Charged Higgs bosons in supersymmetric extended Higgs sectors at the LHC

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with A. Costantini, C. Coriano, K. Huitu, A. Sabanci and S. Niyogi

Priyotosh Bandyopadhyay
IIT Hyderabad, India
So far we have observed only one Higgs boson!
Status of minimal supersymmetric scenarios

Light Higgs boson around 125 GeV

• Trivial solution: Very large mass for super-partners
  \[ \gtrsim \text{few TeV} \]

• Or large mass splitting between the super-partners

• Fine tuning is necessary
Solution?

- Are there other Higgs bosons?
- Any theoretical possibility?
May be yes!

What are there gauge representations?

Another SU(2) doublet?

or/and singlet?

or/and triplet?
• There are possibility in different SU(2) representations

\[ S = s_r + i s_i \]

\[ Y = 0 \]

\[ T = \begin{pmatrix} T^0 \over \sqrt{2} & T^+ \\ T^- & -T^0 \over \sqrt{2} \end{pmatrix} \]
Triplet extension

- Model I: $Y=0$ Triplet extension

$$W_T = \lambda H_d \cdot T \cdot H_u + \mu_D H_d \cdot H_u + \mu_T Tr(T^2)$$

- It gives two additional triplet-like charged Higgs bosons
- Extra CP even and CP odd neutral Higgs bosons
- None of them couple to fermions
• Model II: A scale invariant superpotential with $Y=0$ SU(2) triplet and a singlet

$$W_S = \lambda_T H_d \cdot T H_u + \lambda_S S H_d \cdot H_u + \lambda_{TS} S T \text{Tr}[T^2] + \frac{\kappa}{3} S^3$$

• The complete Lagrangian with the soft SUSY breaking terms has an $Z_3$ symmetry

• During electro-weak symmetry breaking neutral parts get vev

$$< H_{u,d}^0 >= \frac{v_{u,d}}{\sqrt{2}}, \quad < S >= \frac{v_S}{\sqrt{2}}, \quad < T^0 >= \frac{v_T}{\sqrt{2}}$$

• Triplet vev contributes to the $W$ mass but not the $Z$ mass

$$m_W^2 = g_2^2 (v^2 + 4v_T^2) / 2 \quad \rho = 1 + 4v_T^2 / v^2$$

$$v_T \leq 5 \text{ GeV}$$
\[ V_{\text{soft}} = m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + m^2_S|S|^2 \\
+ m^2_T|T|^2 + m^2_Q|Q|^2 + m^2_U|U|^2 + m^2_D|D|^2 \\
+(A_S SH_d H_u + A_T H_d T H_u + A_T S S T r(T^2) \\
+ A_\kappa S^3 + A_U U H_U Q + A_D D H_D Q + h.c), \]

- In the limit where all the A parameters vanish the scalar potential accrues an enhanced U(1) symmetry

\[ (\hat{H}_u, \hat{H}_d, \hat{T}, \hat{S}) \rightarrow e^{i\phi}(\hat{H}_u, \hat{H}_d, \hat{T}, \hat{S}) \]

- If this symmetry is softly broken by very small A parameters \( \mathcal{O}(1)\text{GeV} \),

- We get a very light pseudoscalar as pseudo-Nambu-Goldstone boson of the symmetry.
Possibility of hidden scalars

- $h_4$
- $h_3$
- $a_3$
- $h_3^\pm$
- $a_2$
- $h_2^\pm$
- $h_2$
- $h_{125}$
- $h_1^\pm$
- $a_1$

Light pseudoscalar

What happened to the Higgs sector?

CP-even
$h_1, h_2, h_3, h_4$

CP-odd
$a_1, a_2, a_3$

Charged
$h_1^\pm, h_2^\pm, h_3^\pm$

Many Higgs bosons are possible
What is the gain?

\[ \Delta m_h \simeq \]

\[ m_{h_1}^2 \leq m_Z^2 (\cos^2 2\beta + \frac{\lambda_T^2}{g_L^2 + g_Y^2} + \frac{2\lambda_S^2}{g_L^2 + g_Y^2} \sin^2 2\beta) \]

Do not need much help from ‘super partners’

Supersymmetry can still exists below TeV!
Are there other theoretical motivations?

