Extended Scalar Sectors and new Physics Beyond the Standard Model

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Talk given at
First Pan-African Astro-Particle and Collider Physics Workshop.

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March 22, 2022

Outline

1. Arts of states of Standard Model

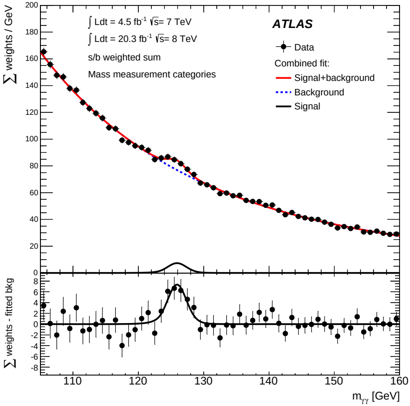
2. Two Higgs doublet model: potential and Yukawa couplings

3. LHC strategies searches for $H^{\pm}$ at the LHC

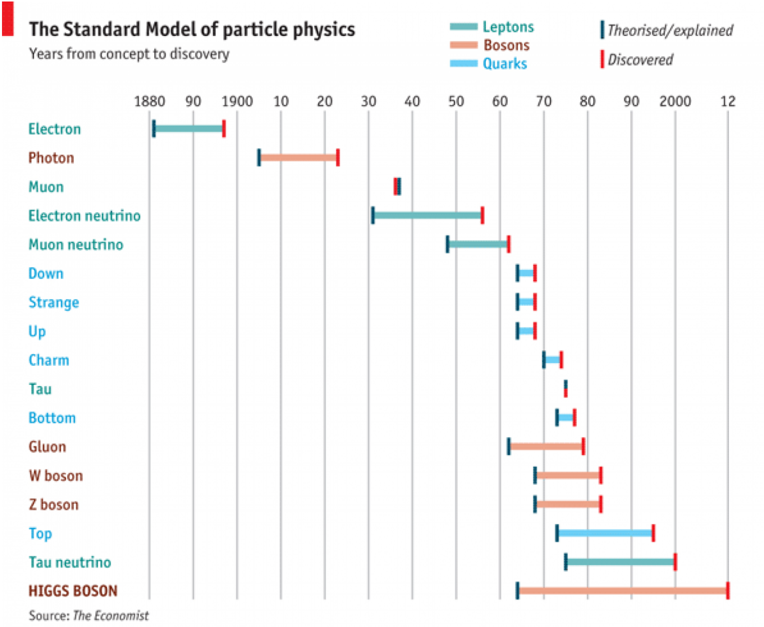
4. Conclusions and perspectives

Evidence for a Standard Model like Higgs boson

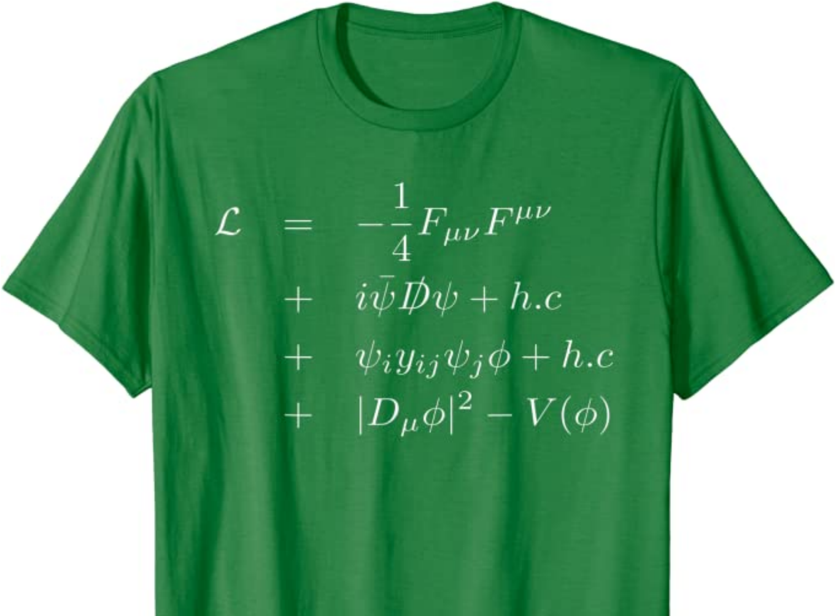
- In the summer of 2012 an SM-like particle (h) was found at the LHC.
- So far its properties agree with SM predictions at tthe 20% level.
- Its mass derived from the $\gamma\gamma$ and ZZ channels is



Status of SM particle physics



SM Lagrangian: Short form



SM Lagrangian: complete form before EWSB (A. Djouadi: Phys. Rept. **457** (2008), 1-216)

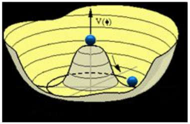
$$
\begin{aligned}
\mathcal{L}_{SM} = \; & \underbrace{\frac{1}{4} W_{\mu\nu} \cdot W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} G^{\alpha}_{\mu\nu} G^{\mu\nu}_{\alpha}}_{\text{kinetic energies and self-interactions of the gauge bosons}} \\
+ \; & \underbrace{\bar{L} \gamma^{\mu} \left(i\partial_{\mu} - \frac{1}{2} g \tau \cdot W_{\mu} - \frac{1}{2} g' Y B_{\mu} \right) L + \bar{R} \gamma^{\mu} \left(i\partial_{\mu} - \frac{1}{2} g' Y B_{\mu} \right) R}_{\text{kinetic energies and electroweak interactions of fermions}} \\
+ \; & \underbrace{\frac{1}{2} \left| \left(i\partial_{\mu} - \frac{1}{2} g \tau \cdot W_{\mu} - \frac{1}{2} g' Y B_{\mu} \right) \phi \right|^{2} - V(\phi)}_{W^{\pm}, Z, \gamma \text{ and Higgs masses and couplings}} \\
+ \; & \underbrace{g'' \left(\bar{q} \gamma^{\mu} T_{a} q \right) G^{\alpha}_{\mu}}_{\text{interactions between quarks and gluons}} + \underbrace{\left(G_{1} \bar{L} \phi R + G_{2} \bar{L} \phi_{c} R + h.c. \right)}_{\text{fermion masses and couplings to Higgs}}
\end{aligned}
$$

