Beyond Standard Model Higgs Bosons: Phenomenology and Observation Strategy

Majid Hashemi

University of Shiraz

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Outline

1. SM vs 2HDM
2. Searches for the charged Higgs
3. Searches for the neutral Higgs
4. Higgs couplings in 2HDM
5. My activities
   - Charged Higgs
   - Neutral Higgs
   - Inert doublet model
6. Conclusions

SM

- SM contains a single $SU(2)$ doublet :
  $$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} (\phi_1 + i\phi_2)/\sqrt{2} \\ (\phi_3 + i\phi_4))/\sqrt{2} \end{pmatrix}$$
- After SSB, ϕ acquires a vev through $\phi_3 = v$ and $\phi_1 = \phi_2 = \phi_4 = 0$
- $\phi = \begin{pmatrix} 0 \\ v \end{pmatrix} \to \begin{pmatrix} 0 \\ v + h \end{pmatrix}$
- Result: massless photon, massive $W^\pm$ and Z, and a single physical Higgs boson: h

2HDM

- 2HDM contains two $SU(2)$ doublets : $\phi_i = \begin{pmatrix} i\omega_i^+ \\ v_i + h_i - iz_i \end{pmatrix}$
- Using two mixing angles α and β, neutral and charged Higgs bosons are identified :

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

$$\begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} z \\ A \end{pmatrix}$$

$$\begin{pmatrix} w_1^+ \\ w_2^+ \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} w^+ \\ H^+ \end{pmatrix}$$

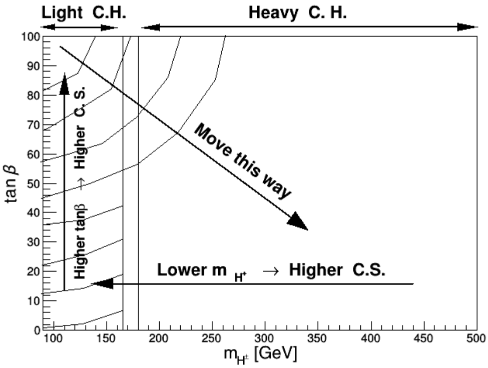
- v_1 and v_2 are also related through $\tan\beta = v_2/v_1$
- Result: five Higgs bosons : $h_{(SM\ like)}, H,\ A,\ H^{\pm}$

Searches for the charged Higgs

Focus on :

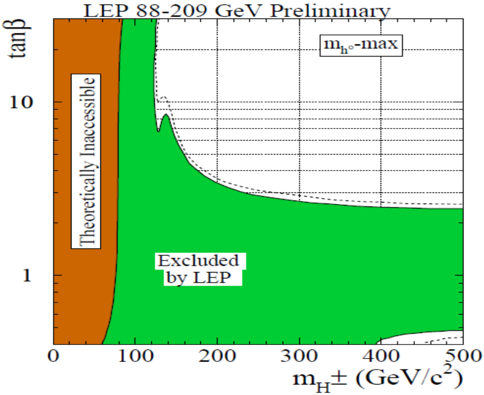
- LEP
- CMS
- ATLAS

Tevatron results supreseded by LHC!

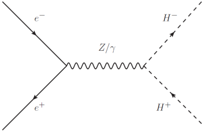


LEP results

- Light charged Higgs with $m_{H^\pm} < 125$ GeV excluded.
- Heavy CH excluded only at low $\tan\beta$.



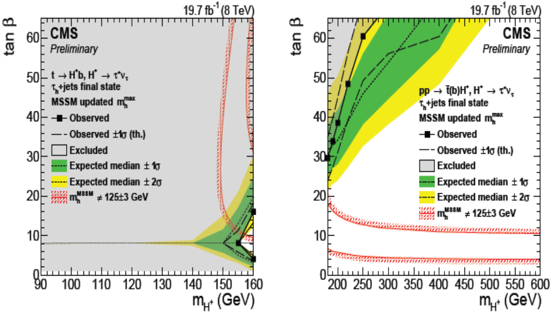
LEP HWG [arXiv:hep-ex/0107030]



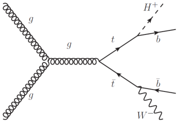
$$e^+e^- \to Z/\gamma \to H^+H^-$$

CMS results

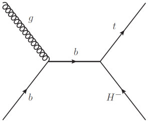
- Light charged Higgs fully excluded (no $m_{H^\pm} < 160$ GeV).
- Heavy CH excluded only at high $\tan\beta$.



