Charged Higgs Beyond the MSSM at the LHC

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Outline:

Motivation

Charged Higgs in MSSM

Charged Higgs in singlet extensions

$H^{\pm} \rightarrow aW^{\pm}$

Charged Higgs in triplet extensions

$H^{\pm} \rightarrow ZW^{\pm}$

light $H^{\pm\pm}$

Summary

Motivation

A Higgs boson, *h,* was detected in 2012, and is now well established:

$m_h \sim 125.09 \pm 0.24$ GeV

Higgs couplings to fermions still have uncertainties, but so far compatible with the Standard Model

Problems of the Standard Model are evident:

dark matter, neutrino masses, hierarchy problem, CP, flavour, ….

Many of these may be related to the scalar sector!

Scalars natural ingredients in the particle spectrum in supersymmetric framework

In susy extensions of the SM, always another doublet (2HDM II)

→ $h, H, A, H^{\pm}$

Note: in supersymmetric extensions of the SM, always $H^{\pm}$

To study the charged Higgs, needs to be discovered!

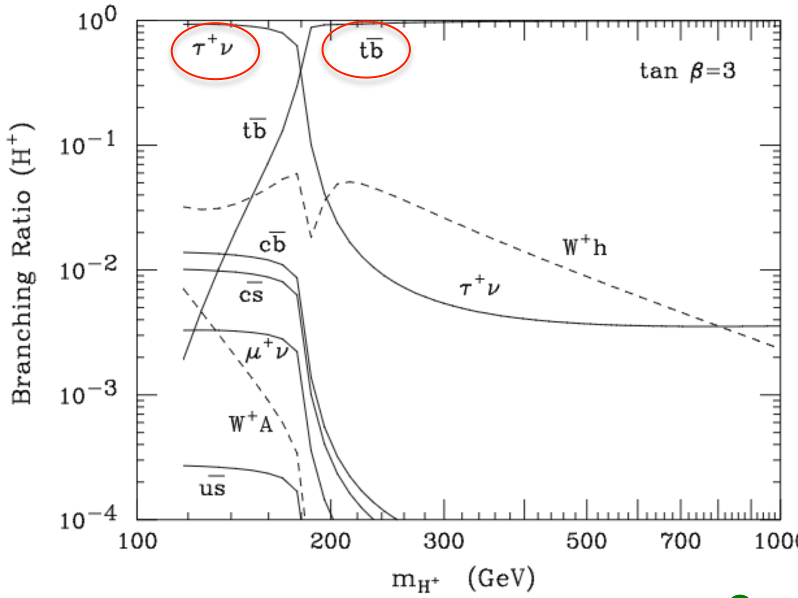
Both production and decay depend on the particular model
Mass and mass relations also depend on the particular model
Identify the model with model specific signals

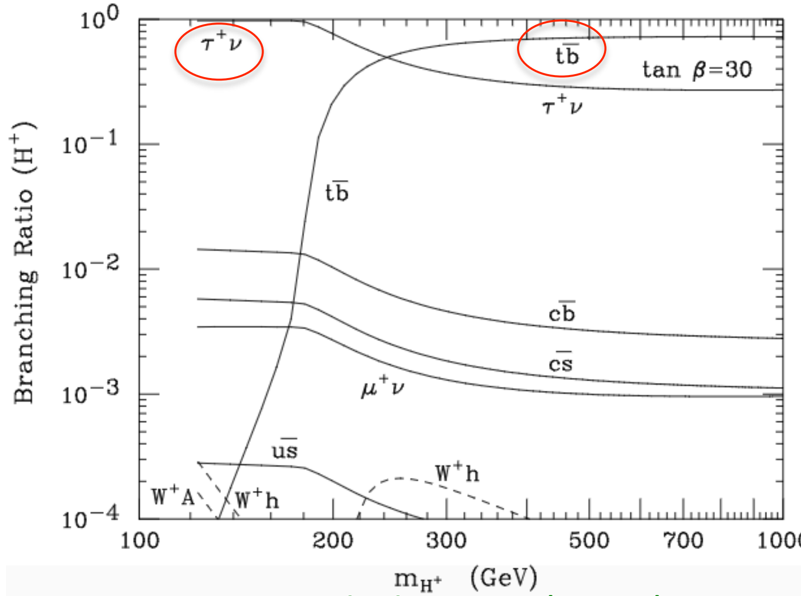
Charged Higgs in MSSM

At tree-level:

$$m^2_{H,h} = \frac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{\left(m_A^2+m_Z^2\right)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta}\right),\quad m^2_{H^\pm} = m_A^2 + m_W^2$$

Heavy H, A, $H^\pm$ nearly degenerate in MSSM





Carena, Haber, Prog.Part.Nucl.Phys. 50 (2003) 63-152

Charged Higgs main production channels: gg and gb fusions

Charged Higgs has been searched at the LHC.