SM Lagrangian: Higgs Mechanism

SM Higgs Mechanism

- Standard Model includes complex Higgs SU(2) doublet

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$



- With SU(2) x U(1) invariant scalar potential

$$V = \mu^2 \Phi^+ \Phi + \lambda (\Phi^+ \Phi)^2$$

- If $\mu^2 < 0$, then spontaneous symmetry breaking
- Minimum of potential at: $$\Phi \Rightarrow \frac{e^{i\omega_j \cdot \sigma_j / v}}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H \end{pmatrix}$$
  - Choice of minimum breaks gauge symmetry

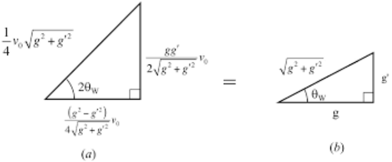
SM Lagrangian: From unphysical to physical states: Symmetry breaking

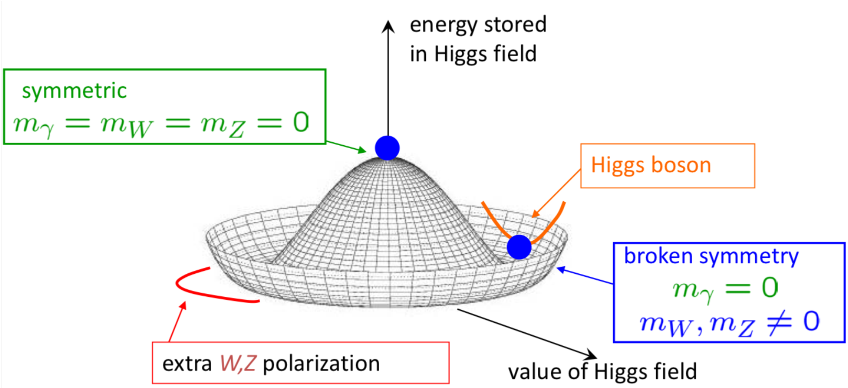
photon

?

$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B_\mu \\ (W_\mu)_3 \end{pmatrix}$$

Z particle

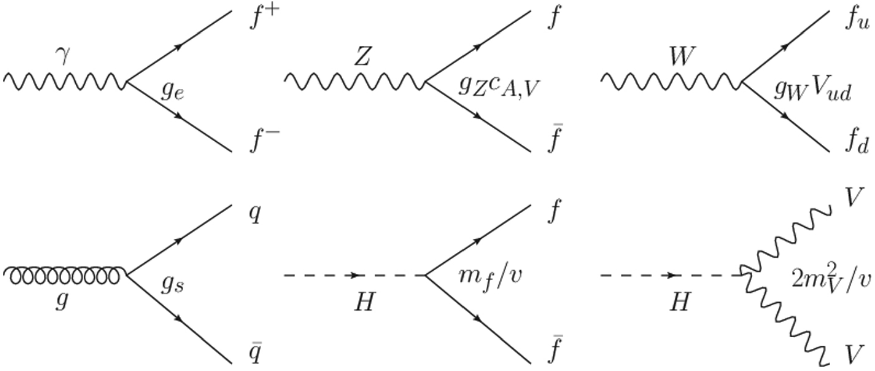




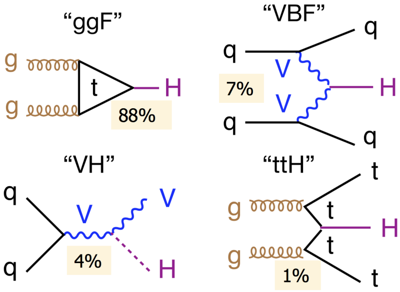
SM Lagrangian: complete form after SSB

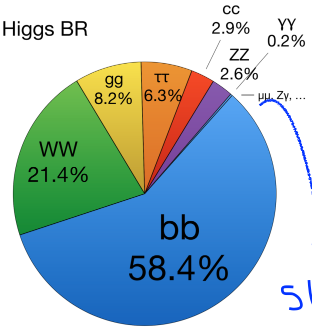
$$
\begin{gathered}
-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2G^a + g_s f^{abc}\partial_\mu\bar{G}^aG^bg^c_\mu - \partial_\nu W^+_\mu\partial_\nu W^-_\mu - \\
M^2W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H\partial_\mu H - \\
\tfrac{1}{2}m_h^2H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \\
\tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - \\
W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\tfrac{1}{2}g^2W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2s_wc_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^1s_w^2A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \\
\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \\
\tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - \\
1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \gamma^5)\nu^\lambda) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 + \gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1 + \gamma^5)\nu^\lambda) + (\bar{d}^\kappa_jC^\dagger_{\lambda\kappa}\gamma^\mu(1 + \\
\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1 - \gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1 + \gamma^5)\nu^\lambda)] - \\
\tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_jC_{\lambda\kappa}(1 - \gamma^5)d^\kappa_j) + \\
m_u^\lambda(\bar{u}^\lambda_jC_{\lambda\kappa}(1 + \gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1 + \gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1 - \\
\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_ju^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_jd^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \\
\tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \\
\tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \\
\partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \\
\partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \\
\partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H] + \\
\tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \\
igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]
\end{gathered}
$$

