Higgs properties in a softly broken Inert Doublet Model

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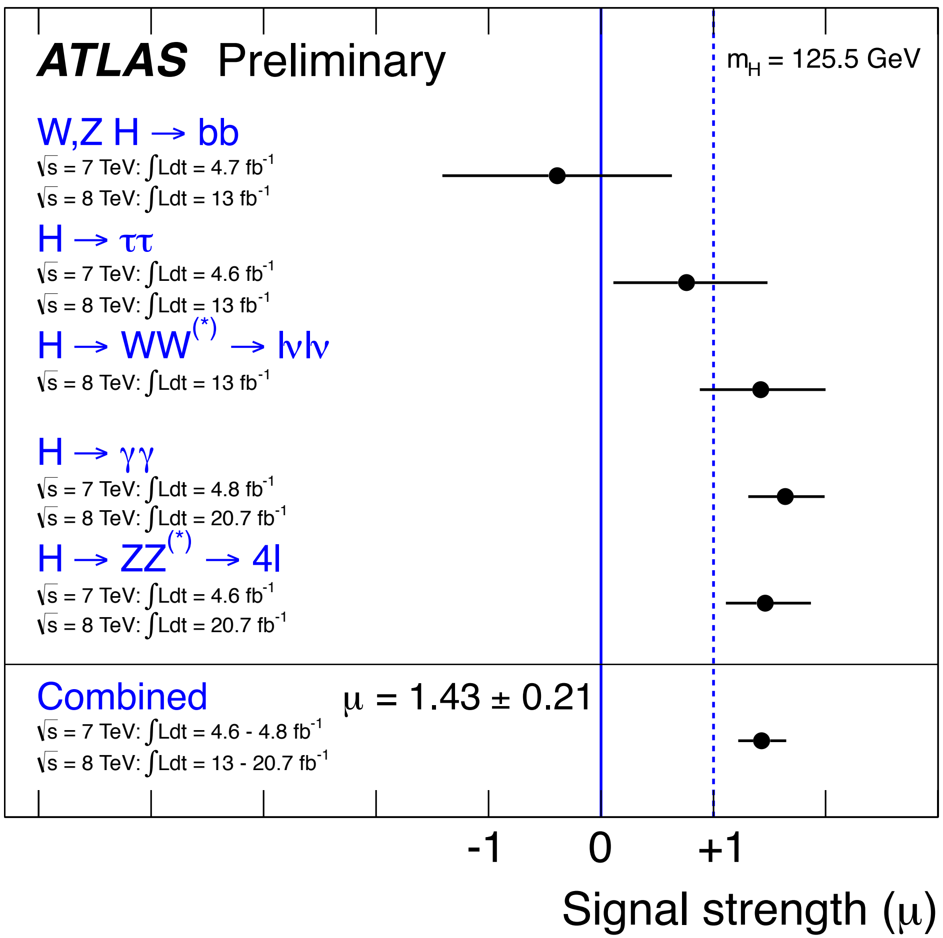
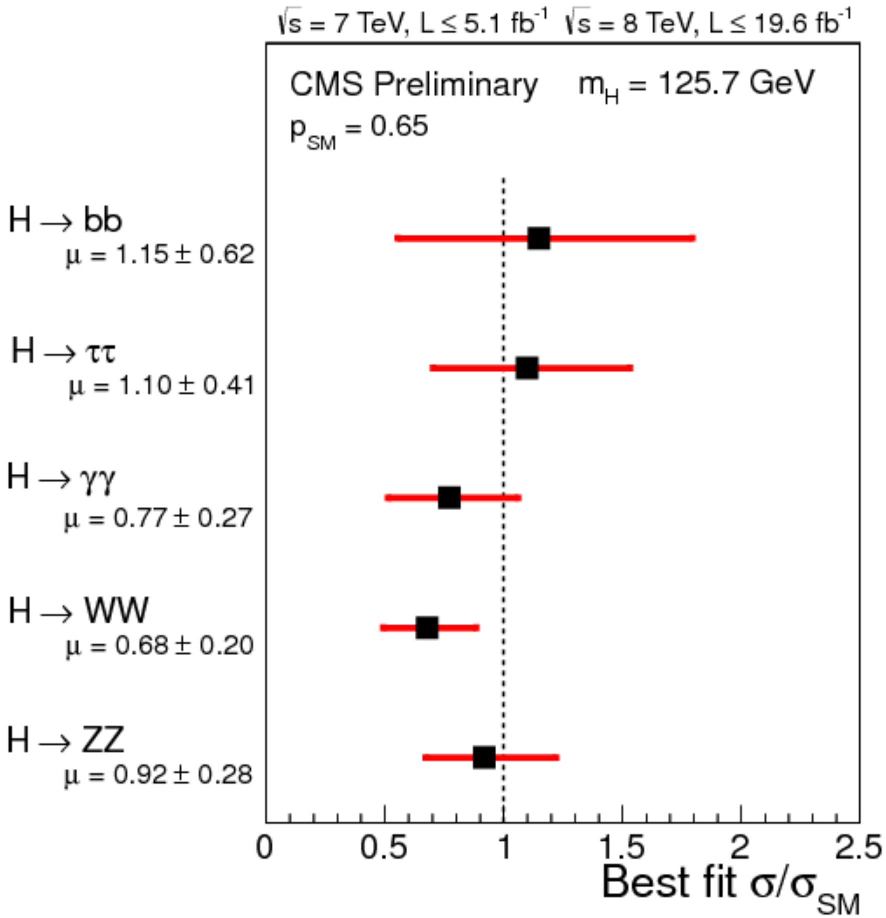
Based on work with Johan Rathsman and Glenn Wouda,
JHEP 1308 (2013) 79, arXiv:1304.1714
+ arXiv:1309.xxxx

