Higgs properties in a Stealth Doublet Model

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based on work with Rikard Enberg and Glenn Wouda,
arXiv:1304.1714 [hep-ph], accepted for publication in JHEP

Nordita, 2013-07-27

Higgs discovery

Stealth Doublet Model

Johan Rathsman

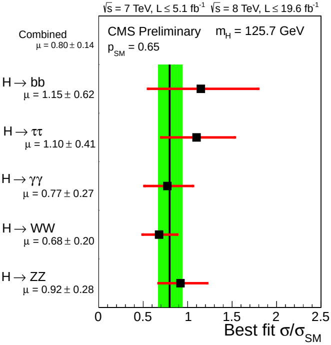
Higgs discovery

The Stealth Doublet Model

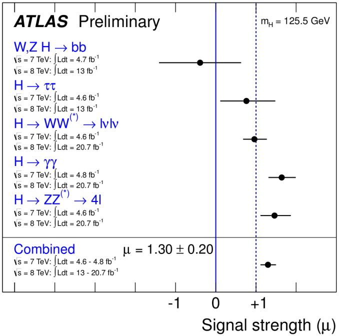
Phenomenology

Observations in agreement with standard model

CMS



ATLAS

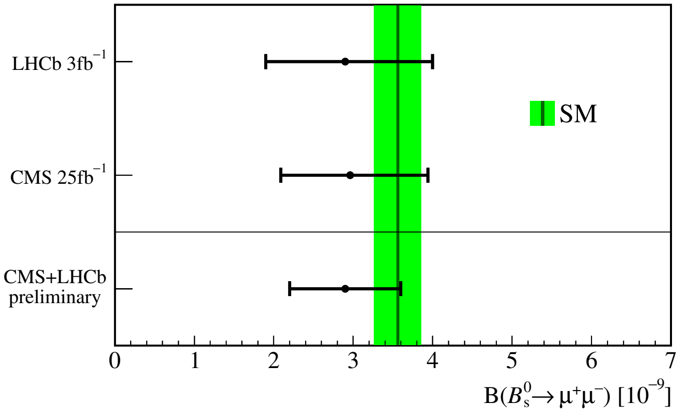


What (if anything) is beyond?

Bottom up approach in two Higgs Doublet model

Constraints from flavour sector - neutral currents

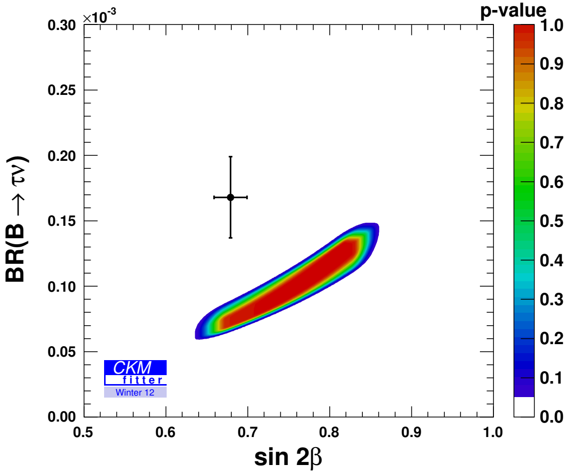
$B_s \to \mu^+\mu^-$



also from $b \to s\gamma$

Constraints from flavour sector - charged currents

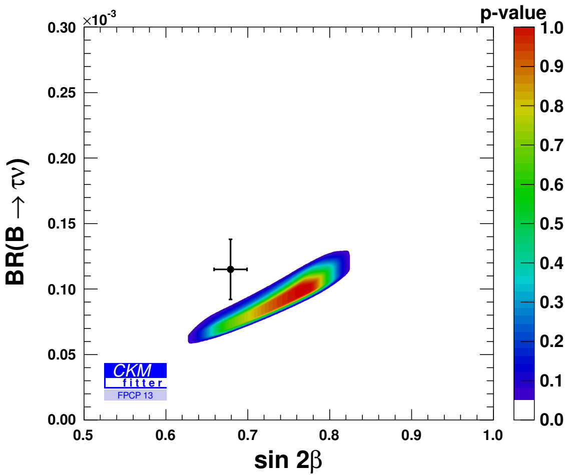
$B^+ \to \tau^+ \nu_\tau$, winter 2012



experimental errors at 1σ

Constraints from flavour sector - charged currents

$B^+ \to \tau^+\nu_\tau$, summer 2013



experimental errors at 1σ

The Stealth Doublet Model

General two Higgs doublet model potential

- Two complex $SU(2)_L$ doublets with hypercharge Y=1: Φ_1 ,Φ_2
- Invariance under global $SU(2)$: $\Phi_a \to U_{ab}\Phi_b$