CMS PAS HIG-14-020 (7 & 8 TeV)



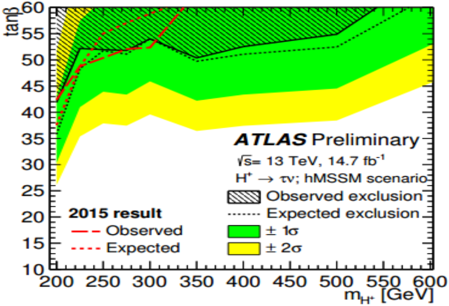
$pp \to t\bar{t} \to H^+ bW^- \bar{b}$



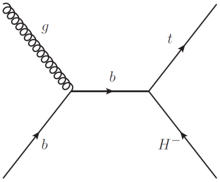
$gb \to tH^-$

ATLAS results

- Heavy CH exclusion extended at 13 TeV
- $\tan\beta > 50$ excluded



ATLAS-CONF-2016-088 (13 TeV)



$gb \to tH^-$

Searches for the neutral Higgs

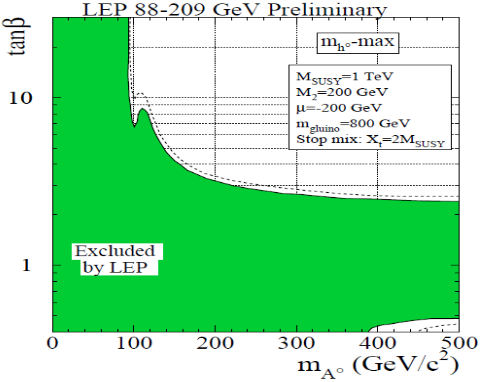
Results of searches for the neutral Higgs in different experiments will be shown in the next slides ...

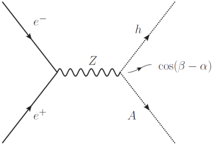
Again the focus is on :

- LEP
- CMS
- ATLAS

LEP results

- Only a scenario in which $m_A < m_h$ and $\tan\beta > 8$,
- Results presented for A: $m_A < 90$ GeV excluded.



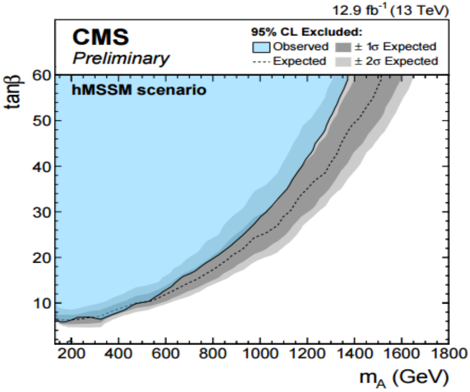


$e^+e^- \to Z \to hA$

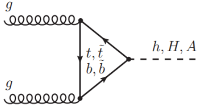
LEP HWG [arXiv:hep-ex/0107030]

CMS results

- Search based on MSSM with $m_h = 125$ GeV (hMSSM),
- Results presented for m_A vs. $\tan\beta$.



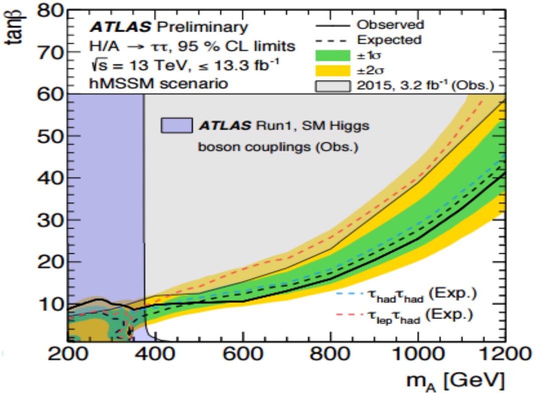
CMS PAS HIG-16-037 (13 TeV)



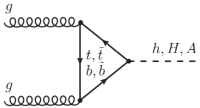
$pp \to h/H/A$

CMS results

- Search based on hMSSM,
- The same strategy, results presented for m_A vs. $\tan\beta$.



ATLAS-CONF-2016-085 (13 TeV)



$pp \to h/H/A$

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BSM Higgs: Pheno. (15th Feb. 2017)

Majid Hashemi

Higgs couplings in 2HDM : Higgs-gauge int.