Higgs discovered: very SM-like





And nothing else seen yet

Other Higgses

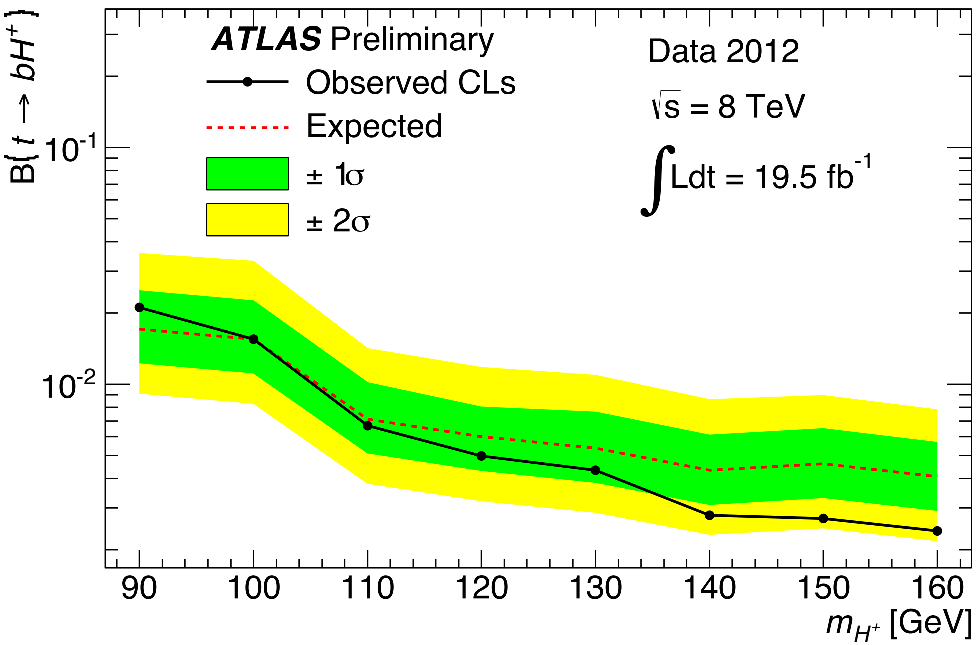
Discover other Higgs bosons → sure sign we aren't dealing with the SM Higgs sector