General potential

$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger\Phi_1 + m_{22}^2 \Phi_2^\dagger\Phi_2 - \left[m_{12}^2 \Phi_1^\dagger\Phi_2 + \mathrm{h.c.}\right] + \frac{1}{2}\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2$$
$$+\frac{1}{2}\lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right)$$
$$+\left\{\frac{1}{2}\lambda_5\left(\Phi_1^\dagger\Phi_2\right)^2 + \left[\lambda_6\left(\Phi_1^\dagger\Phi_1\right) + \lambda_7\left(\Phi_2^\dagger\Phi_2\right)\right]\left(\Phi_1^\dagger\Phi_2\right) + \mathrm{h.c.}\right\}$$

- Potential real $\Rightarrow \{m_{11}^2,\ m_{22}^2,\ \lambda_{1-4}\}$ real, $\{m_{12}^2,\ \lambda_{5-7}\}$ complex
- No explicit CP-violation $\Rightarrow \{m_{12}^2,\ \lambda_{5-7}\}$ real

Softly broken $\mathbb{Z}_2$ symmetry

- Potential symmetric under $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$
  $\Rightarrow m_{12}^2 = 0$, $\lambda_{6-7} = 0$ in general basis
- $m_{12}^2 \neq 0 \Rightarrow$ soft breaking

Yukawa sector

General Yukawa couplings for SM fermions (neutrinos massless)

$$\begin{aligned}
-\mathcal{L}_{\text{Yuk}} &= \kappa_0^L \bar{L}_L \Phi_1 E_R + \kappa_0^U \bar{Q}_L \widetilde{\Phi}_1 U_R + \kappa_0^D \bar{Q}_L \Phi_1 D_R \\
&+ \rho_0^L \bar{L}_L \Phi_2 E_R + \rho_0^U \bar{Q}_L \widetilde{\Phi}_2 U_R + \rho_0^D \bar{Q}_L \Phi_2 D_R
\end{aligned}$$

where $\widetilde{\Phi}_i = -\mathrm{i}\sigma_2 \Phi_i^*$

Impose even $\mathbb{Z}_2$ parities on all fermions $\Rightarrow \rho^F = 0$ at tree level

Electroweak symmetry breaking

Fermions only couple to $\Phi_1 \Rightarrow$ Higgs basis physically realized

- EW symmetry broken by non-zero vev of Φ_1 ($v \approx 246$ GeV)

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} G^+ \\ v - h \sin\alpha + H \cos\alpha + \mathrm{i} G^0 \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} H^+ \\ h \cos\alpha + H \sin\alpha + \mathrm{i} A \end{pmatrix}$$

- Three Goldstone bosons: $G^\pm$, $G^0 \Rightarrow$ masses to W and Z
- Two CP-even Higgs boson states: h, H with mixing angle α
- Three scalar states: one CP-odd A and two charged $H^\pm$
- Higgs-gauge couplings from $s_\alpha \equiv \sin\alpha$, $c_\alpha \equiv \cos\alpha$
- $\tan\beta$ not defined

Higgs fermion couplings

Yukawa couplings for SM fermions with mass eigenstates
$D = \{d, s, b\}$, $U = \{u, c, t\}$, $L = \{e, \mu, \tau\}$

$$-\mathcal{L}_{\rm Yuk} = \frac{1}{v}\left(\sum_D \overline{D} m_D D + \sum_U \overline{U} m_U U + \sum_L \overline{L} m_L L\right)(s_\alpha h - c_\alpha H)$$