Evidence for a Standard Model like Higgs boson



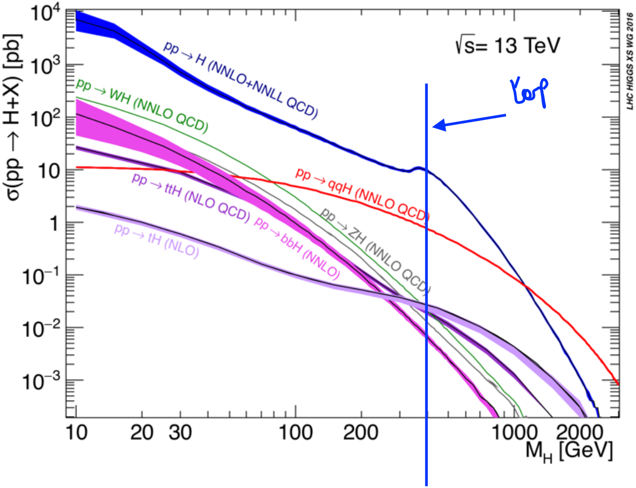
Evidence for a Standard Model like Higgs boson



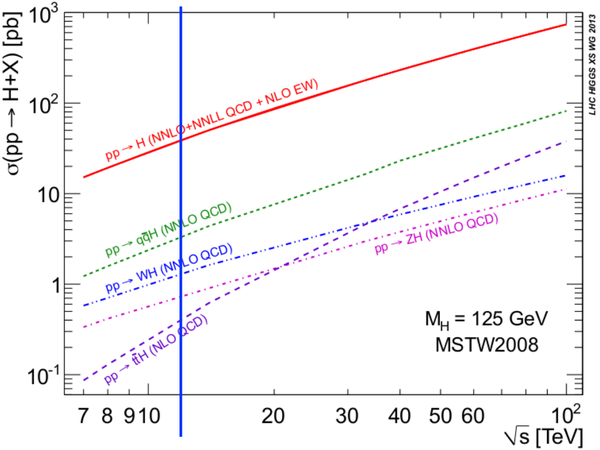


Still

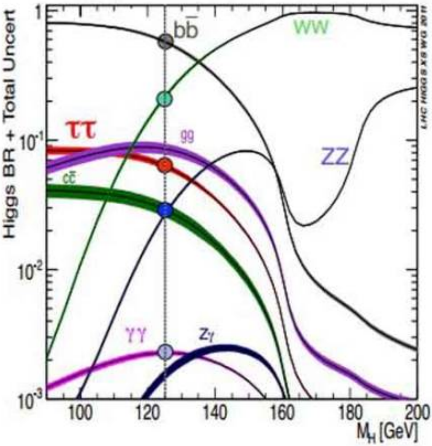
Evidence for a Standard Model like Higgs boson (Sushi, ggHiggs,...)



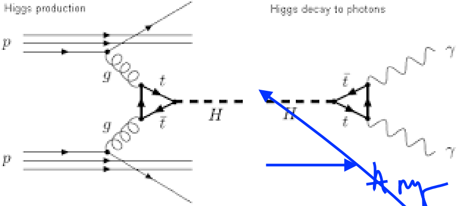
Evidence for a Standard Model like Higgs boson (Sushi, ggHiggs,...)

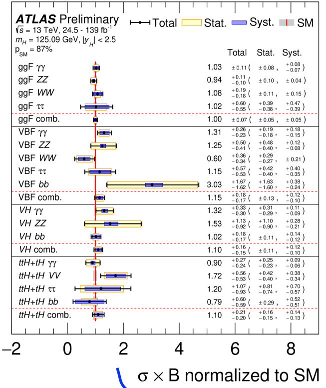


Evidence for a Standard Model like Higgs boson (http://tiger.web.psi.ch/hdecay/)

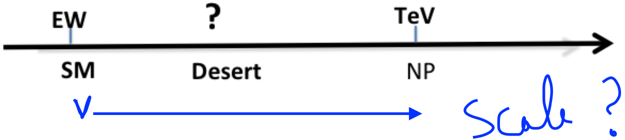


Evidence for a Standard Model like Higgs boson





Beyond the SM



- The SM-like limit exists in various models with extra neutral Higgs.
- Any extended Higgs sector a Charged Higgs would be a signal.
- Such scalars appear in multi-Higgs doublet (MHDM).
- From EWO are in agreement with SM with $\rho = 1$.

Potential with sotf Z_2-violating

$$
\begin{aligned}
V(\Phi_1,\Phi_2) = &-\frac{1}{2}\left\{m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + \left[m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right]\right\} \\
&+ \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\
&+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right]. \qquad (1)
\end{aligned}
$$

Apart from the term m_{12}^2, this potential exhibits a Z_2 symmetry,

$$(\Phi_1,\Phi_2) \leftrightarrow (\Phi_1,-\Phi_2) \quad \text{or} \quad (\Phi_1,\Phi_2) \leftrightarrow (-\Phi_1,\Phi_2). \qquad (2)$$

The most general potential contains in addition two more quartic terms, with coefficients λ_6 and λ_7, and violates Z_2 symmetry in a hard way T.D.Lee PRD8,1226'73,"JF.Gunion *et al.*The HHG".

- The parameters λ_1–λ_4, m_{11}^2 and m_{22}^2 are real.
- The potential (1) can lead to CP violation when λ_5 and m_{12}^2 may be are complex.