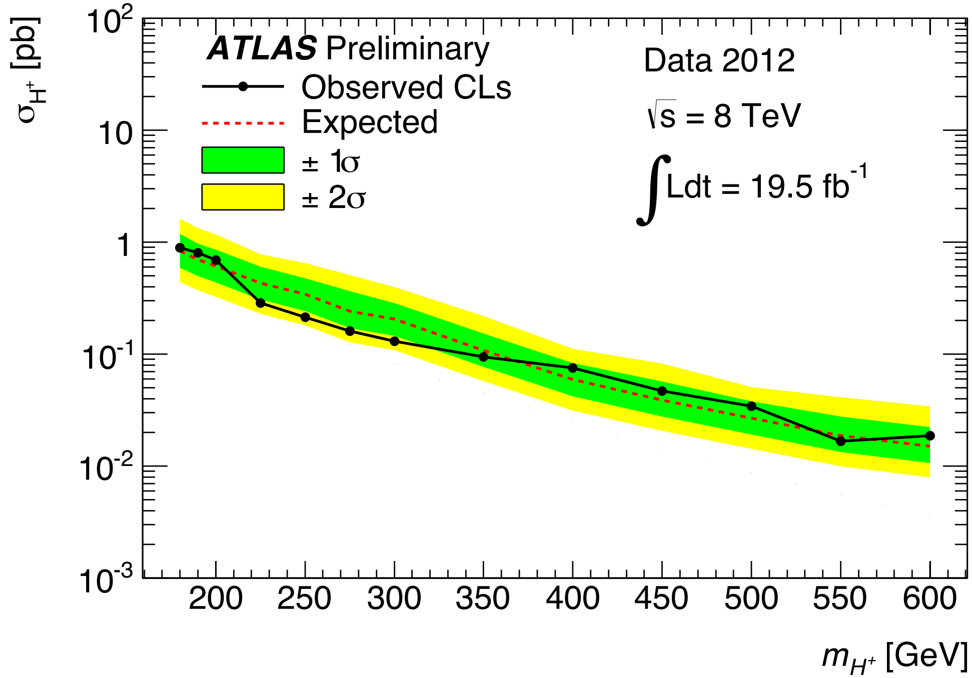
For example: the **charged Higgs** in MSSM and 2HDMs has these standard main channels for production and decay:

	Light ($m_{H+} < m_{top}$)	Heavy ($m_{H+} > m_{top}$)
Main production	$t \to H^+b$	$bg \to H^-t$ **or** $gg \to H^-tb$
Main decay	$H^+ \to \tau^+\nu$, cs	$H^+ \to tb$, $\tau^+\nu$

All involve fermion couplings

$H^{\pm}$ searches assuming τν decay:





Produced in top decays

Produced with top

(New results at this conference)

Other possibilities

- But, the “standard” assumptions on decay channels of the scalars are of course model dependent.
- Examples:
  - In the NMSSM, could have $H^+ \to W^+ A_1$
  - In models with triplets, can have $H^+ \to W^+ Z$ ($H^+ \to W^+ \gamma$ never allowed at tree level)
- It’s important to not miss alternative models

One alternative: Inert Doublet Model (IDM)

- Inert Doublet Model: [Barbieri, Hall, Rychkov; Deshpande, Ma] two scalar doublets, Φ_1 gets a vev and couples to fermions: a Z_2 symmetry forbids mixing and Yukawas for Φ_2
- One SM-like Higgs boson; the other scalars are (exactly) fermiophobic and the lightest one is stable
- Thus: dark matter protected by the Z_2
- What if the Z_2 is broken by higher scale operators?