Mass spectrum

Minimization:

$$\begin{aligned} m_{11}^2 &= -\frac{1}{2} v^2 \lambda_1 \\ m_{12}^2 &= \frac{1}{2} v^2 \lambda_6 \\ m_{22}^2 & \quad \text{unconstrained} \end{aligned}$$

Masses of scalars

$$\begin{aligned} m_A^2 &= m_{22}^2 + \frac{1}{2} v^2 (\lambda_3 + \lambda_4 - \lambda_5) \\ m_{H^\pm}^2 &= m_{22}^2 + \frac{1}{2} v^2 \lambda_3 \end{aligned}$$

Mass-matrix of Higgses ($\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$)

$$\mathcal{M}^2 = \begin{pmatrix} \lambda_1 v^2 & \lambda_6 v^2 \\ \lambda_6 v^2 & m_{22}^2 + \lambda_{345} v^2 \end{pmatrix}$$

Diagonalization: $\sin 2\alpha = \dfrac{2v^2\lambda_6}{m_H^2 - m_h^2} = \dfrac{4m_{12}^2}{m_H^2 - m_h^2}$

- $\sin\alpha \propto m_{12}^2$ ($m_{12}^2 = 0$ restores Z_2 symmetry)

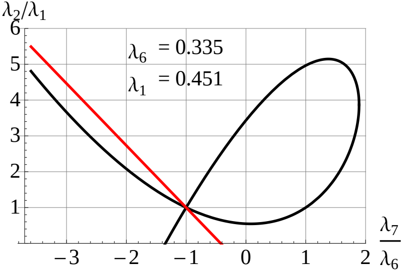
Conditions for soft $\mathbb{Z}_2$ breaking

$m_{12}^2 = \frac{1}{2}v^2\lambda_6 \Rightarrow m_{12}^2 \neq 0$ gives hard $\mathbb{Z}_2$ breaking?

Sufficient if there exists a basis where $\lambda_6 = \lambda_7 = 0$ and $m_{12}^2 \neq 0$ (Davidson and Haber '05)

$$(\lambda_1 - \lambda_2)\left[\lambda_{345}(\lambda_6 + \lambda_7) - \lambda_2\lambda_6 - \lambda_1\lambda_7\right] - 2(\lambda_6 - \lambda_7)(\lambda_6 + \lambda_7)^2 = 0$$
$$(\lambda_1 - \lambda_2)m_{12}^2 + (\lambda_6 + \lambda_7)(m_{11}^2 - m_{22}^2) \neq 0$$

Solution $\Rightarrow \lambda_2$ fixed, λ_7 constrained (upper limit)



black line allowed

red line not allowed

note:

$\lambda_2 = \lambda_1$, $\lambda_7 = \lambda_6$

always allowed

Parameterisation of potential: $\{\ \lambda_3, \lambda_7, m_h, m_H, m_A, m_{H^\pm}, s_\alpha\ \}$

Theoretical constraints

Positivity of potential

Demanding that the potential is bounded from below $\Rightarrow$

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1 \lambda_2}, \quad \lambda_3 + \lambda_4 - \lambda_5 > -\sqrt{\lambda_1 \lambda_2}$$

plus more complicated expressions

Perturbativity

Cross-section for $2 \to 2$ Higgs scattering processes $\propto \dfrac{\lambda_{HHHH}^2}{16\pi^2}$
$\Rightarrow$ the quartic Higgs couplings λ_{HHHH} cannot be too large for the perturbative series to make sense

Tree-level unitarity

requiring tree-level unitarity for HH and HV_L scattering $\Rightarrow$ limits on eigenvalues of the corresponding scattering matrices

Phenomenology

Mass spectrum

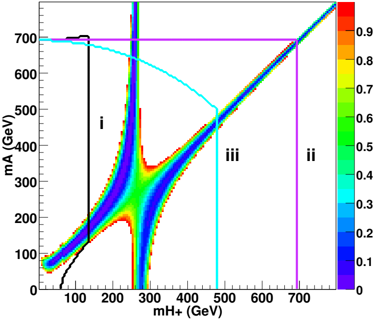
Agreement between LHC data and SM $\Rightarrow$ two possibillities

