pi)$	0.11 (0.08)	0.29 (0.2)	1.5 (1.1)
S/B $(H^\pm A^0, \rho)$	0.066 (0.05)	0.14 (0.1)	0.7 (0.55)
$\sqrt{LL}$ $(H^\pm A^0, \pi)$	2.2 (2.8)	2.8 (3.5)	5.6 (7.2)
$\sqrt{LL}$ $(H^\pm A^0, \rho)$	2.7 (3.3)	3.0 (3.8)	6.1 (8.1)
S/B $(H^\pm h^0, \pi)$	0.1 (0.077)	0.26 (0.19)	1.4 (1.1)
S/B $(H^\pm h^0, \rho)$	0.063 (0.047)	0.13 (0.095)	0.67 (0.53)
$\sqrt{LL}$ $(H^\pm h^0, \pi)$	2.1 (2.6)	2.6 (3.4)	5.1 (7.1)
$\sqrt{LL}$ $(H^\pm h^0, \rho)$	2.5 (3.1)	2.8 (3.6)	5.9 (7.9)

- $q\bar{q} \to Z^*/\gamma^* \to H^+H^- \to \tau^+\nu_\tau\tau^-\bar{\nu}_\tau$ Production

We also demand the two tau leptons hadronically decay into charged pion and neutrino. Thus, the signal would be two opposite-sign pions plus missing energy. The leading SM backgrounds are

$$W^+W^- \to \tau^+\nu_\tau\ \tau^-\bar{\nu}_\tau, \quad ZZ \to \tau^+\tau^-\ \nu\bar{\nu}, \quad W^\pm Z \to \ell^\pm\nu_\ell\tau^+\tau^-.$$

The differential cross section distributions of the signal H^+H^- and backgrounds after basic cuts at 14 TeV LHC



$15\ \mathrm{fb}^{-1}$

events with 8 (14) TeV	basic cuts+$\not{E}_T > 50$ GeV	$p_T(\pi/\rho) > 50$ GeV
H^+H^- (π)	3.5 (7.6)	3.2 (7.0)
H^+H^- (ρ)	18 (39)	16 (36)
WW (π)	0.52 (1.1)	0.44 (0.97)
WW (ρ)	12 (23)	8.4 (17)
ZZ (π)	0.77 (1.9)	0.58 (1.3)
ZZ (ρ)	5.7 (11)	4.2 (9.0)
WZ (π)	0.057 (0.16)	0.043 (0.12)
WZ (ρ)	0.37 (1.1)	0.26 (0.80)
S/B (π)	2.6 (2.4)	3.0 (2.9)
S/B (ρ)	1.0 (1.1)	1.2 (1.3)
$\sqrt{LL}$ (π)	2.3 (3.3)	2.3 (3.4)
$\sqrt{LL}$ (ρ)	3.7 (5.7)	3.8 (5.9)

- $q\bar{q} \to Z^* \to A^0 h^0 \to b\bar{b}\tau^+\tau^-$ Production

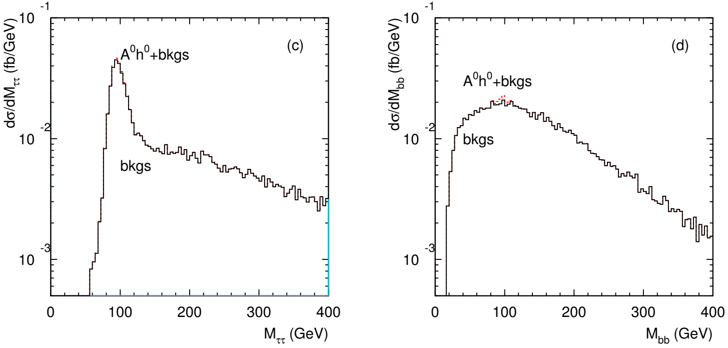
The leading signal channel is $A^0 h^0 \to b\bar{b}b\bar{b}$ which, however, is overwhelmed by huge QCD background. Thus, we consider the clearer but subleading signal, two b-jets plus two opposite sign tau leptons, from $A^0 h^0 \to b\bar{b}\tau^+\tau^-$ decay with $BR(h^0(A^0) \to \tau^+\tau^-) \approx 10\%$. The dominant SM backgrounds to this channel are

$$b\bar{b}Z \to b\bar{b}\tau^+\tau^-, \qquad t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}\tau^+\tau^-\nu\bar{\nu}.$$

Note that all the τs produced in signal events are relatively energetic. The missing momentum will be along the direction of the charged track. We thus assume the momentum of the missing neutrinos to be reconstructed by

$$\overrightarrow{p}(\text{invisible}) = \kappa_1 \overrightarrow{p}(\pi_1) + \kappa_2 \overrightarrow{p}(\pi_2).$$

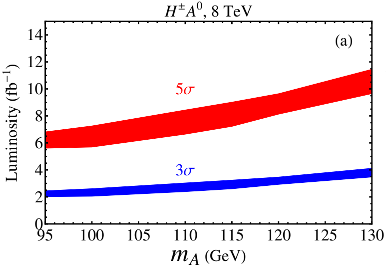
The proportionality constants κ_1, κ_2 can be determined from the missing energy measurement as long as the two charged tracks are linearly independent.