Mass eigenstates

We use the following decomposition of the doublets:

$$\Phi_1 = \begin{pmatrix} \varphi_1^+ \\ (v_1 + \eta_1 + i\chi_1)/\sqrt{2} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \varphi_2^+ \\ (v_2 + \eta_2 + i\chi_2)/\sqrt{2} \end{pmatrix}, \tag{3}$$

Here $v_1 = \cos\beta\, v$, $v_2 = \sin\beta\, v$, $v = 2\, m_W/g$, with $\tan\beta = v_2/v_1$. The charged Higgs bosons are the combination orthogonal to the charged Nambu–Goldstone bosons:

$$H^\pm = -\sin\beta\varphi_1^\pm + \cos\beta\varphi_2^\pm \tag{4}$$

and their mass is given by

$$M_{H^\pm}^2 = \mu^2 - \frac{v^2}{2}(\lambda_4 + \Re\lambda_5), \tag{5}$$

where we define a mass parameter μ by

$$\mu^2 \equiv (v^2/2v_1v_2)\Re m_{12}^2. \tag{6}$$

Mass eigenstates and gauge couplings

With all momenta incoming, we have the $H^{\mp}W^{\pm}\phi$ gauge couplings:

$$\begin{aligned}
H^{\mp}W^{\pm}h: &\quad \frac{\mp ig}{2}\cos(\beta-\alpha)(p_\mu - p_\mu^{\mp}), \\
H^{\mp}W^{\pm}H: &\quad \frac{\pm ig}{2}\sin(\beta-\alpha)(p_\mu - p_\mu^{\mp}), \\
H^{\mp}W^{\pm}A: &\quad \frac{g}{2}(p_\mu - p_\mu^{\mp}).
\end{aligned} \tag{7}$$

The strict SM-like limit corresponds to $\sin(\beta-\alpha)=1$.

$$\begin{aligned}
VVh: &\quad \sin(\beta-\alpha), \\
VVH: &\quad \cos(\beta-\alpha), \\
VVA: &\quad 0.
\end{aligned} \tag{8}$$

$V = W^{\pm}, Z$

Theoretical constraints

The 2HDM is subject to various theoretical constraints.

- Stability or positivity of the potential:

$$V(\Phi_1, \Phi_2) > 0 \qquad \text{as} \qquad |\Phi_1|, |\Phi_2| \to \infty. \tag{9}$$

  This requirement gives the following conditions on λ's
  PM. Ferreira *et al* ,PLB,2005

$$\lambda_1 > 0\,,\ \lambda_2 > 0\,,\ \lambda_3 + 2\sqrt{\lambda_1\lambda_2} > 0\ ,\ \lambda_3 + \lambda_4 - |\lambda_5| > 2\sqrt{\lambda_1\lambda_2}. \tag{10}$$

- Perturbativity: satisfy $|\lambda_i| \leq 8\pi$ $(i = 1, ..., 5)$. has significant effect on $(\tan\beta, M_{H^\pm})$ plane.
- Unitarity: all $2 \to 2$ processes scattering are under control.

$$\mathrm{Max(Eigenvalues(M))} < 0.5 \tag{11}$$

Yukawa Interaction for the 2HDM T.D.Lee PRD8,1226'73

$$-\mathcal{L}_{\text{Yukawa}} = \overline{Q}_L \Phi_a F_a^D D_R + \overline{Q}_L \widetilde{\Phi}_a F_a^U U_R + \overline{L}_L \Phi_a F_a^L L_R + \text{h.c.}, \quad (12)$$

Model	d	u	ℓ
I	Φ_2	Φ_2	Φ_2
II	Φ_1	Φ_2	Φ_1
III	$\Phi_1 \& \Phi_2$	$\Phi_1 \& \Phi_2$	$\Phi_1 \& \Phi_2$
X	Φ_2	Φ_2	Φ_1
Y	Φ_1	Φ_2	Φ_2

Table 1: The most popular models of the Yukawa interactions in the 2HDM.

in Type II (MSSM)

$$H^+ b\bar{t}: \qquad \frac{ig}{2\sqrt{2}\, m_W} V_{tb}[m_b \overbrace{(1+\gamma_5)}^{P_R} \tan\beta + m_t \overbrace{(1-\gamma_5)}^{P_L} \cot\beta],$$

$$H^- t\bar{b}: \qquad \frac{ig}{2\sqrt{2}\, m_W} V_{tb}^*[m_b(1-\gamma_5)\tan\beta + m_t(1+\gamma_5)\cot\beta].$$

Charged Higgs boson decays

a charged Higgs boson can decay to a fermion-antifermion pair

$$
\begin{aligned}
H^+ &\to c\bar{s}, && (14a)\\
H^+ &\to c\bar{b}, && (14b)\\
H^+ &\to \tau^+\nu_\tau, && (14c)\\
H^+ &\to t\bar{b}, && (14d)
\end{aligned}
$$

Tree

to gauge bosons,

$$
\begin{aligned}
H^+ &\to W^+\gamma, && (15a)\\
H^+ &\to W^+Z, && (15b)
\end{aligned}
$$

loop small

or to a neutral Higgs boson and a gauge boson:

$$
H^+ \to hW^+, \quad AW^+ \tag{16}
$$

Tree

and their charge conjugates.

Light H^+ ($M_{H^\pm} < m_t$)

- We focus on CPC case and set $M_h = 125$ GeV.
- Use 2HDMC and HDECAY software
- We consider 3-body modes via off-shell of $H^+ \to t\bar{b}$, $H^+ \to hW^+$, $H^+ \to HW^+$ and $H^+ \to AW^+$.
- We use $B \to X_s\gamma$ constraints: light charged Higgs is excluded in type-II.