At Run 1 charged Higgs also lighter than top quark was searched

$$pp \to t\bar{t} \to bW^+\bar{b}H^-,\ Br\left(t \to bH^\pm\right) \times Br\left(H^+ \to \tau^+\nu_\tau\right)$$

At 13 TeV no signal of charged Higgs has been seen so far:

$$H^+ \to \tau^+\nu_\tau \quad 200 < m_{H^\pm} < 2000\,\text{GeV},\ \text{ATLAS}\,14.7\,\text{fb}^{-1}$$

$$H^+ \to t\bar{b} \quad 300 < m_{H^\pm} < 1000\,\text{GeV},\ \text{ATLAS}\,13.2\,\text{fb}^{-1}$$

$$H^+ \to W^+Z \quad 200 < m_{H^\pm} < 1000\,\text{GeV},\ \text{CMS}\,15.2\,\text{fb}^{-1}$$

(Georgi-Machachek model)

Note: Large BR to other channels may change the limits

Other representations in extensions of MSSM

For possible representations a constraint from electroweak ρ-parameter. At tree level

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{\sum_{T,Y}(4T(T+1)-Y^2)|V_{T,Y}|^2 c_{T,Y}}{\sum_{T,Y} 2Y^2 |V_{T,Y}|^2}$$

Experimentally $\rho = 1.0004^{+0.0003}_{-0.0004}$

For singlets and doublets with Y=±1, ρ=1 at the tree level. Constrains VEVs of Y=0 and Y=2 triplet models unless contributions cancel (e.g. Georgi-Machacek –model).

Charged Higgs in singlet extensions, NMSSM

In NMSSM an additional singlet (assume $\boldsymbol{Z}_3$):

$$W_{NMSSM} = W_{MSSM}^{\mu=0} + \lambda_S S H_u \cdot H_d + \frac{1}{3}\kappa S^3$$

NMSSM Higgs content: h_1, h_2, h_3, a_1, a_2, $h^\pm$

Motivations for NMSSM beyond MSSM:

-generate the μ-term through $\langle S \rangle$, $\mu_{eff}=\lambda_S \langle S \rangle$

-have new contributions to the lightest Higgs mass

$$\Delta m_h^2 = \frac{\lambda^2}{g^2} M_Z^2 \sin^2 2\beta$$

→ does not necessarily need large radiative corrections;
no Landau poles →$\lambda<0.7$

Charged Higgs is in doublet, and thus couples to fermions like in MSSM

Different from the MSSM, the lightest pseudoscalar can be a singlet and light.

LHC searches for $h \rightarrow aa$ has not seen a signal. We assume that $m_a > 125$ GeV/2

Top decay to $h^{\pm}$ has not been seen ⇨ we assume that $h^{\pm}$ is slightly heavier than the top quark.

One may search in $h^{\pm} \rightarrow a_1 W^{\pm}$

if kinematically possible

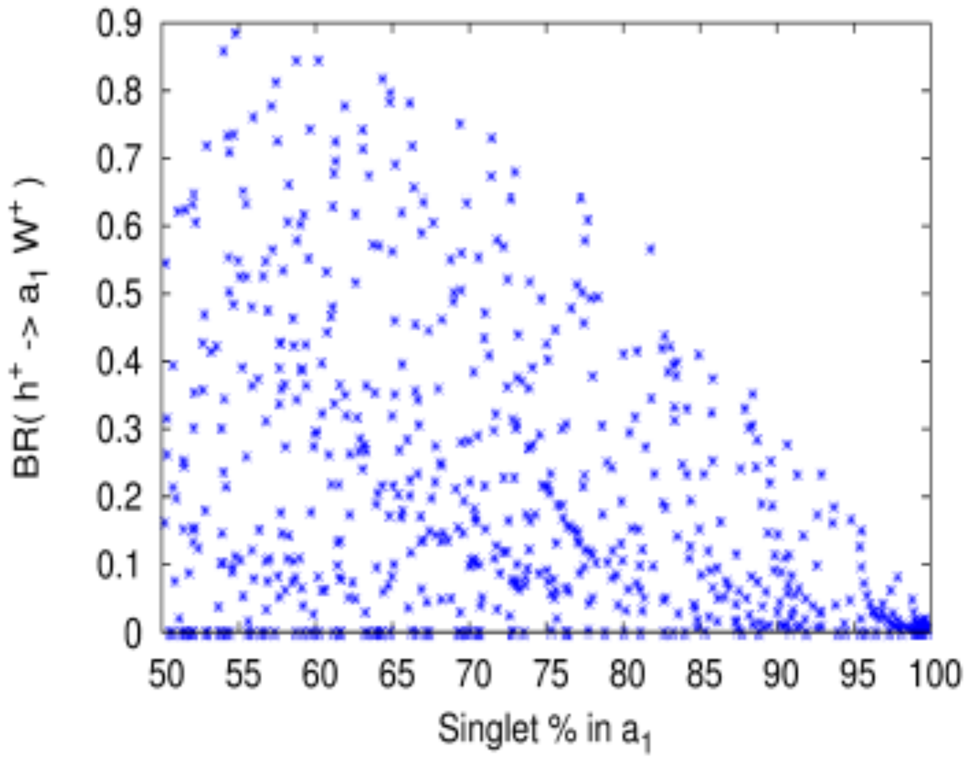
if $h^{\pm} - a_1 - W$ –coupling exists ⇨ need doublet component in a_1

