# Twisted Higgs Phenomenology at Hadron Colliders

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# Flashback in 94

$$m_t = 169^{+16+17}_{-18-20}\ \text{GeV}$$

PDG value, best fit of all indirect EW data

First top candidate events:

$$m_t = 174 \pm 10^{+13}_{-12}\ \text{GeV}$$

# Top mass prediction

In Standard Model, at one loop

$$\hat{\rho} \equiv \frac{M_W^2}{\hat{c}_Z^2 M_Z^2} \neq 1$$

mainly due to the non degenerate doublet $(t, b)$:

$$\Delta_t \hat{\rho} = \frac{3 G_F}{8\sqrt{2}\pi^2} \left( m_t^2 + m_b^2 - \frac{4 m_t^2 m_b^2}{m_t^2 - m_b^2} \log \frac{m_t}{m_b} \right)$$

# Higgs mass dependence

$$\Delta_H \hat{\rho} = -\frac{3\alpha}{16\pi \hat{c}_W^2}\left(\log\frac{m_{h^0}^2}{m_W^2} + \frac{1}{6} + \frac{1}{\hat{s}_W^2}\log\frac{m_W^2}{m_Z^2}\right)$$

but only logarithmic so

$$m_t^{pred} = 149^{+16}_{-18}\ \text{GeV for } m_h = 60\ \text{GeV}$$
$$m_t^{pred} = 186^{+16}_{-18}\ \text{GeV for } m_h = 1\ \text{TeV}.$$

# Why not quadratic in $m_h$ ?

Accidental $SU(2)_L \times SU(2)_R \simeq SO(4)$ symmetry in SM scalar potential:

$$V(\phi) = -m^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

$$\phi^\dagger\phi = \pi_1^2 + \pi_2^2 + \pi_3^2 + \sigma_0^2 \quad \text{if} \quad \phi = \begin{pmatrix} \pi_1 + i\pi_2 \\ \sigma_0 + i\pi_3 \end{pmatrix}$$

$\langle\sigma_0\rangle = v$, $SO(4)$ broken to custodial $SO(3) \simeq SU(2)_{L+R}$ under which Goldstone $\pi_i$'s transform as a triplet

# Custodial symmetry breaking in SM

- Gauge sector: triplet of degenerate vector bosons recovered if $g_Y \longrightarrow 0$ or $g_L \longrightarrow 0$

$$m^2_{W^\pm} = m^2_{Z^0} \left( \frac{g_L^2}{g_L^2 + g_Y^2} \right)$$

- Yukawa sector: breaks $SU(2)_L \times SU(2)_R$ if $\lambda_u \neq \lambda_d$

$$\mathcal{L}_Y \ni \lambda_d \overline{Q}_L \phi d_R + \lambda_u \overline{Q}_L \tilde{\phi} u_R$$

# Outline

1. 2HDM with a twisted custodial symmetry
2. Constraining the model
3. Phenomenology at hadron colliders

# Outline

# Generic 2HDM

4 hermitian operators: $\hat{A} = \phi_1^\dagger \phi_1$, $\hat{B} = \phi_2^\dagger \phi_2$, $\hat{C} = \frac{1}{2}\left(\phi_1^\dagger \phi_2 + \phi_2^\dagger \phi_1\right)$, $\hat{D} = -\frac{i}{2}\left(\phi_1^\dagger \phi_2 - \phi_2^\dagger \phi_1\right)$

Generic 2HDM potential (14 parameters):

$$\begin{aligned} V &= -m_1 \hat{A} - m_2 \hat{B} - m_{12} \hat{C} - \tilde{m}_{12} \hat{D} \\ &\quad + \lambda_1 \hat{A}^2 + \lambda_2 \hat{B}^2 + \lambda_3 \hat{C}^2 + \lambda_4 \hat{D}^2 \\ &\quad + \lambda_5 \hat{A}\hat{B} + \lambda_6 \hat{A}\hat{C} + \lambda_7 \hat{A}\hat{D} \\ &\quad + \lambda_8 \hat{B}\hat{C} + \lambda_9 \hat{B}\hat{D} + \lambda_{10} \hat{C}\hat{D} \end{aligned}$$