1. Spontaneous CP-violation
2. Solution of the $\mu$-D in supersymmetry
3. Possibility of hidden Higgs bosons
4. Vacuum stability

....
How exotic are they?

- Triplet does not couple to fermions
- Singlet does not couple to fermions
- Singlet does not couple to gauge bosons
- Neutral part of $Y=0$ Triplet does not couple to $Z$ boson
Gauge structure of charged Higgs boson

\[ h_i^{\pm} = R_{i1}^C H_u^+ + R_{i2}^C T_2^+ + R_{i3}^C H_d^- + R_{i4}^C T_1^- \]

- In particular the charged Goldstone has contribution from triplets

\[ R_{ij}^C = f_{ij}^C (v_u, v_d, v_T, v_S, \lambda_T, \lambda_{TS}, \lambda_S, A_i) \]

\[ h_0^{\pm} = \pm N_T \left( \sin \beta H_u^+ - \cos \beta H_d^- \pm \sqrt{2} \frac{v_T}{v} (T_2^+ + T_1^-) \right) \]

\[ N_T = \frac{1}{\sqrt{1 + 4 \frac{v_T^2}{v^2}}} \]

\[ \text{has a triplet contribution} \]

No \( \lambda_i \)
\( \lambda_T \approx 0 \) limit

\( \lambda_T = 0 \)

- \( h_{2,3}^\pm \) only can be pure triplets
- \( h_1^\pm \) has some doublet parts as perpendicular mode of the charged Goldstone

Not 100%
Charged Higgs boson search

- Standard Model does not have any charged Higgs boson
- Finding a charged Higgs boson is obvious proof of extended Higgs sectors, thus new physics
- Supersymmetry needs at least one charged Higgs boson
- Mostly searched Charged Higgs bosons are doublet type and couple to fermions
- Viz. 2HDM, MSSM
Experimental searches of the charged Higgs boson

- LHC looked for this doublet type charged Higgs bosons via mainly its couplings to fermions

- Light charged Higgs boson: \( pp \rightarrow t\bar{t} \rightarrow bW^{+}\bar{b}H^{-} \)

- Heavy charged Higgs boson: \( pp \rightarrow t\bar{b}H^{\pm} \)

- Where charged Higgs boson is search in decay modes \( \tau + \nu \ \text{and} \ t + b \)
CMS puts 95% Cl upper limits as: $E_{cm} = 13$ TeV and 12.9 fb$^{-1}$

$$B(t \rightarrow bH^\pm) \times B(H^\pm \rightarrow \tau\nu) = 0.004 - 0.05 \text{ for } m_{H^\pm} \sim 80 - 160 \text{ GeV}$$

$$\sigma(pp \rightarrow H^\pm W^\pm b\bar{b}) \times B(H^\pm \rightarrow \tau\nu) = 2 - 0.01 \text{ pb for } m_{H^\pm} \sim 180 \text{ GeV} - 3 \text{ TeV}$$

CMS-PAS-HIG-16-031

ATLAS puts 95% Cl upper limits as: $E_{cm} = 13$ TeV and 3.2 fb$^{-1}$

$$\sigma(pp \rightarrow tbH^\pm) \times B(H^\pm \rightarrow \tau\nu) = 1.9 \text{ pb} - 15 \text{ fb for } m_{H^\pm} \sim 200 - 2000 \text{ GeV}$$

PLB 759(2016)555-574
Charged Higgs in NMSSM

- NMSSM has one doublet like charged Higgs boson

- NMSSM, TNSSM with $Z_3$ symmetry has a light pseudoscalar which opens a new mode
  \[ h^\pm \rightarrow a_1 W^\pm \]

- bg fusion processes are important

$1b + 2\tau + 2\ell + E_T, \ 1b + 2\tau + 2j + 1\ell + E_T, \ 3b + 2\ell + E_T$ final states can probe the light charged Higgs bosons with the early data at the LHC @14 TeV


Similar analysis in Type II 2HDM by Coleppa, Kling, Su
Triplet charged Higgs bosons do not decay into fermions

\[ W = \lambda_T H_d.T.H_u + m_T Tr[T^2] \]