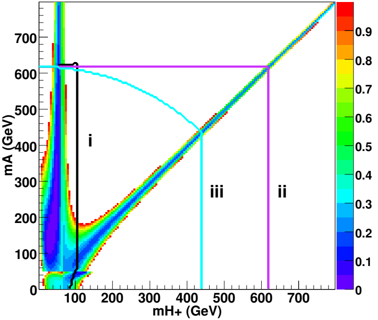
1. m_h=125 GeV, $s_\alpha \sim 0.9$, $m_H \gtrsim$300 GeV
2. m_H=125 GeV, $s_\alpha \sim 0.1$, $m_h \sim$75 GeV

Electroweak precision tests

- using 2HDMC `http://2hdmc.hepforge.org/` (JR, O. Stål)

$m_{h/H}$=125/300 GeV, $s_\alpha = 0.9$ $m_{h/H}$=75/125 GeV, $s_\alpha = 0.1$





- Allowed regions (90% C.L.) - custodial symmetry: $m_A \approx m_{H^\pm}$ or $m^2_{H^\pm} \approx m^2_H s^2_\alpha + m^2_h c^2_\alpha$
- Theoretical constraints (for $\lambda_2 = \lambda_1$ and $\lambda_7 = \lambda_6$): (i) $\lambda_3 = 0$, (ii) $\lambda_3 = 2m^2_{H^\pm}/v^2$, (iii) $\lambda_3 = 4m^2_{H^\pm}/v^2$ regions inside the lines are allowed

Compatibility with Higgs signal

Signal strength compared to SM ($\mathcal{H} = h/H$)

$$\mu_{\mathcal{H}XX} = \frac{\sum_i \sigma_i(pp \to \mathcal{H})\mathrm{BR}(\mathcal{H} \to XX)}{\sum_i \sigma_i(pp \to H_{\mathrm{SM}})\mathrm{BR}(H_{\mathrm{SM}} \to XX)}$$

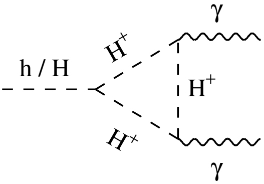
universal rescaling of couplings to fermions and W/Z bosons

$$\mu_{h\gamma\gamma} = s_\alpha^2 \frac{\mathrm{BR}(h \to \gamma\gamma)}{\mathrm{BR}(H_{\mathrm{SM}} \to \gamma\gamma)}, \quad \mu_{hff} = \mu_{hVV} = s_\alpha^2$$

$$\mu_{H\gamma\gamma} = c_\alpha^2 \frac{\mathrm{BR}(H \to \gamma\gamma)}{\mathrm{BR}(H_{\mathrm{SM}} \to \gamma\gamma)}, \quad \mu_{Hff} = \mu_{HVV} = c_\alpha^2$$

assuming $m_A, m_{H^\pm} > m_h/2$ for $\mu_{\mathcal{H}ff}, \mu_{\mathcal{H}VV}$

Enhancement of $h/H \to \gamma\gamma$ from charged scalar



$$g_{hH^+H^-} = -iv(-s_\alpha\lambda_3 + c_\alpha\lambda_7)$$
$$g_{HH^+H^-} = -iv(c_\alpha\lambda_3 + s_\alpha\lambda_7)$$

scan: $-5 \leq \lambda_3 \leq 5$, $-5 \leq \lambda_7 \leq \min\{5, \lambda_7^{\max} = \lambda_6 + \frac{(\lambda_1-\lambda_{345})^2}{8\lambda_6}\}$