Scan over

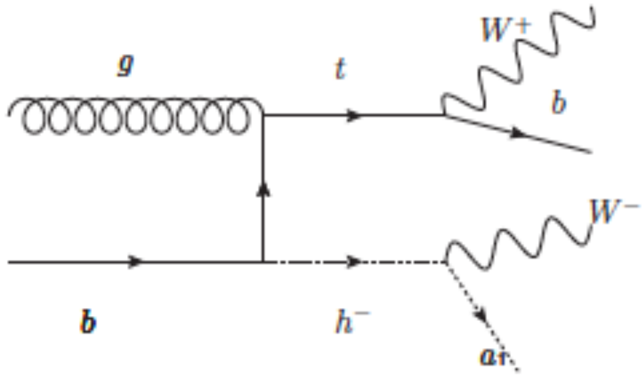
$$\begin{array}{rcccl} 2.0 & \leq & \tan\beta & \leq & 40.0 \\ -1000.0 & \leq & \mu & \leq & 1000.0 \\ 0.01 & \leq & \lambda, \kappa & \leq & 1.0 \\ 0 & \leq & M_A & \leq & 400.0 \\ -1000.0 & \leq & A_\kappa & \leq & 1000.0 \\ -2000.0 & \leq & A_t & \leq & 2000.0 \end{array}$$

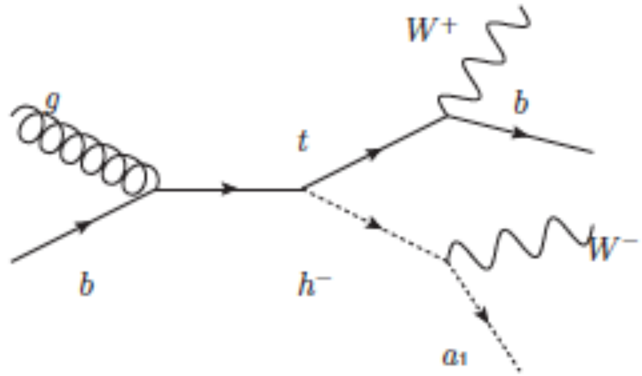
with fixed

$$M_1 = 100 \text{ GeV}, \quad M_2 = 200 \text{ GeV}, \quad M_3 = 1.5 \text{ TeV},$$
$$M_{L_{1,2}} = 500 \text{ GeV} = M_{E_{1,2}}, \quad M_{L_3} = 500 \text{ GeV} = M_{E_3},$$
$$M_{Q_{1,2}} = 1.0 \text{ TeV} = M_{U,D_{1,2}},$$
$$M_{Q_3} = 700 \text{ GeV}, \; M_{U_3} = 900 \text{ GeV}, \; M_{D_3} = 800 \text{ GeV},$$
$$A_{b,\tau} = 100 \text{ GeV},$$



Dominant production mode both at small and large tan β:





a_1 decays to bb (~90%) or to $\tau\tau$ (~10%)

Studied signals:

$a_1 \rightarrow \tau\tau$, both W decay leptonically: $1b+2\tau+2lepton+E_{tmiss}$, 5σ with $122fb^{-1}$

$a_1 \rightarrow \tau\tau$, one W leptonically, one hadronically: $1b+2\tau+2j+1lepton +E_{tmiss}$, 5σ with $10fb^{-1}$

$a_1 \rightarrow bb$, both W decay leptonically, $3b+2lepton+E_{tmiss}$

Model with Y=0 triplet (TESSM)

Superpotential:

$$W_{TESSM} = W_{MSSM}^{\mu=\mu_D} + \lambda H_d \cdot T H_u + \mu_T TR\left(TT\right)$$

The triplet can be written as

$$T = \begin{pmatrix} \sqrt{\frac{1}{2}} T^0 & T_2^+ \\ T_1^- & -\sqrt{\frac{1}{2}} T^0 \end{pmatrix}$$

The electroweak symmetry breaks and the gauge bosons achieve masses when

$$\langle H_u^0 \rangle = \frac{v_u}{\sqrt{2}}, \ \ \langle H_d^0 \rangle = \frac{v_d}{\sqrt{2}}, \ \ \langle T^0 \rangle = \frac{v_T}{\sqrt{2}}$$