Stealth doublet model

We have introduced a generalization of the IDM: the Z_2 is softly broken — this leads to mixing of the CP-even scalars and loop-generated fermion couplings

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} G^+ \\ v + \phi_1 + \mathrm{i} G^0 \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} H^+ \\ \phi_2 + \mathrm{i} A \end{pmatrix}$$

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}, \quad 0 \leq \alpha \leq \frac{\pi}{2}$$

The scalars H^+ and A^0 from Φ_2 are ***fermiophobic*** at tree level

[R. Enberg, J. Rathsman, G. Wouda, 1304.1714]

2-higgs doublet scalar potential

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

- Many symmetries, e.g. U(2) rotations
- Freedom to choose basis for doublets:
  the physical basis is then fixed by Yukawa sector

- Our model: physical realization of Higgs basis

Stealth doublet model

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

Z_2 symmetry $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$ would forbid m_{12}, λ_6 and λ_7

Inert Doublet Model: Z_2 is conserved, lightest Higgs is stable, only one doublet has a vev

We break Z_2 : m_{12}, λ_6 and λ_7 are non-zero → leads to mixing

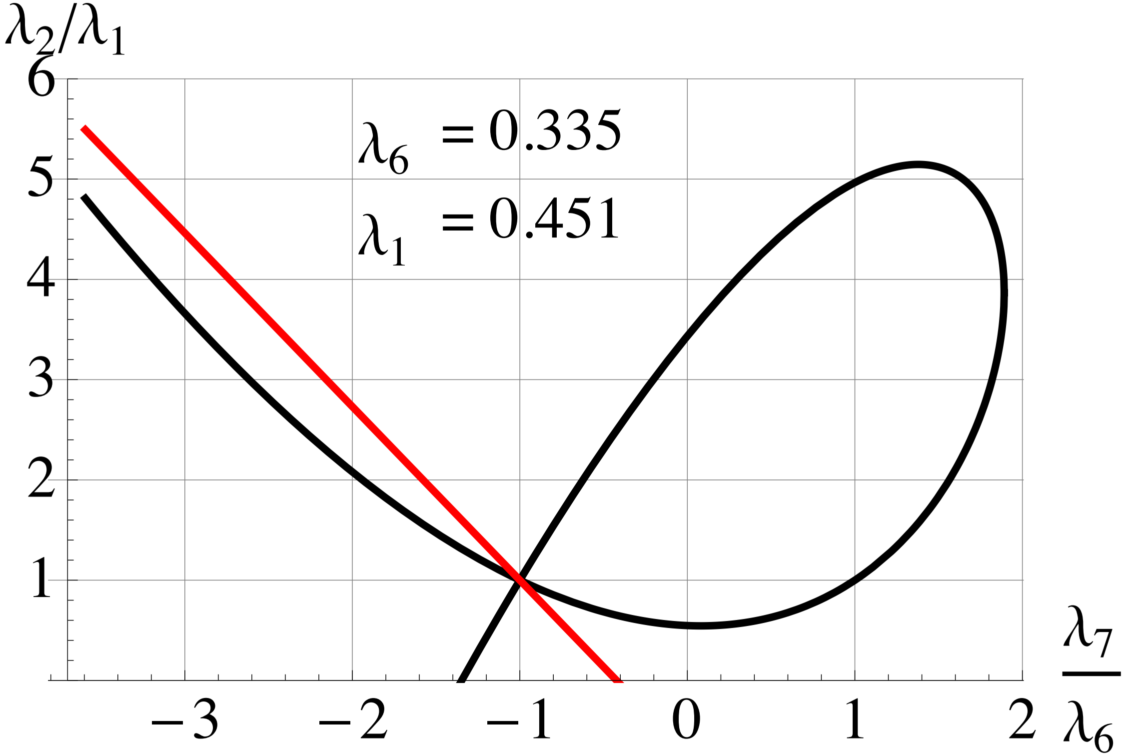
m_{12}: soft breaking – $\lambda_{6,7}$ hard breaking