- Higgs-gauge couplings in 2HDM vs SM :
  $\frac{g_{hVV}^{2HDM}}{g_{hVV}^{SM}} = \sin(\beta - \alpha), \qquad \frac{g_{HVV}^{2HDM}}{g_{hVV}^{SM}} = \cos(\beta - \alpha)$
- Set $\sin(\beta - \alpha) = 1$ to obtain SM Higgs (h) couplings
- No Heavy Higgs boson interaction with gauge bosons : Gaugophobic Higgs boson (H)
- A model beyond SM but consistent with SM Higgs :
  $h_{(SM\ like)}, \qquad H$ to be observed ...
- What about Higgs-fermion interactions ?

Higgs couplings in 2HDM : Higgs-fermion int.

- Yukawa sector of the Lagrangian :

$$-\mathcal{L}_Y = \frac{1}{\sqrt{2}}\bar{D}\left[\kappa^D s_{\beta-\alpha} + \rho^D c_{\beta-\alpha}\right] Dh + \frac{1}{\sqrt{2}}\bar{D}\left[\kappa^D c_{\beta-\alpha} - \rho^D s_{\beta-\alpha}\right] DH + \frac{i}{\sqrt{2}}\bar{D}\gamma_5\rho^D DA$$
$$+ \frac{1}{\sqrt{2}}\bar{U}\left[\kappa^U s_{\beta-\alpha} + \rho^U c_{\beta-\alpha}\right] Uh + \frac{1}{\sqrt{2}}\bar{U}\left[\kappa^U c_{\beta-\alpha} - \rho^U s_{\beta-\alpha}\right] UH - \frac{i}{\sqrt{2}}\bar{U}\gamma_5\rho^U UA$$
$$+ \frac{1}{\sqrt{2}}\bar{L}\left[\kappa^L s_{\beta-\alpha} + \rho^L c_{\beta-\alpha}\right] Lh + \frac{1}{\sqrt{2}}\bar{L}\left[\kappa^L c_{\beta-\alpha} - \rho^L s_{\beta-\alpha}\right] LH + \frac{i}{\sqrt{2}}\bar{L}\gamma_5\rho^L LA$$
$$+ \left[\bar{U}(V_{CKM}\rho^D P_R - \rho^U V_{CKM} P_L)DH^+ + \bar{\nu}\rho^L P_R LH^+ + h.c.\right]$$

- Parameter definition : $\kappa^f = \sqrt{2}\frac{m_f}{v}$, $s_{\beta-\alpha} = \sin(\beta-\alpha)$, $c_{\beta-\alpha} = \cos(\beta-\alpha)$, $P_{L/R} = \frac{1\mp\gamma^5}{2}$

- ρ^f are defined according to the 2HDM type:

Type	ρ^U	ρ^D	ρ^L
I	$\kappa^U \cot\beta$	$\kappa^D \cot\beta$	$\kappa^L \cot\beta$
II	$\kappa^U \cot\beta$	$-\kappa^D \tan\beta$	$-\kappa^L \tan\beta$
III/Y	$\kappa^U \cot\beta$	$-\kappa^D \tan\beta$	$\kappa^L \cot\beta$
IV/X	$\kappa^U \cot\beta$	$\kappa^D \cot\beta$	$-\kappa^L \tan\beta$

F. Mahmoudi, O.Stal, Phys.Rev.D81 (2010) 035016 [arXiv:0907.1791]

- Set $s_{\beta-\alpha} = 1$:
  all h-fermion couplings equal to their SM values!

2HDM type I

Type I

ρ^U	ρ^D	ρ^L
$\kappa^U \cot\beta$	$\kappa^D \cot\beta$	$\kappa^L \cot\beta$

- Basically suitable for low $\tan\beta$, couplings suppress with growing $\tan\beta$
- Since all couplings have a common $\cot\beta$ factor, the fermion mass plays the key role
- Higgs-top coupling sizable at low $\tan\beta$ or moderate values
- $H \to t\bar{t}$ has a visible decay(event) rate : di-top invariant mass on top of the background.
- Higgs-gauge-Higgs interactions dominate if kinematically allowed : $A \to ZH$ if $m_A - m_H > m_Z$

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2HDM type II

Type II

ρ^U	ρ^D	ρ^L
$\kappa^U \cot\beta$	$-\kappa^D \tan\beta$	$-\kappa^L \tan\beta$

- Used in MSSM (Minimal Supersymmetric SM)
- Down type quarks couplings enhanced as $\tan\beta$ grows
- When $\kappa^t \cot\beta = \kappa^b \tan\beta$ or $\tan\beta \simeq 6.5$, the same Higgs coupling with bottom and top quarks
- At high $\tan\beta$, ρ^L exceeds κ^L which is SM value