Higgs sector: h_1, h_2, h_3, a_1, a_2, $h^{\pm}_1$, $h^{\pm}_2$, $h^{\pm}_3$

Constraint from the electroweak ρ parameter (new contribution to W mass):

$$\rho = 1 + \frac{4v_T^2}{v_u^2 + v_d^2}$$ Using $\rho = 1.0004^{+0.0003}_{-0.0004}$ we find $v_T < 5$ GeV

➡ Cannot get rid of μ_D –parameter

Tree-level Higgs mass contribution:

$$m_{h_1^0}^2 \leq m_Z^2 \left(\cos 2\beta + \frac{\lambda^2}{g_Y^2 + g_L^2} \sin 2\beta \right)$$

Correction important for small tan β, large λ

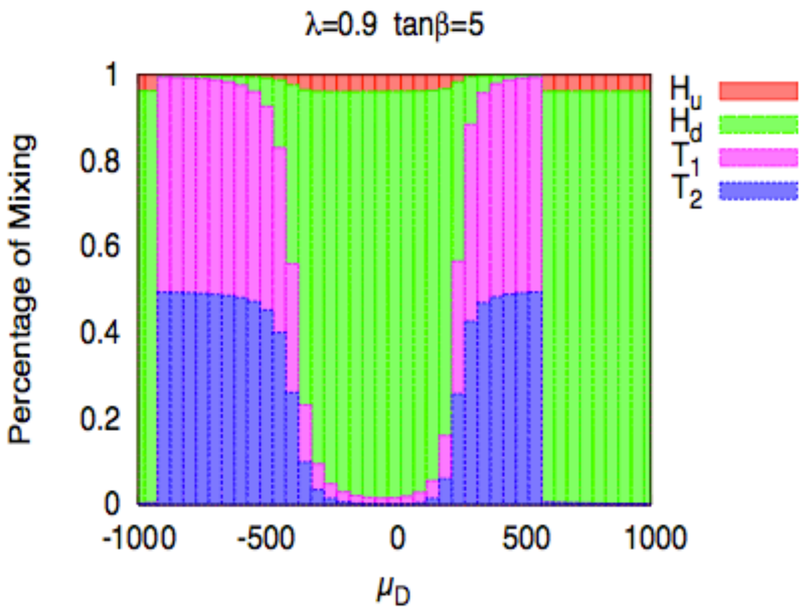
In addition: new radiative corrections from the Higgs sector; also corrections from neutralinos and charginos for the lightest Higgs are important Bandyopadhyay,DiChiara, KH, Keceli, JHEP 1411 (2014) 062

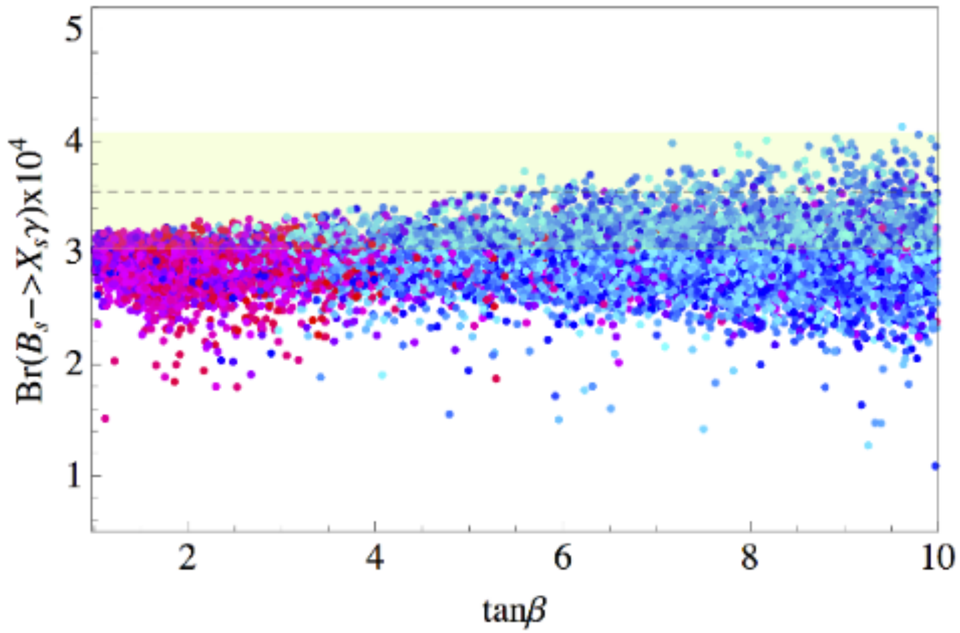
The triplet component in charged Higgs changes constraint from B→$X_s\gamma$:

More charged Higgses: more top-charged Higgs and stop-chargino –loops

If the lightest charged Higgs triplet dominated

→ no strong constraint from B→$X_s\gamma$





Different from MSSM and NMSSM:

$H^{\pm}WZ$ –coupling at the tree level.

Triplets do not couple directly to the fermions.