# Higgs basis

Arbitrary $(\phi_1, \phi_2)$ basis:

$$\begin{pmatrix} \phi'_1 \\ \phi'_2 \end{pmatrix} = U_{2\times2} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \quad \text{with} \quad U_{2\times2} \in U(2)$$

+ redefinition of $m_i$'s and $\lambda_i$'s

Higgs basis: $\langle\phi_1^0\rangle = v$ and $\langle\phi_2^0\rangle = 0.$

# Generic custodial symmetry

*Phys. Rev. Lett.* ***98****: 251802, 2007. hep-ph/0703051*
*J.-M. Gérard and M.H.*

$SU(2)_L \times SU(2)_R$ acts on the $[1/2, 1/2]$ representation $M_1$ of $\phi_1$:

$$M_1 \equiv \frac{1}{\sqrt{2}}(\sigma_0 \mathbb{I} + i\pi_a \tau^a)$$

$$M_1 \to U_L M_1 U_R^\dagger$$

Sufficient to ensure $\hat{\rho} = 1$ since all GBs $\in \phi_1$ in Higgs basis

# Generic custodial symmetry

Only $SU(2)_L \times U(1)_Y$ is a local symmetry $\rightarrow$ right transformation of $M_2$ not completely fixed:

$$M_2 \rightarrow U_L M_2 V_R^\dagger$$

with

$$V_R = X^\dagger U_R X$$

and

$$X = \begin{pmatrix} \exp(i\frac{\gamma}{2}) & 0 \\ 0 & \exp(-i\frac{\gamma}{2}) \end{pmatrix}$$

# Generic custodial symmetry

Only $\hat{A}$, $\hat{B}$ and

$$\hat{C}' \equiv \frac{1}{2}\mathrm{Tr}(M_1 X M_2^\dagger) = \cos(\frac{\gamma}{2})\hat{C} + \sin(\frac{\gamma}{2})\hat{D}$$

are invariants of this generic custodial symmetry

Imposing it: $14 \rightarrow 9$ free parameters

# CP transformation

We can choose

$$\begin{aligned}(\mathcal{CP})\phi_1(t,\vec{r})(\mathcal{CP})^\dagger &= \phi_1^*(t,-\vec{r})\\(\mathcal{CP})\phi_2(t,\vec{r})(\mathcal{CP})^\dagger &= \phi_2^*(t,-\vec{r}).\end{aligned}$$

$\hat{A}$, $\hat{B}$ and $\hat{C}$ are $CP$-even while $\hat{D}$ is $CP$-odd
$\rightarrow$ Imposing explicit $CP$ invariance: 10 free parameters

What happens if we consider both $CP$ and custodial symmetries ?

2 possibilities...

# Usual custodial symmetry $\gamma = 0$

- Invariance under $CP$ guaranteed since $\hat{C}' = \hat{C} \rightarrow 9$ free parameters
- Degenerate $SU(2)_{L+R}$ triplet $(H^{\pm}, A^0)$ and two singlets $h^0$ and $H^0$ which mix
- Limit of MSSM if $g_L \rightarrow 0$ since $m^2_{H^{\pm}} = m^2_{A^0} + m^2_{W^{\pm}}$

# Twisted custodial symmetry $\gamma = \pi$

- Custodial and $CP$ symmetries must be imposed since $\hat{C}' = \hat{D} \rightarrow 6$ free parameters
- Degenerate $SU(2)_{L+R}$ triplet $(H^{\pm}, H^0)$ and two orthogonal singlets $h^0$ and $A^0$
- SM $h^0$ since $CP$ forbids mixing with $A^0$

# $\mathbb{Z}_2$ symmetry

Twisted custodial + $CP$ symmetry $\rightarrow$ accidental unbroken $\mathbb{Z}_2$ symmetry:

$$\phi_1 \rightarrow \phi_1 \quad \text{and} \quad \phi_2 \rightarrow -\phi_2$$

To avoid FCNCs, impose it to be at most softly broken in all basis with an additional $SO(2)_H$ on the quartic potential