  Consequences :
  - Charged Higgs coupling with τ increases with increasing $\tan\beta$
  - $H^+ \to \tau\nu$ is added to SM $W^+ \to \tau\nu$ leading to an apparent violation of "leptonic decay universality"

2HDM type III

Type III

ρ^U	ρ^D	ρ^L
$\kappa^U \cot\beta$	$-\kappa^D \tan\beta$	$\kappa^L \cot\beta$

- Similar to type II but with lepton coupling suppressed as $\cot\beta$
- Quark couplings slightly larger due to the leptonic coupling suppression at high $\tan\beta$
- Neutral Higgs bosons are "leptophobic"

2HDM type IV

Type IV

ρ^U	ρ^D	ρ^L
$\kappa^U \cot\beta$	$\kappa^D \cot\beta$	$-\kappa^L \tan\beta$

- Couplings to all quarks suppressed as $\cot\beta$
- Leptonic coupling is enhanced as $\tan\beta$ at high $\tan\beta$ values
- Clear leptonic decay signals can be observed at colliders
- Neutral Higgs decays like $H \to \mu\mu$ is visible at high $\tan\beta$
- The Higgs boson is called “Leptophilic”

But why 2HDM?

2HDM fits to the collected experimental data better than SM!

Observable	Experimental	SM prediction	$\Delta\chi^2_{\rm SM}$	2HDM fit	$\Delta\chi^2_{\rm 2HDM}$	Pull
$\mathrm{BR}(\mathrm{B} \to \mathrm{X_s}\gamma)$	3.52×10^{-4}	3.07×10^{-4}	1.65	3.59×10^{-4}	0.04	0.21
$\Delta_0(B \to K^*\gamma)$	3.1×10^{-2}	7.8×10^{-2}	2.82	7.0×10^{-2}	1.88	1.37
ΔM_{B_d} (ps^{-1})	0.507	0.53	0.08	0.53	0.10	0.32
$\mathrm{BR}(\mathrm{B_u} \to \tau\nu_\tau)$	1.73×10^{-4}	0.95×10^{-4}	1.71	0.95×10^{-4}	1.72	-1.31
$\xi_{D\ell\nu}$	0.416	0.30	0.84	0.30	0.84	-0.91
$R_{\ell 23}(K \to \mu\nu_\mu)$	1.004	1.000	0.33	1.000	0.33	-0.58
$\mathrm{BR}(\mathrm{D_s} \to \mu\nu_\mu)$	5.8×10^{-3}	4.98×10^{-3}	3.32	4.98×10^{-3}	3.36	-1.83
$\mathrm{BR}(\mathrm{D_s} \to \tau\nu_\tau)$	5.7×10^{-2}	4.82×10^{-2}	3.82	4.82×10^{-2}	3.82	-1.95
		Total $\chi^2(\nu)$:	14.6 (8)		12.1 (6)	

F. Mahmoudi, O.Stal, Phys.Rev.D81 (2010) 035016 [arXiv:0907.1791]

My current activities

(I) Charged Higgs (MSSM, LHC)

My current activities

(I) Charged Higgs (MSSM, LHC)

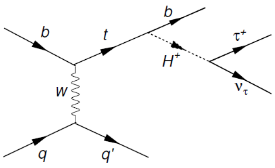
(II) Neutral Higgs (2HDM, Linear collider)

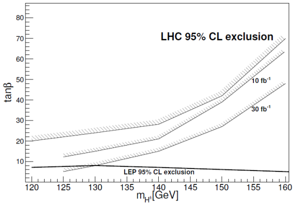
My current activities

(I) Charged Higgs (MSSM, LHC)
(II) Neutral Higgs (2HDM, Linear collider)
(III) Inert Doublet Model (LC and LHC)

Charged Higgs phenomenological search

(I) Light CH in single top events



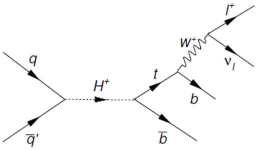


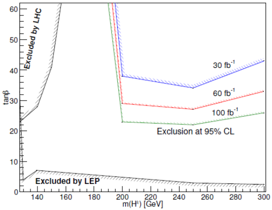
M. H. JHEP 1305 (2013) 112
[arXiv:1305.2096]