→ Decay channel $h^{\pm} \to ZW^{\pm}$

Production through vector boson fusion

$H^{\pm}WZ$-coupling in TESSM:

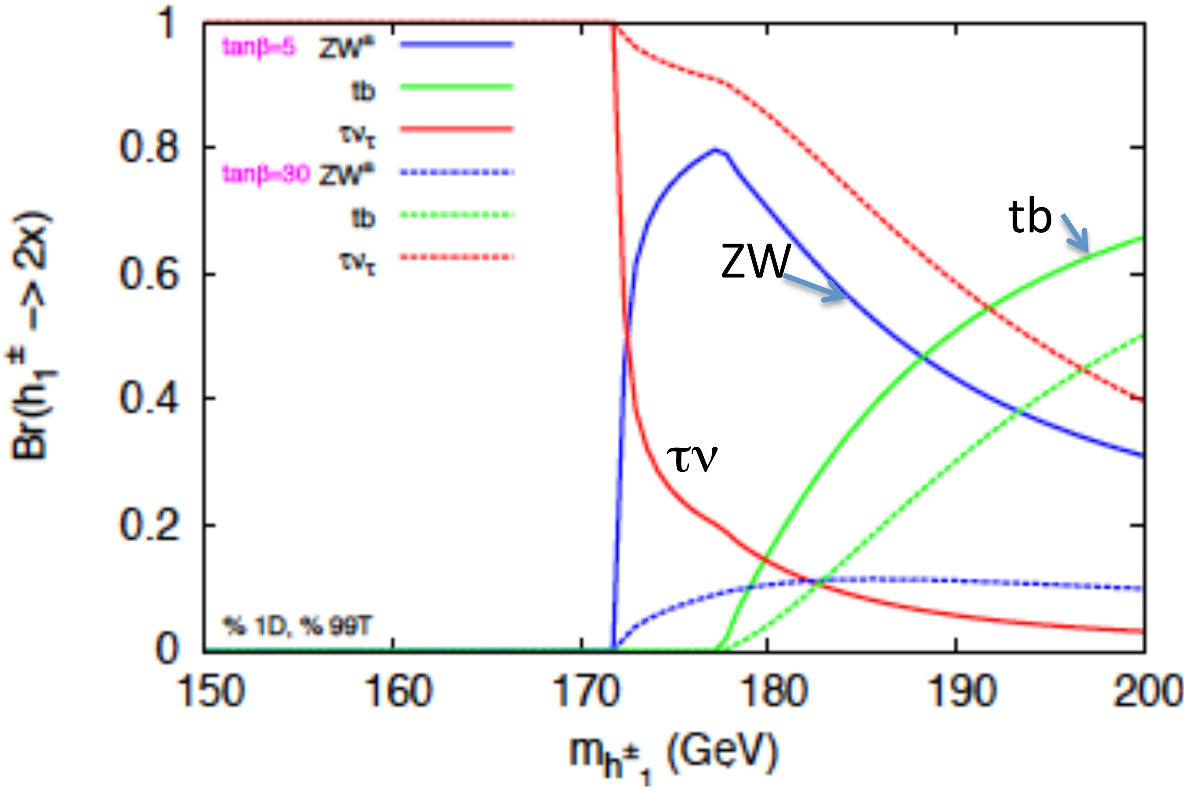
$$g_{h_i^{\pm}W^{\mp}Z} = -\frac{1}{2} i g_2 \Big[g_1 \sin\theta_w (v_u R_{(i+1)1} - v_d R_{(i+1)2}) + \sqrt{2} g_2 v_T \cos\theta_w (R_{(i+1)3} + R_{(i+1)4}) \Big]$$

$$h_i = R_{ij} H_j$$

Note: for $H^{\pm}W\gamma$-coupling to vanish, need $v_T \neq 0$

Important decay modes:

$$h_i^\pm \to tb$$
$$\to ZW^\pm$$
$$\to \tau\nu$$
$$\to h_j W^\pm$$



Study the production processes and decay channels with non-negligible $H^\pm WZ$ –vertex

Consider a rather light charged Higgs (~200 GeV);