$\mu_{h\gamma\gamma}$

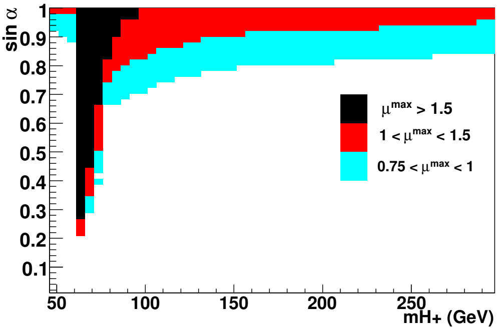
$m_h = 125$ GeV

$m_H = 300$ GeV

$m_A = m_{H^\pm} + 50$ GeV

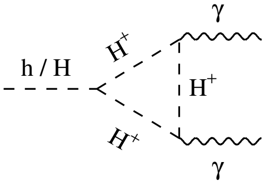
$\lambda_2 = \lambda_1$

Other channels
$s_\alpha^2 \gtrsim 0.7$



- Other Higgs constraints included using HiggsBounds

Enhancement of $h/H \to \gamma\gamma$ from charged scalar



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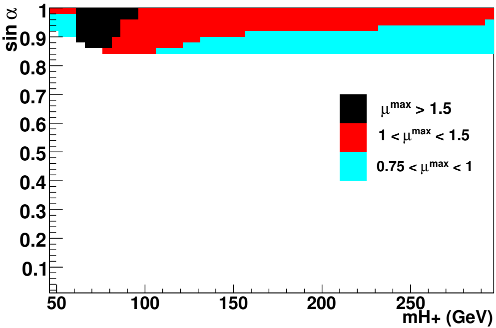

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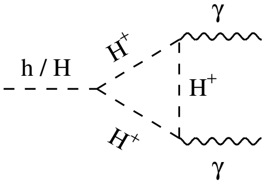

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scan: $-5 \leq \lambda_3 \leq 5,\ -5 \leq \lambda_7 \leq \min\{5, \lambda_7^{max} = \lambda_6 + \frac{(\lambda_1-\lambda_{345})^2}{8\lambda_6}\}$

$\mu_{H\gamma\gamma}$

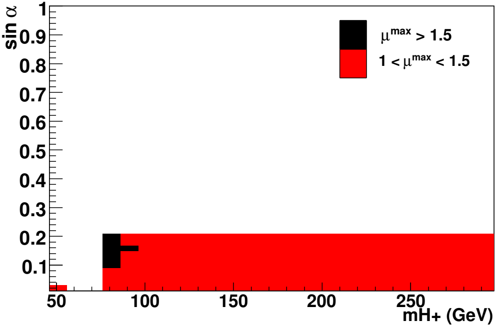
$m_h = 75$ GeV

$m_H = 125$ GeV

$m_A = m_{H^\pm}$

$\lambda_2 = \lambda_1$

Other channels $s_\alpha^2 \lesssim 0.3$



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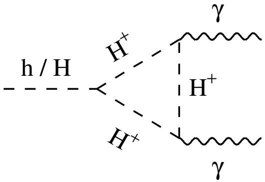
Enhancement of $h/H \to \gamma\gamma$ from charged scalar



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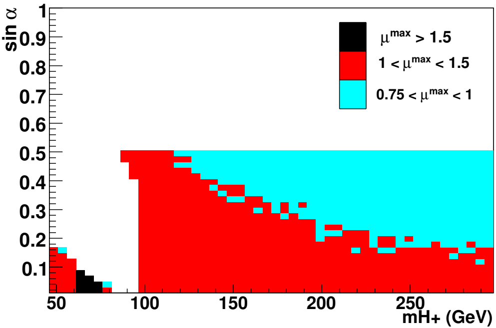
$\mu_{H\gamma\gamma}$



$m_h = 95$ GeV

$m_H = 125$ GeV

$m_A = m_{H^\pm}$

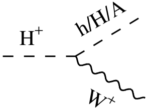
$\lambda_2 = \lambda_1$

Other channels
$s_\alpha^2 \lesssim 0.3$

- Other Higgs constraints included using HiggsBounds

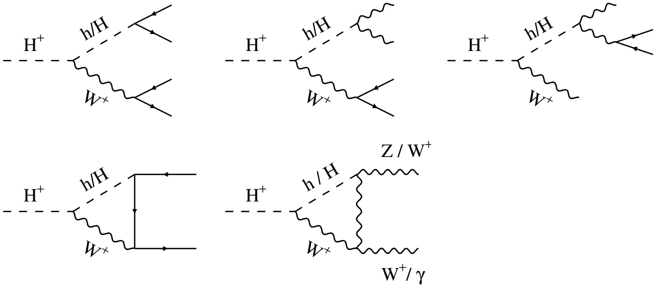
Other signals at LHC - charged scalar

Basic decay vertex



cosα / sinα / 1

Decays into fermions and SM gauge bosons ($m_{H^\pm} < m_A$)