Charged Higgs phenomenological search

(I) Light CH in single top events

(II) Heavy CH in single top events





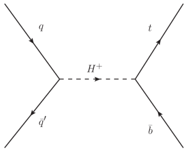
M. H. JHEP 1311 (2013) 005 [arXiv:1310.5209]

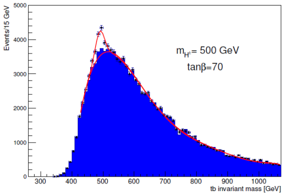
Charged Higgs phenomenological search

(I) Light CH in single top events

(II) Heavy CH in single top events

(III) Heavy CH in single top events (top tagging)

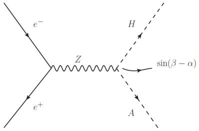


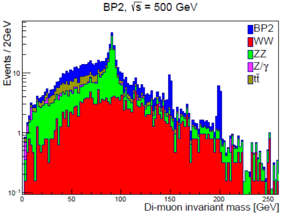


M. H., G. Haghighat, JHEP 1602 (2016) 040 [arXiv:1511.00874]

Neutral Higgs phenomenological search

(I) Synchronized leptophilic H and A search (type IV, linear collider)

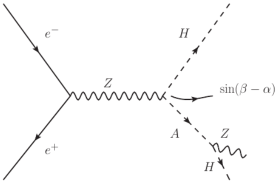


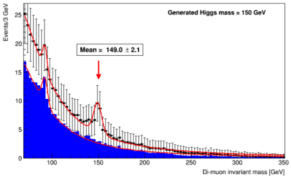


Neutral Higgs phenomenological search

(I) Synchronized leptophilic H and A search (type IV, linear collider)

(II) Search for H through $A \to ZH$ (type IV, linear collider)





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Neutral Higgs phenomenological search

(I) Synchronized leptophilic H and A search (type IV, linear collider)

(II) Search for H through $A \to ZH$ (type IV, linear collider)

(III) Search for $H \to t\bar{t}$ in type I

Ongoing work ...

Shiraz University

BSM Higgs: Pheno. (15th Feb. 2017)

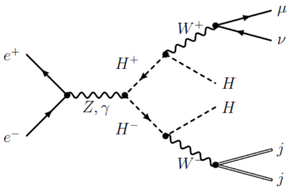
Majid Hashemi

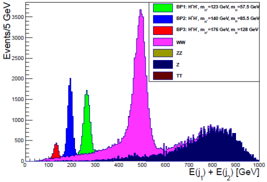
Inert doublet model

- IDM contains two $SU(2)$ doublets :
  $\phi_S = \begin{pmatrix} G^\pm \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix}$, $\phi_D = \begin{pmatrix} H^\pm \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix}$
- ϕ_S couples to SM fermions but ϕ_D remains "dark": No $H/A/H^\pm$ decays to fermions
- Dark sector decays like $A \to ZH$ or $H^+ \to W^+H$ can still occur
- In scenarios where $m_H^\pm > m_A > m_H$, H is the dark matter candidate
- Observability only through the decay products of gauge bosons Z and $W^\pm$
- m_H, m_A and $m_H^\pm$ can be well measured at a linear collider

Inert Doublet model searches

(I) IDM at a linear collider (CLIC, ILC, ...)





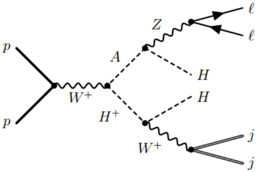
(b) $e^+e^- \to \ell\nu jjHH$ at $\sqrt{s} = 1$ TeV

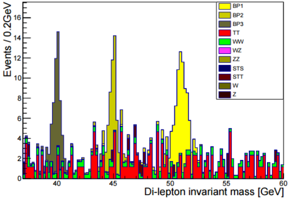
M. H., et. al., JHEP 1602 (2016) 187 [arXiv:1512.01175]

Inert Doublet model searches

(I) IDM at a linear collider (CLIC, ILC, ...)

(II) IDM at LHC, observable at low luminosity





- There is much room for the BSM Higgs searches from MSSM, 2HDM, IDM, ...
- Heavy charged Higgs to be searched through single top events
- Neutral Higgs searches should be performed at linear colliders: clear signals
- IDM can be verified at LHC low luminosity. A source of dark matter at LHC!
- There is much to be observed at LHC high luminosity and linear colliders.

Thank you for invitation!