tan $\beta \leq 10$, large λ →need for loop corrections in h_1 not sizable

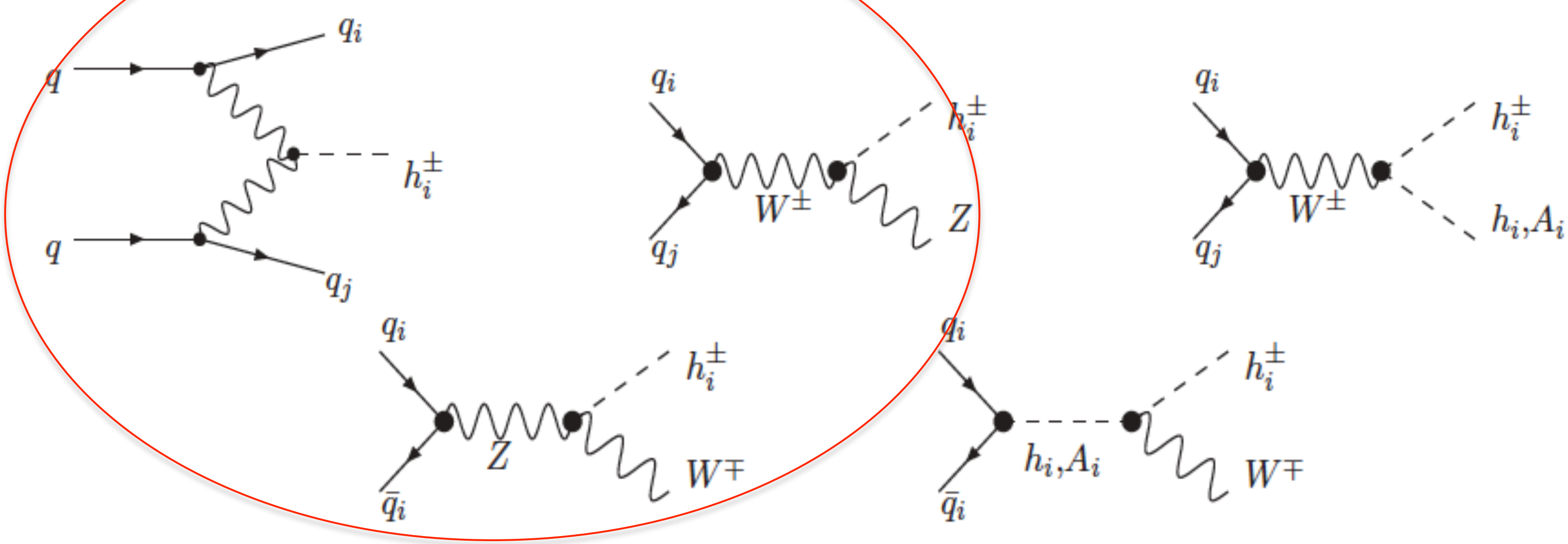
h_2 or A_1 not degenerate with charged Higgs

→ h_2 or A_1 → $h_1^{\pm}W$ kinematically possible contrary to MSSM

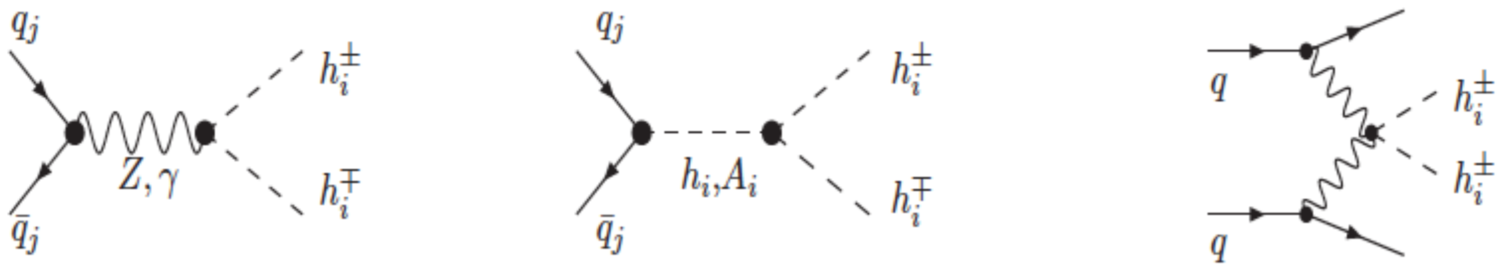
Benchmark Points	$\tan\beta$	m_{h_2} (GeV)	m_{A_1} (GeV)	$m_{h_1^\pm}$ (GeV)	Doublet % in h_2	Doublet % in A_1	Triplet % in $h_1^\pm$
BP1	8.63	182.898	610.91	182.942	1.34	99.967	98.88
BP2	4.89	216.94	451.453	216.41	0.2	$< 10^{-5}$	99.88
BP3	6.32	441.507	198.438	197.854	0.12	$< 10^{-5}$	99.99
BP4	7.23	362.843	184.706	183.637	0.78	0.006	99.98

Production not dominantly through top decay, gg or gb –fusions or qq –annihilation, since triplet does not couple to fermions!