Light H^+ ($M_{H^\pm} < m_t$)

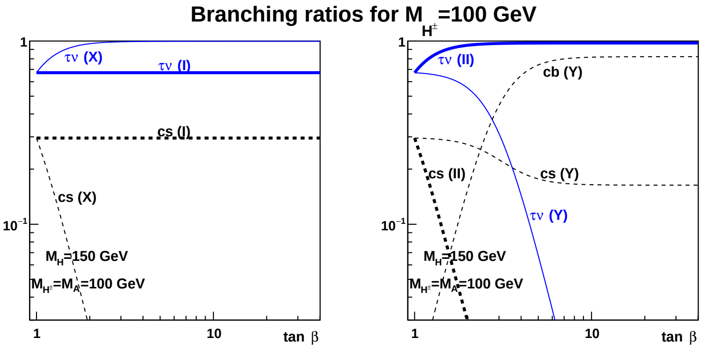


Figure 1: Light charged-Higgs branching ratios vs $\tan\beta$.

- We focus on CPC case and set $M_h = 125$ GeV.
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- We use $B \to X_s\gamma$ constraints: light charged Higgs is excluded in type-II.

Heavy H^+ ($M_{H^\pm} > m_t$)

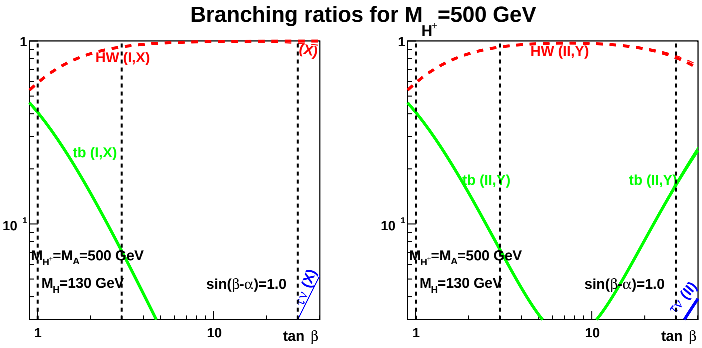


Figure 2: Heavy charged-Higgs branching ratios vs tan β.

- $\sin(\beta - \alpha) = 1$.

Heavy H^+ ($M_{H^\pm} > m_t$)

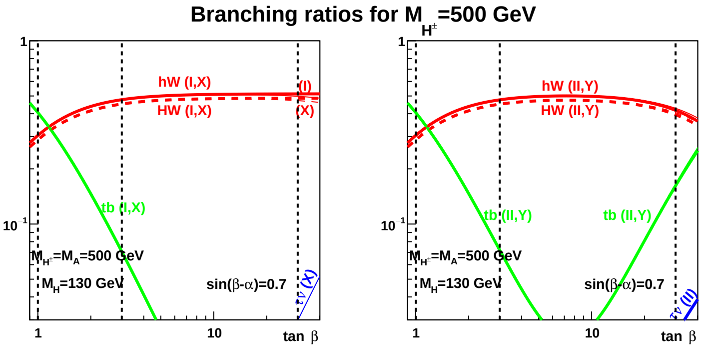


Figure 3: Heavy charged-Higgs branching ratios vs $\tan\beta$.

- $\sin(\beta - \alpha) = 0.7$

Branching ratios vs $M_{H^\pm}$ in Type I

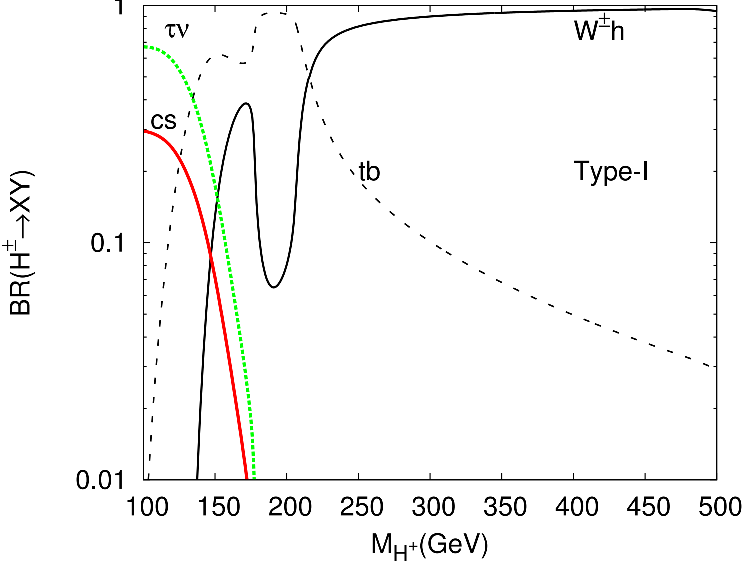


Figure 4: Branching ratios of charged-Higgs as a function of $M_{H^\pm}$ in Type I with $\sin(\beta - \alpha) = 0.81$ and $\tan\beta = 8$.

Branching ratios vs $M_{H^\pm}$ in Type X

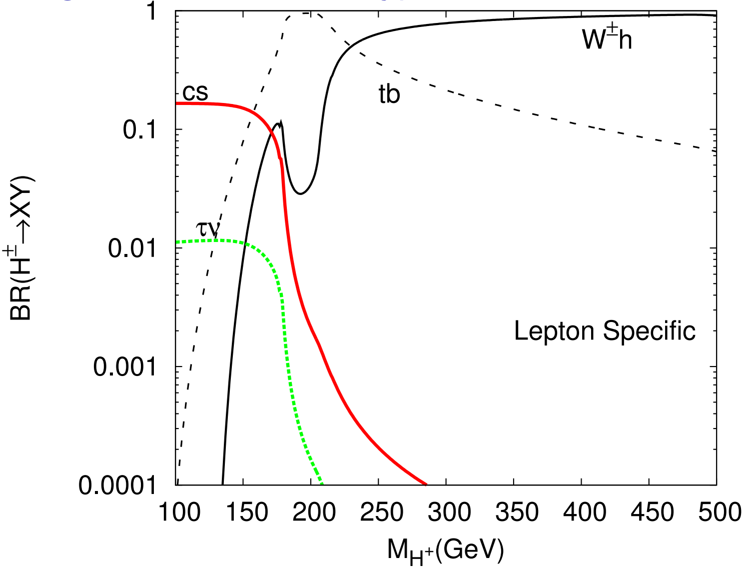


Figure 5: Branching ratios of charged-Higgs as a function of $M_{H^\pm}$ in Type I with $\sin(\beta - \alpha) = 0.81$ and $\tan\beta = 8$.