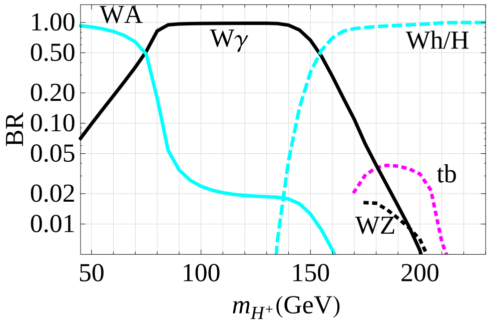


- Note: all diagrams proportional to $\sin(2\alpha) \Rightarrow$ vanish in no-mixing limit $\sin\alpha \to 0$ or $\cos\alpha \to 0$
- Proper calculation of loops require (on-shell) renormalisation

Tree-level dominates if open (on-shell or slightly off-shell)

Examples:

$$m_h = 125 \text{ GeV}$$
$$m_H = 300 \text{ GeV}$$
$$s_\alpha = 0.9$$
$$m_A = m_{H^\pm} - 10 \text{ GeV}$$
$$\lambda_3 = 2m_{H^\pm}^2/v^2$$
$$\lambda_2 = \lambda_1, \lambda_7 = \lambda_6$$



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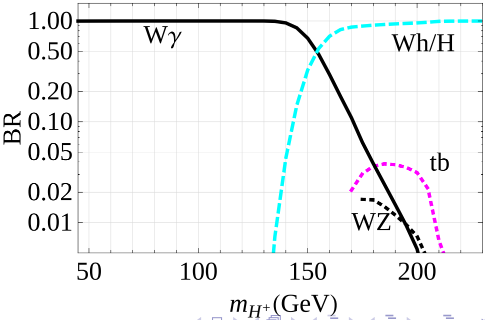

Other signals at LHC - pseudoscalar

Similar to $H^{\pm}$ except no decay to pair of SM gauge bosons

Example:

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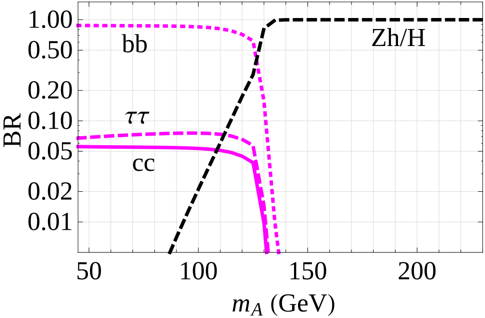
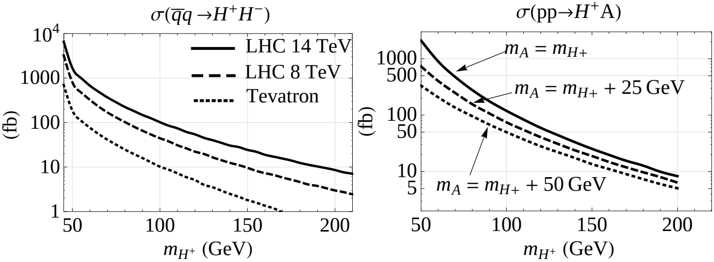
$$m_H = 300 \text{ GeV}$$
$$s_\alpha = 0.9$$
$$m_A = m_{H^\pm}$$
$$\lambda_3 = 0$$
$$\lambda_2 = \lambda_1, \lambda_7 = \lambda_6$$



Production of $H^{\pm}$ and A through Drell-Yann



Conclusions

Higgs discovery

- precision measurements probe for physics beyond the SM

Stealth Doublet model

- naturally avoids flavour contraints
- makes definite predictions for Higgs properties
- predicts extra scalars with unusual decay modes

more work needed to investigate possibility of observing extra scalars