Single production:



Pair production:



5σ signal can be achieved in favourable part of parameter space by multilepton final states with ~100 fb^{-1}:

$$h_i^{\pm} \to ZW^{\pm} \to (\ell\ell)(\ell\nu)$$

From the associated h_2/a_1, $W^{\pm}$, $h^{\pm}$ one can get two light jets, leading to

$$\geq 3\ell\left(\left|M_{\ell\ell} - M_Z\right| \leq 5\,\mathrm{GeV}\right) + \geq 2j + \not{p}_T$$

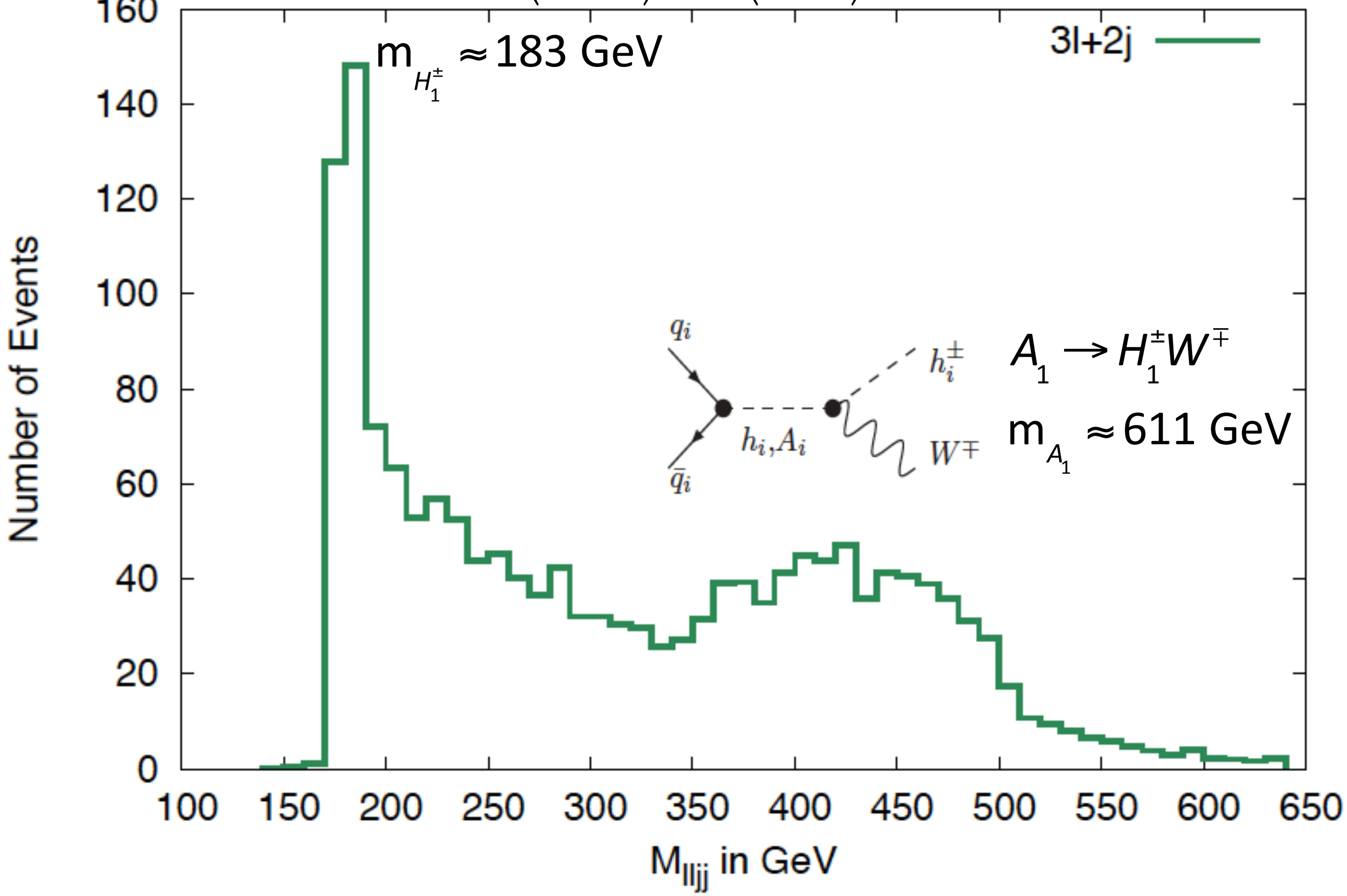
Similarly >3leptons + (>2 b-jets or > 1 tau-jet) final state can be probed with ~100 fb^{-1}.

Final states with four, five or six leptons need more than 1000 fb^{-1}

Bandyopadhyay, KH, Keceli, JHEP 05 (2015) 026

Information on other heavy Higgses from the edges in kinematical distributions (BP1):

$H_1^\pm \to Z(\to \ell\ell)W^\pm\ (\to jj)$



Model with Y=2 triplet (SUSYLR: $SU(2)_L xSU(2)_R xU(1)_{B-L}$)

-Gauge symmetry extended to $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$; e.g. from SO(10) or E_6 unified model
-B-L as gauge symmetry leads to conserved (or spontaneously broken) R-parity → LSP is a dark matter candidate
-neutrino masses can arise via seesaw if triplets included