Constraints From B Physics

- $b \to s\gamma$ (yellow), $B_s^0 \to \mu\mu$ (red), $B_d^0 \to \mu\mu$ (magenta)
- ΔM_s (blue), ΔM_d (cyan).

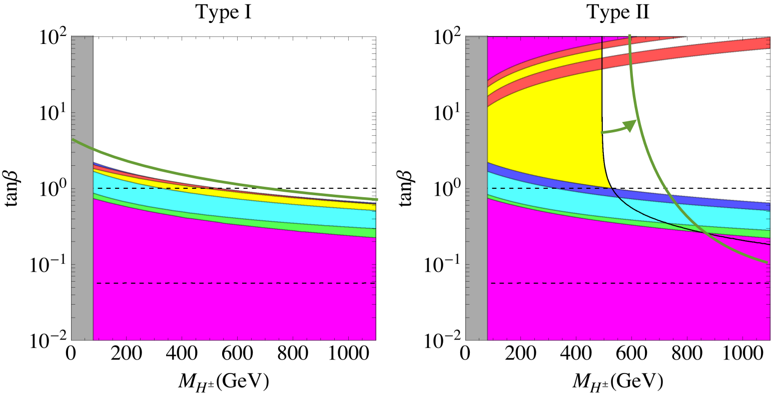


Figure 6: Exclude regions from B Physics in $(M_{H^\pm}, \tan\beta)$*plane* in Type I a,d II with $\sin(\beta - \alpha) = 1$ and $m_h = 125$ GeV, $m_H = m_A = M_{H^\pm}$

Production processes: Single production at the LHC

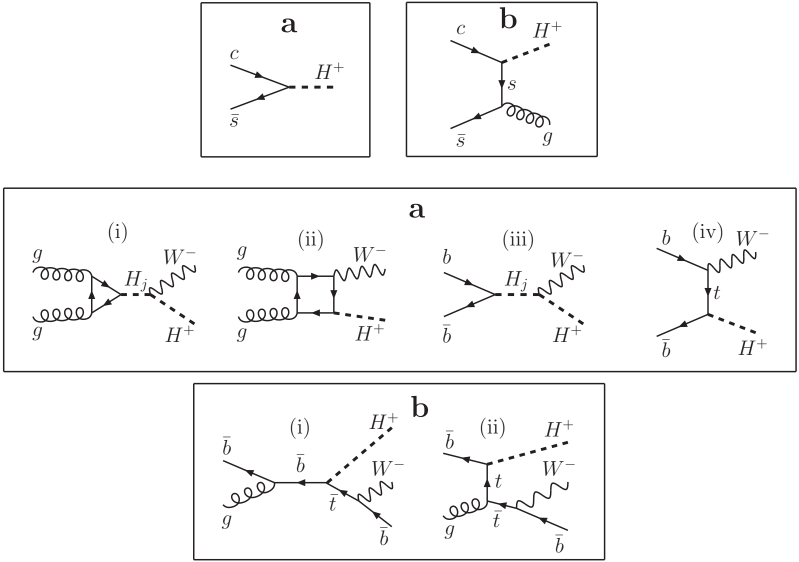
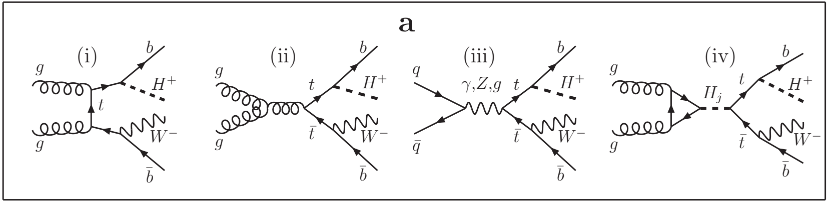
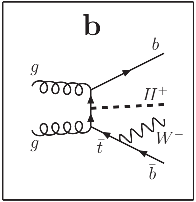
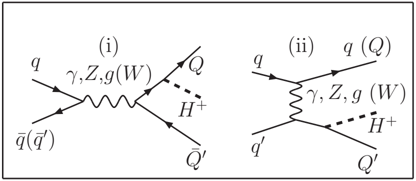


Figure 7: Feynman diagrams contributing in Single production at the LHC production processes.

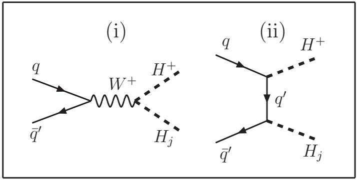
Production processes: Single production at the LHC

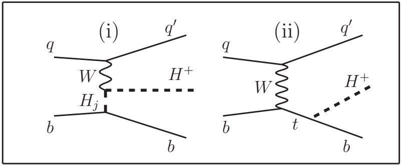




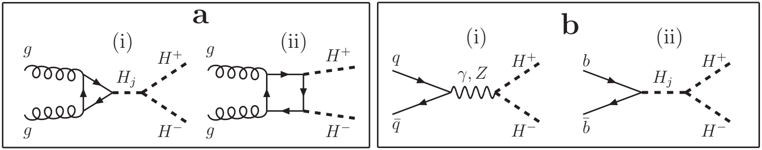


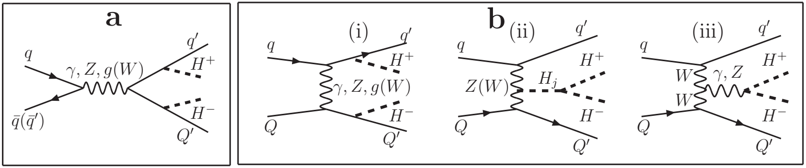
Production processes: Single production at the LHC





Production processes: Pair production at the LHC





Production cross sections $pp \to H^{\pm}X$

We use CTEQ6L, $\sqrt{s} = 14$ TeV and $\sin(\beta - \alpha) = 1$ in Types I and II.