Soft Z_2 breaking

Davidson-Haber formalism to find soft breaking conditions:

$$(\lambda_1 - \lambda_2)\left[\lambda_{345}(\lambda_6 + \lambda_7) - \lambda_2\lambda_6 - \lambda_1\lambda_7\right] - 2(\lambda_6 - \lambda_7)(\lambda_6 + \lambda_7)^2 = 0,$$

$$(\lambda_1 - \lambda_2)m_{12}^2 + (\lambda_6 + \lambda_7)(m_{11}^2 - m_{22}^2) \neq 0.$$



black line allowed

red line not allowed

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

Masses etc

Minimization conditions:

$$m_{11}^2 = -\frac{1}{2}v^2\lambda_1$$

$$m_{12}^2 = \frac{1}{2}v^2\lambda_6$$

Masses for A and H^+:

$$m_A^2 = m_{H^\pm}^2 - \frac{1}{2}v^2(\lambda_5 - \lambda_4)$$

$$m_{H^\pm}^2 = m_{22}^2 + \frac{1}{2}v^2\lambda_3.$$

Mixing angle of h and H: $\sin 2\alpha = \dfrac{2v^2\lambda_6}{m_H^2 - m_h^2}$

Can use m_{12} or λ_6 to specify amount of Z_2 breaking – or mixing α

Parameters: m_h, m_H, m_A, $m_{H\pm}$, s_α, λ_3, λ_7

Interactions

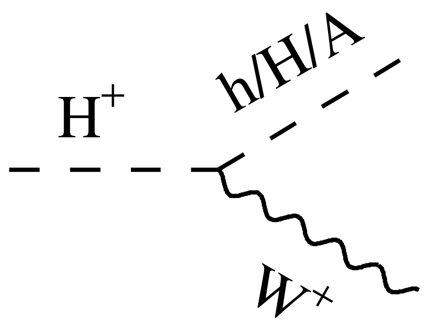
The h and H couple to fermions at tree level:

$$-\mathcal{L}_{\text{Yukawa}} = \frac{m_f}{v} \bar{\Psi}_f \Psi_f \left(H \cos\alpha - h \sin\alpha \right)$$

The H^+ and A couple to scalars and gauge bosons

E.g: we have the H^+ vertex:

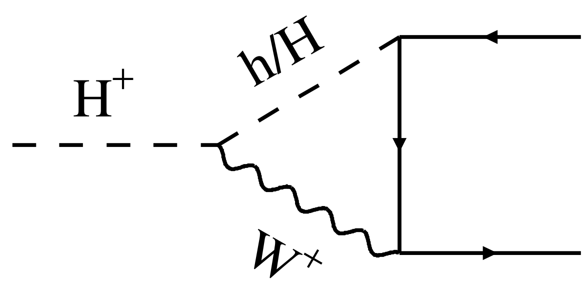
~ cos α for h , ~ sin α for H



H^+ and A get fermion couplings

at one-loop level, e.g.

~ sin α cos α (→ 0 for no mixing)



Constraints

- Theoretical constraints:

  Positivity, perturbativity, (tree-level) unitarity

- Electroweak:

  S,T,U parameters

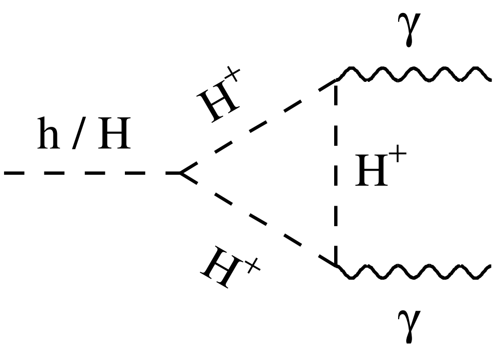
- Flavor:

  n/a (because of fermiophobicity. 2-loop FCNC only)

- Higgs discovery:

  allowed signal strengths

  no extra neutral Higgses



(Won't have time to discuss these, see 1304.1714)

Phenomenology

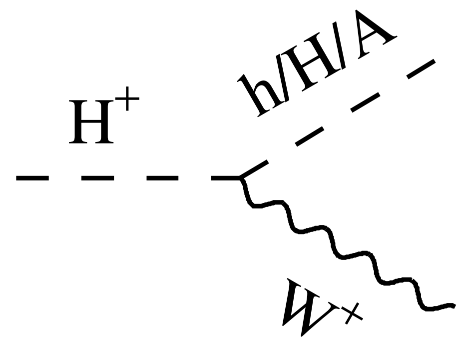
- Production mechanisms and decays are very different for the fermiophobic H^+ and A^0