Higgs sector:

$$\Phi_1 = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} = (\mathbf{1}, \mathbf{2}, \mathbf{2}^*, 0) \,, \qquad \Phi_2 = \begin{pmatrix} \chi_1^0 & \chi_2^+ \\ \chi_1^- & \chi_2^0 \end{pmatrix} = (\mathbf{1}, \mathbf{2}, \mathbf{2}^*, 0) \,,$$

$$\Delta^c = \begin{pmatrix} \frac{\delta^{c\,-}}{\sqrt{2}} & \delta^{c\,0} \\ \delta^{c\,--} & \frac{-\delta^{c\,-}}{\sqrt{2}} \end{pmatrix} = (\mathbf{1}, \mathbf{1}, \mathbf{3}, -2) \,, \qquad \bar{\Delta}^c = \begin{pmatrix} \frac{\bar{\delta}^{c\,+}}{\sqrt{2}} & \bar{\delta}^{c\,++} \\ \bar{\delta}^{c\,0} & \frac{-\bar{\delta}^{c\,+}}{\sqrt{2}} \end{pmatrix} = (\mathbf{1}, \mathbf{1}, \mathbf{3}, 2) \,,$$

$$S = (\mathbf{1}, \mathbf{1}, \mathbf{1}, 0) \,.$$

Higgs sector: $h_{1\ldots7}$, $a_{1\ldots5}$, $h^{\pm}{}_{1\ldots4}$, $h^{\pm\pm}{}_{1\ldots2}$

Two step breaking $SU(2)_R \times U(1)_{B-L} \xrightarrow{M_R} U(1)_Y$, $SU(2)_L \times U(1)_Y \xrightarrow{M_W} U(1)_{em}$

$$\langle S\rangle = \frac{v_s}{\sqrt{2}} e^{i\alpha_s}\,, \quad \langle\Phi_1\rangle = \begin{pmatrix} \frac{v_1}{\sqrt{2}} & 0 \\ 0 & \frac{v_1'}{\sqrt{2}} e^{i\alpha_1} \end{pmatrix}\,, \quad \langle\Phi_2\rangle = \begin{pmatrix} \frac{v_2'}{\sqrt{2}} e^{i\alpha_2} & 0 \\ 0 & \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

$$\langle\Delta^c\rangle = \begin{pmatrix} 0 & \frac{v_R}{\sqrt{2}} \\ 0 & 0 \end{pmatrix}, \quad \langle\bar{\Delta}^c\rangle = \begin{pmatrix} 0 & 0 \\ \frac{\bar{v}_R}{\sqrt{2}} & 0 \end{pmatrix}.$$

Small $W_L - W_R$ mixing proportional to $v_i v'_i e^{i\alpha}$

$$\Rightarrow \quad v_R, \bar{v}_R \gg v_2, v_1 \gg v_1' = v_2' \approx 0 \qquad \text{and} \qquad \alpha_1 = \alpha_2 = \alpha_s \approx 0$$

Extra contribution to tree level m_h:

$$m_h^2 \leq \left(1 + \frac{g_R^2}{g_L^2}\right) m_{W_L}^2 \cos^2 2\beta,$$

Frank, Ghosh, KH, Rai, Saha, Waltari, PRD 90 (2014) 115021
KH, Pandita, Puolamaki, PLB 423 (1998) 97

Radiative corrections are needed in order to have stable vacuum: radiative corrections take care of charge conservation

One doubly charged Higgs always light (a few 100 GeV)

- tau-stau –loop raises doubly charged Higgs mass positive

→ the Yukawa coupling to triplets > 0.6 favored

⇒ Assume $H^{--} \to \tau\tau$

Different from MSSM, NMSSM, TESSM: triplet has doubly charged Higgs bosons.

⇒ Singly charged and light doubly charged Higgs bosons
Potentially large contribution to $h \to \gamma\gamma$

Doubly charged particles couple with double strength to photons, BUT

$$H_1^{++} \equiv a\delta^{c++} + b\overline{\delta}^{c++}, \quad a \sim b$$

$$g_{hH^{++}H^{--}} \approx O\left(a^2 - b^2\right)$$

coupling to the lightest neutral Higgs for consistent models always suppressed,

$$g_{hH^{\pm\pm}H^{\mp\mp}} / g_{hH^{\pm}H^{\mp}} \approx 1/20$$

and the singly charged Higgs contribution to $\gamma\gamma$ decay is larger.

Frank, Ghosh, KH, Rai, Saha, Waltari, PRD 90 (2014) 115021

The lightest charged Higgs mostly doublet, similar to MSSM charged Higgs.

Summary

Extended models are less fine-tuned than MSSM

Properties of the charged Higgs may tell about the structure and symmetries of the Higgs sector.

It is important to cover all possibilities for final states – even a light charged Higgs can escape detection

"Exotic" channels, like $h^{\pm} \to a_1 W^{\pm}, \quad h^{\pm} \to ZW^{\pm}$, are probing the Higgs representations.

Doubly charged Higgs may decay to same sign taus
→ possible to find if kinematically accessible.