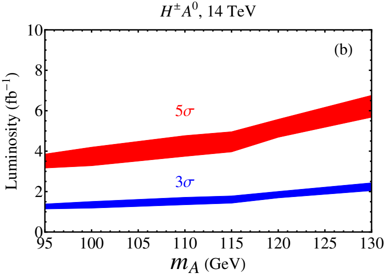


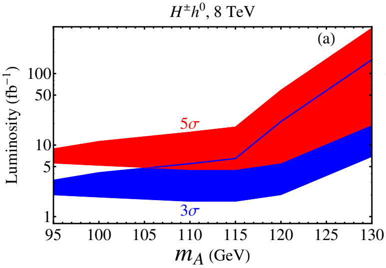
We could only reach a signal-to-background ratio of approximately 1:7. The signal rate is also low. With an integrated luminosity of 100 fb^{-1} at 14 TeV, one would have only 20 events for the rho mode. We thus conclude that the neutral Higgs pair production of A^0h^0 would not be a feasible channel for the MSSM Higgs pair search.

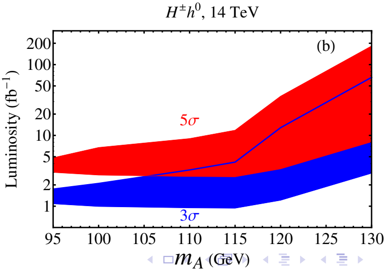
Sensitivity

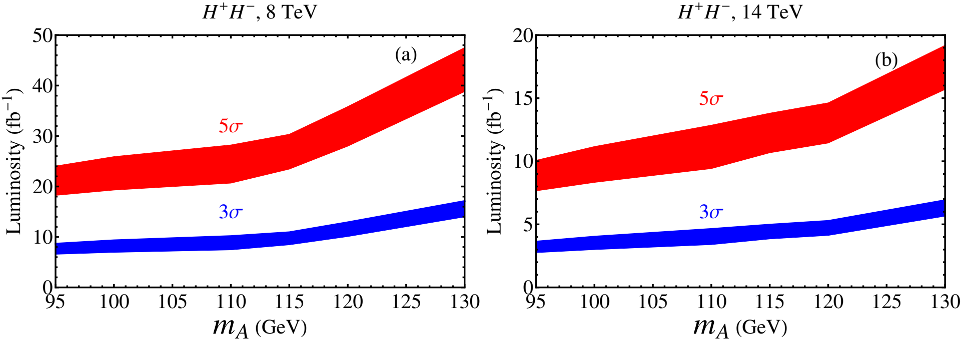
We estimate the span of integrated luminosities required for a 3σ and 5σ measurement of the signal.










H^+H^-, 8 TeV
(a)
Luminosity (fb^{-1})
50
40
30
20
10
0
5σ
3σ
95
100
105
110
115
120
125
130
m_A (GeV)
H^+H^-, 14 TeV
(b)
Luminosity (fb^{-1})
20
15
10
5
0
5σ
3σ
95
100
105
110
115
120
125
130
m_A (GeV)

Next Step

- Non-decoupling region:
  extend to general 2HDM and NMSSM

  T. Han, TL and S. Su, work in progress

- Decoupling region:
  $B_s \to \mu^+\mu^-$ favors mediate and small $\tan\beta$, $t\bar{t}$ channel dominant, but $b\bar{b}$ and $\tau\tau$ modes still useful

  W. Altmannshofer, M. Carena, N. R. Shah and F. Yu, JHEP 1301, 160 (2013)

  What's the reachable limit of LHC on heavy H^0 and A^0?

  TL, work in progress

  CP? TeV ILC?

  Kaoru Hagiwara, TL, Kentarou Mawatari, Junya Nakamura, arXiv: 1212.6247 [hep-ph];

  TL, Kentarou Mawatari, work in progress

Summary

- The discovery of 125 GeV Higgs boson $\Longrightarrow$ two distinctive regions in MSSM: decoupling region and non-decoupling region
- Non-decoupling region is more interesting: all Higgses are light.
- Flavor physics and direct search for stop and sbottom put stringent constraints on non-decoupling region, but there exist solutions due to subtle cancellation.
- The Higgs boson signals from pair production $H^{\pm}A^0$ and H^+H^- are only governed by pure electroweak gauge interactions. $H^{\pm}h^0$ and A^0h^0 productions depend on SUSY parameters. Probing the productions of $H^{\pm}A^0, H^{\pm}h^0, H^+H^-$ is optimistic.

Go and search for them!