- Instead of normal decays (e.g. $H^+ \rightarrow \tau^+\nu, cs, tb$) we get
  - Loop-induced 2-body decays or
  - 4- or 6-fermion decays

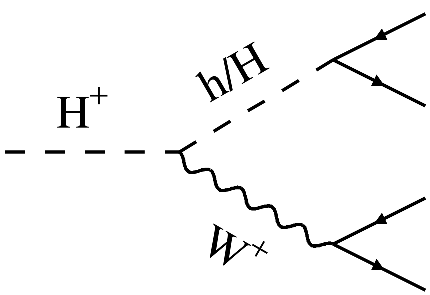
- LHC motivated: define two cases:
  1. **$m_h = 125$ GeV**, $s_\alpha \sim 0.9$, $m_H \geq 300$ GeV
  2. **$m_H = 125$ GeV**, $s_\alpha \sim 0.1$, $m_h \sim 75$ GeV

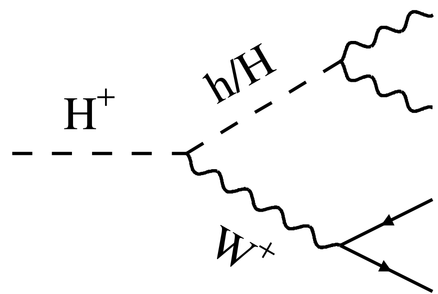
Charged scalar

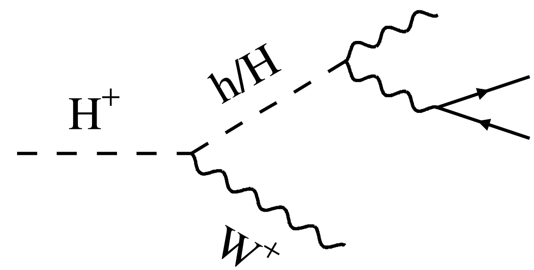
Main H^+ vertex:

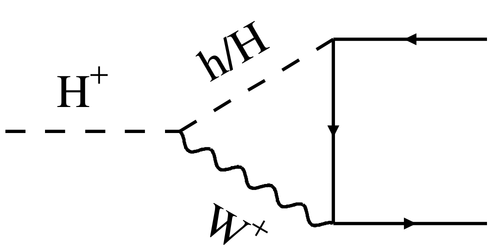


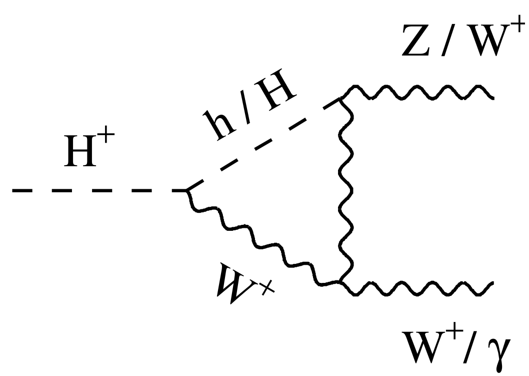
H+ decays:







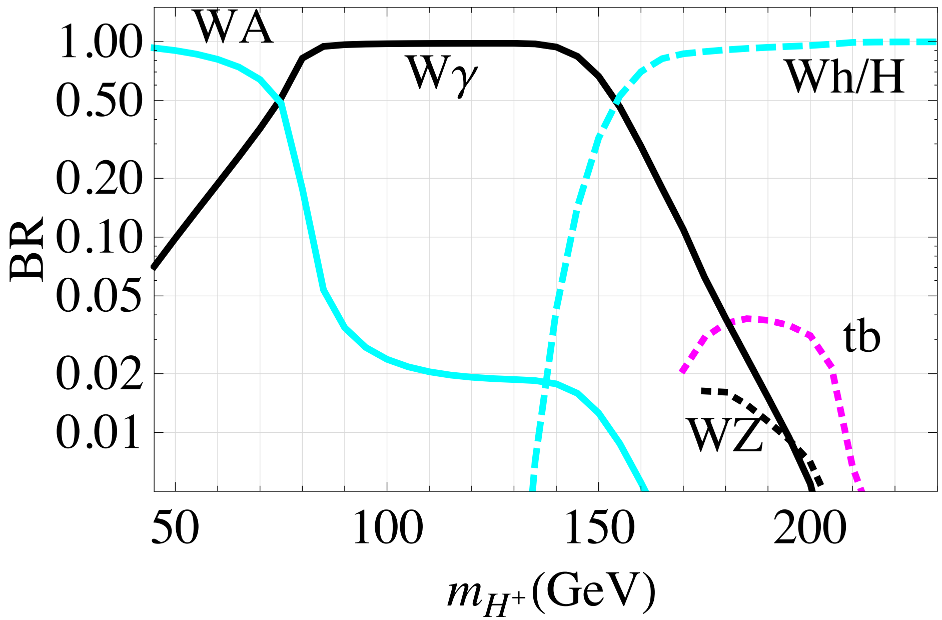


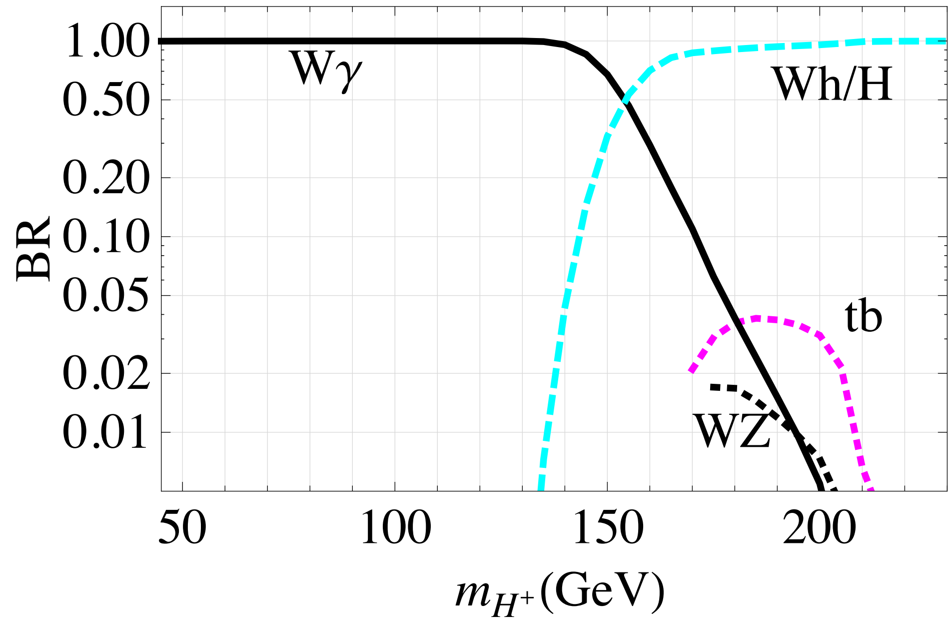


All diagrams ~ sin α cos α
→ 0 for no mixing
(= inert doublet model)