- $g\bar{b} \to H^+\bar{t}$, (solid),
- $gg \to H^+ b\bar{t}$, (dotted),
- $gg \to H_j \to H^+W^-$, (dash-dotted).

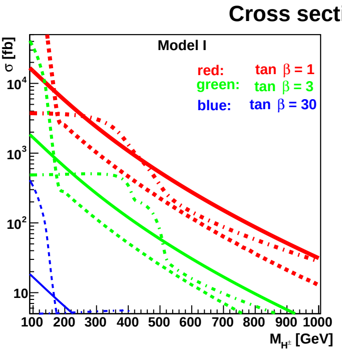
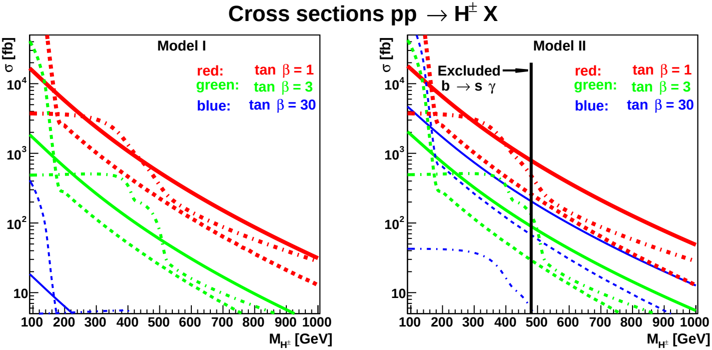


Figure 8: Charged Higgs production cross sections in the 2HDM, at 14 TeV

Production cross sections $pp \to H^{\pm}X$

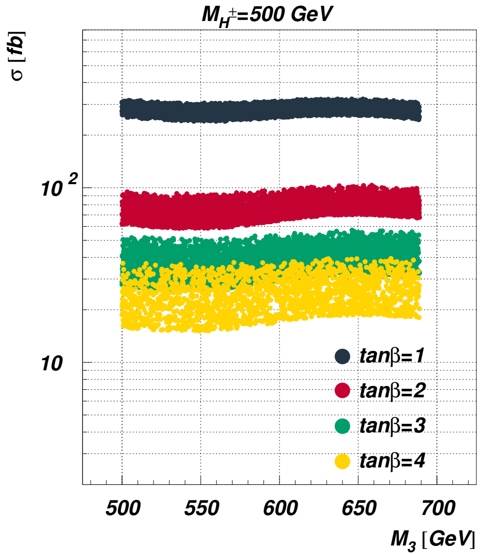
We use CTEQ6L, $\sqrt{s} = 14$ TeV and $\sin(\beta - \alpha) = 1$ in Types I and II.

- For $\tan\beta = 1$, type-I and type-II are diffrent due to sign Yukawa.
- Models X and Y will have the same predictions except for $(\tau\nu)$.
- The bumpy structure is due to resonance of neural Higgs.



Production cross sections $pp \to H^{\pm}X$

We use CTEQ6L, $\sqrt{s} = 14$ TeV and $\sin(\beta - \alpha) = 1$ in Type II.



LHC strategies searches: ATLAS results at 8 TeV

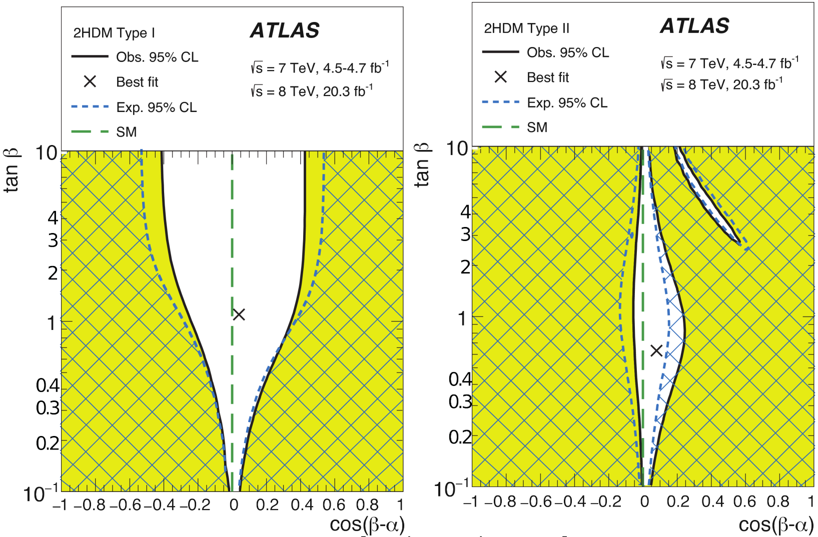


Figure 9: ATLAS regions of the $[\cos(\beta-\alpha), \tan\beta]$ plane for the 2HDM Model I (left) and Model II (right) excluded by fits to the measured rates of Higgs boson production and decays.

LHC strategies searches: ATLAS results at 13 TeV

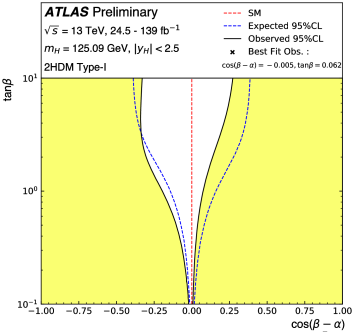


Figure 10: ATLAS regions of the $[\cos(\beta-\alpha), \tan\beta]$ plane for the 2HDM Model I (left) and Model II (right) excluded by fits to the measured rates of Higgs boson production and decays.