- This makes it hard to produce them at colliders
- Also to detect
- Is there a way to probe this exotic type of charged Higgs bosons?
• Triplet type charged Higgs boson give rise to a non-standard vertex by breaking of custodial symmetry

\[ g_{h_i^\pm W^\pm Z} = -\frac{1}{2}i g_2 \left( g_1 \sin \theta_W (v_u R_{i+1} - v_d R_{i+1}) - \frac{1}{2} i g_2 \left( \sqrt{2} g_2 v_T \cos \theta_W (R_{i+1} + R_{i+1}^\dagger) \right) \right). \]

\[ \theta_W \] is the Weinberg angle and \( h_i = R_{ij} H_j \)

\[ h_i^\pm \rightarrow t b \]
\[ \rightarrow Z W^\pm \]
\[ \rightarrow \tau \nu \]
\[ \rightarrow h_j W^\pm \]

• Mixing with the doublets is crucial for the decays as well as production channels
Vector boson fusion to charged Higgs boson

- $h_1^\pm - W^\mp - Z$ coupling creates additional tree-level production mode for the charged Higgs boson

- This process is absent for doublet-like charged Higgs boson
Experimental bounds on the Triplet charged Higgs

- CMS puts 95% CI upper limits on $\sigma_{VBF} \times (H^\pm \rightarrow W^\pm Z)$ for $200 \leq m_{H^\pm} \leq 2000$ GeV
  
  CMS-PAS-HIG-16-027/PRL119(2017)141802

- ATLAS puts 95% CI upper limits at $E_{cm} = 8$ TeV with 20.3 fb$^{-1}$
  
  $\sigma_{VBF} \times B(H^\pm \rightarrow ZW^\pm) \sim 31 - 1020$ fb for $200 \leq m_{H^\pm} \leq 2000$ GeV
  
  PRL 114,23801(2015)

- Doubly charged Higgs boson: $E_{cm} = 13$ TeV with 36.1 fb$^{-1}$
  
  $m_{H^{++}} > 770 - 870$ GeV
Look for new production modes

- Multi-leptonic final states can probe the triplet mode

- $3\ell + 2j$, $3\ell + 2b$ final states can probe such triplet signature by $\sim 100 \text{ fb}^{-1}$ of integrated luminosity at the LHC@14 TeV

- Higher lepton multiplicities can be probed at further higher luminosities.

P.B, Katri Huitu, Asli Sabanci, JHEP05(2015)026
Is it possible to distinguish different possible extensions?

\[ W_S = \lambda_T H_d . T H_u + \lambda_S S H_d \cdot H_u + \lambda_T S Tr[T^2] + \frac{\kappa}{3} S^3 \]

**Triplet signature**

**Existence of light pseudoscalar**
• Probing $a_1 W^\pm$ and $ZW^\pm$ together is challenging

• $a_1 W^\pm$ can be probed via $2b + 2\tau + 1\ell + m_{jj} \sim m_W$ at the LHC with 43 fb$^{-1}$

• ZW mode can be probed via $3\ell + 1\tau$ with 54 fb$^{-1}$

• Light pseudo scalar mass can probed with early data of 55 fb$^{-1}$

• Probing charged Higgs mass via reconstruction of Z and W will take around 712 fb$^{-1}$ of integrated luminosity

• It is possible to distinguish charged Higgs bosons from different representations of SU(2)

PB, Antonio Costantini, arXiv:1710.03110
Status of non-zero Hyper-charged triplets charged Higgs bosons

- $Y = \pm 1$ invokes $H^{\pm\pm}$ in the spectrum but constrained from $\rho$ parameter
- $Y = \pm 1, 0$ can form custodial triplets known as Georgi-Machacek triplets which can evade the constraints from $\rho$ parameter

For these cases one needs to find out the doubly charged states with the given hierarchy
Conclusions

• So far we have observed one Higgs boson at 125 GeV

• All possible Standard Model modes are yet to be discovered.

• Hidden Higgs is still a possibility.

• Observation of Charged Higgs would be a direct proof of extended Higgs sector.

• Non-standard decay modes \( h^\pm \rightarrow a_1 W^\pm \) and \( h^\pm \rightarrow ZW^\pm \) are direct proofs of higher representations of Higgs sectors.

• Indirect searches can also give us some hints

• We hope LHC bring some more discoveries
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Thank You!