One-loop decays are renormalized in an on-shell scheme

Example: $H^{\pm} \to W^{\pm}\gamma$ dominating





$m_A = m_{H\pm} - 10$ GeV

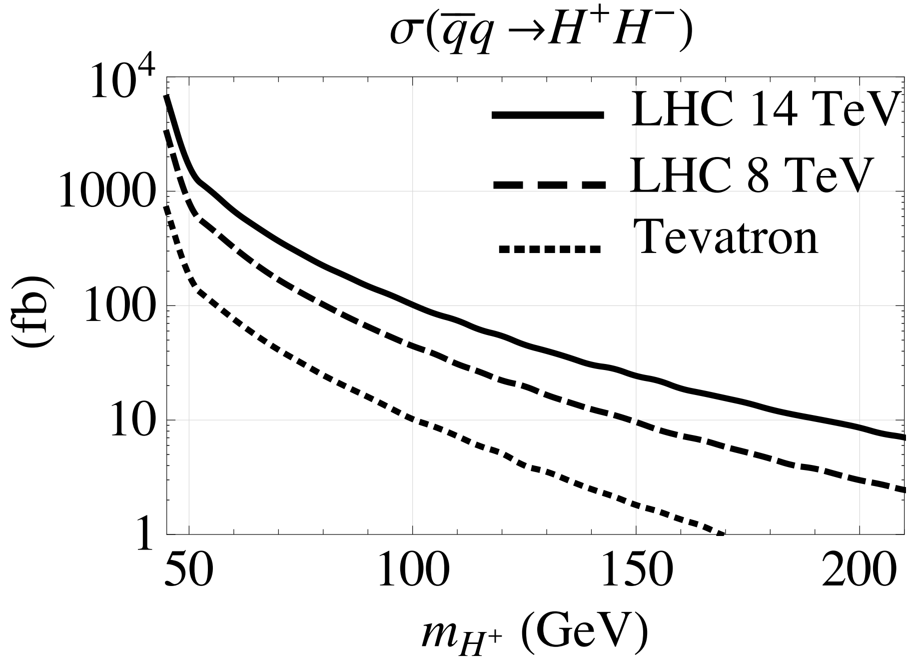
$m_A = m_{H\pm}$

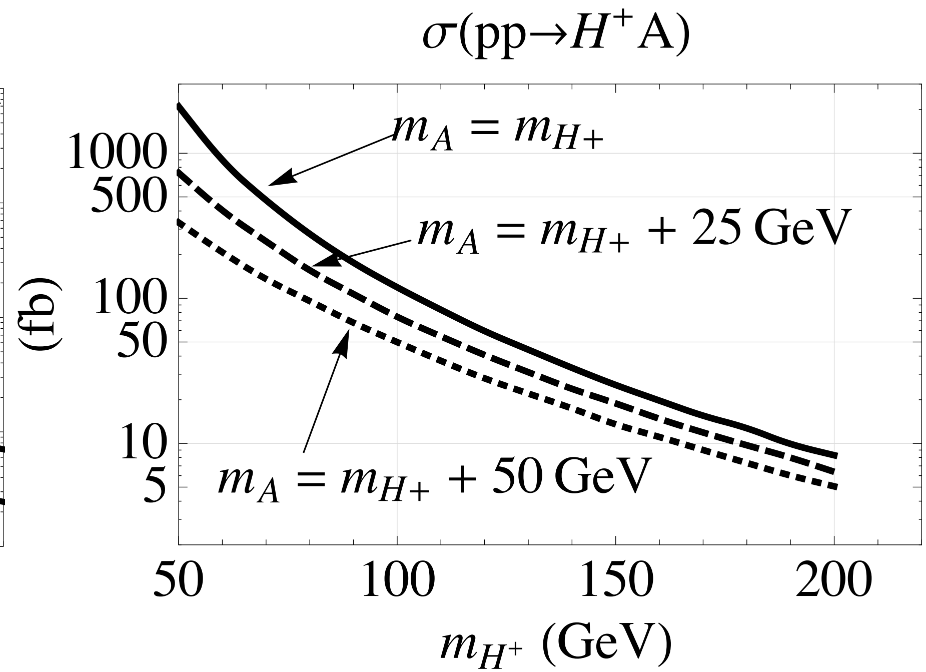
$m_h = 125$ GeV , $m_H = 300$ GeV , $s_\alpha = 0.9$

$\lambda_3 = 2m_{H\pm}^2 / v^2$, $\lambda_2 = \lambda_1$, $\lambda_7 = \lambda_6$

Production

Drell-Yan pair production through Z or W:





Pair production or associated H^+W through scalars also possible

Conclusions

Presented Stealth doublet model which generalizes the IDM:

- Softly broken Z_2
- No FCNC problems (diagonal couplings at one-loop)
- Predicts extra scalars with unusual properties

- LHC pheno study underway (with J. Rathsman, G. Wouda)