Looking $pp \to t\bar{t}$, $t \to H^{\pm}b$, $H^{\pm} \to W\phi$, $(M_{H^{\pm}} < m_t)$

Here we use for $m_t = 172.5$ GeV:

$$\sigma(pp \to t\bar{t}) = 252.89^{+6.39}_{-8.64}(\mathrm{scale}) +^{+11.67}_{-11.67}(\mathrm{PDF})(\mathrm{pb}) \quad \sqrt{s} = 8\,\mathrm{TeV}$$
$$\sigma(pp \to t\bar{t}) = 831.76^{+19.77}_{-29.20}(\mathrm{scale}) +^{+35.06}_{-35.06}(\mathrm{PDF})(\mathrm{pb}) \quad \sqrt{s} = 13\,\mathrm{TeV}$$
$$\sigma(pp \to t\bar{t}) = 984.50^{+23.21}_{-34.69}(\mathrm{scale}) +^{+41.31}_{-41.31}(\mathrm{PDF})(\mathrm{pb}) \quad \sqrt{s} = 14\,\mathrm{TeV}$$

The PDF uncertainty was obtained with MSTW2008 at the 68%CL. The plots shows $\sigma(pp \to t\bar{t}) \times Br(t \to H^{\pm}h) \times Br(H^{\pm} \to W^{\pm}h)$ in type-I including uncertainties from scale variation and 68%CL PDF.

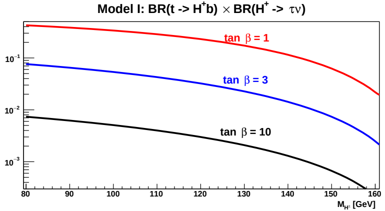


Figure 11: Product of branching ratios, $\mathrm{BR}(t \to H^{+}b) \times \mathrm{BR}(H^{+} \to \tau^{+}\nu)$

Looking $pp \to t\bar{t}$, $t \to H^{\pm}b$, $H^{\pm} \to W\phi$, $(M_{H^{\pm}} < m_t)$

- $\sigma(pp \to t\bar{t}) \times Br(t \to H^{\pm}b) \times Br(H^{\pm} \to W\phi)$ in scenario:1

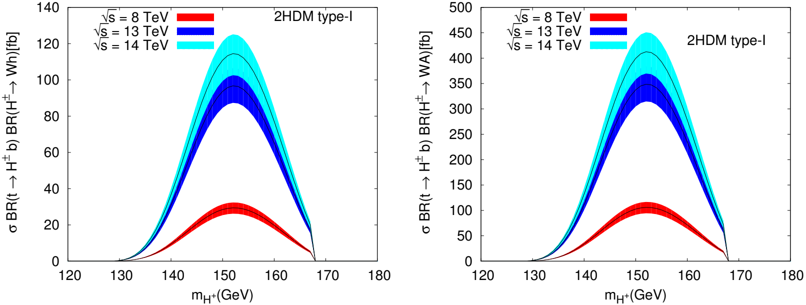


Figure 12: The rates for $\sigma(pp \to t\bar{t}) \times \mathrm{BR}(t \to H^{\pm}b) \times \mathrm{BR}(H^{\pm} \to W^{\pm *}\phi)$ with $\phi = h$ (left) and A (right) in the 2HDM-I as a function of $m_{H^{\pm}}$ with $m_A = m_h = 125$ GeV for $\tan\beta = 5$, $\sin(\beta - \alpha) = 0.85$, $m_H = 300$ GeV and $m_{12}^2 = 16 \times 10^3$ GeV^2. The bands correspond to a 1σ deviation from the $t\bar{t}$ cross section central value as computed at Next-to-Next-to-Leading Order (NNLO) at three LHC energies.

Further search for $H^\pm$ at the LHC

- Channels for $M_{H^\pm} \lesssim m_t$:
  - Single H^+ production

$M_{H^\pm}$	100 GeV		150 GeV	
$\tan\beta$	3	10	3	10
$pp \to H^+ W^- b\bar{b}$	$\surd$	$\surd$	$\surd$	
$q\bar{q}(q') \to H^+ bq$	$\surd$	$(\surd)$	$\surd$	
$pp(\bar{b}g) \to H^+ \bar{t}X,\ H^+ \to W^+ \phi$	$\surd$	$(\surd)$	$\surd$	

  - H^+H^- pair production

$M_{H^\pm}$	100 GeV			150 GeV		
$\tan\beta$	3	10	30	3	10	30
$gg, bb \to H^+ W^-$	$\surd$	$(\surd)$		$\surd$	$(\surd)$	
$gg, bb \to H^+ H^-$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$
$q\bar{q}(q') \to H^+ H^- q' Q'$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$

Table 2: Proposed channels, denoted by $\surd$, for Models I and X, requiring resonant production, at 30 fb^{-1}. The cases denoted by $(\surd)$ would need higher luminosity.

Conclusions and perspectives

- Various SM like models exsist with extra Higgs scalars.
- A charged Higgs would be the most striking signal of a Higgs with extra doublets.
- In this talk we have analyzed different models in 2HDM by focusing on the most decay modes.
- In type I: the most "natural" decay modes are :$\tau\nu$ or $W\phi$ with any neutral Higgs.
- In type II: the most "natural" decay modes are :$t\bar{b}$ or $W\phi$ with ϕ are heavy.
- If a signal were to be found. How to distinguish between MSSM and 2HDM (or even type-1 and type-2)?
- In case where of high mass, QCD background is very challenging, so improved analysis techniques could turn out to be very benefical.

Thank you!