# Potential and spectrum

$$\begin{aligned} V &= -\mu_1 H_1^\dagger H_1 - \mu_2 H_2^\dagger H_2 - \mu_{12}\left(H_1^\dagger H_2 + H_2^\dagger H_1\right) \\ &\quad +\Lambda_S \left(H_1^\dagger H_1 + H_2^\dagger H_2\right)^2 + \Lambda_{AS}\left(H_1^\dagger H_2 - H_2^\dagger H_1\right)^2 \end{aligned}$$

with $\langle H_1^0 \rangle = v_1$, $\langle H_2^0 \rangle = v_2$, $\tan\beta \equiv v_2/v_1$

$$\begin{aligned} m_{h^0}^2 &= 4\Lambda_S v^2 \\ m_{H^0}^2 &= m_{H^\pm}^2 = \frac{2\mu_{12}}{\sin(2\beta)} \equiv m_T^2 \\ m_{A^0}^2 &= m_T^2 - 4\Lambda_{AS} v^2 \end{aligned}$$

# Yukawa couplings: Type I

- $H_1$ and all fermions are $\mathbb{Z}_2$-even while $H_2$ is $\mathbb{Z}_2$-odd:

$$\mathcal{L}_Y \ni \frac{m_d}{v_1} \overline{Q}_L H_1 d_R + \frac{m_u}{v_1} \overline{Q}_L \tilde{H}_1 u_R$$

- $h^0$ has SM-like couplings $m_f/v$ while $H^0$, $A^0$ and $H^{\pm}$ couplings are scaled by $\tan\beta$

  $\tan\beta \to 0$: Inert Doublet Model for DM

*Phys. Rev. D* ***74****: 015007 (2006). R. Barbieri, L.J. Hall and V.S. Rychkov*
*JCAP 0702: 028 (2007). L. Lopez Honorez et al.*

# Yukawa couplings: Type II

- $H_1$ and down type $R$ fermions are $\mathbb{Z}_2$-even while $H_2$ and up type $R$ fermions are $\mathbb{Z}_2$-odd:

$$\mathcal{L}_Y \ni \frac{m_d}{v_1}\overline{Q}_L H_1 d_R + \frac{m_u}{v_2}\overline{Q}_L \tilde{H}_2 u_R$$

- MSSM-like: $h^0$ has SM-like couplings $m_f/v$ while $H^0$, $A^0$ and $H^\pm$ couplings are scaled by $\tan\beta$ ($\cot\beta$) for down type (up type) fermions

# Four free parameters . . .

$$m_{h^0} \; m_T \; m_{A^0} \; \tan\beta$$

How to choose them ?

# Outline

# Light pseudoscalar hypothesis

*S. de Visscher, J.-M. Gérard, V. Lemaitre, F. Maltoni and M.H.*
*Review in preparation*

$$m_{h^0}, m_T > m_{A^0}$$

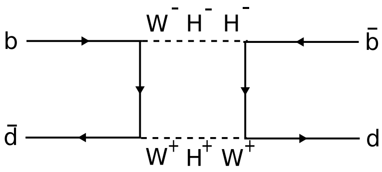
# Theoretical constraints

1. Vacuum stability : $\Lambda_S > 0$ and $\Lambda_S > \Lambda_{AS}$
2. Unitarity : $|\Lambda_S \pm \Lambda_{AS}| < 8\pi$ and $|5\Lambda_S \pm \Lambda_{AS}| < 8\pi$
3. Perturbativity : conservative choice $|\Lambda_{S,AS}| < \pi$

$$m_{h^0}^2 \gtrsim m_{H^\pm}^2 - m_{A^0}^2 \text{ and } m_{h^0} \lesssim 500 \text{ GeV}$$

# $B^0 - \overline{B^0}$ mixing

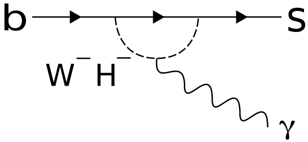
*Using Phys. Rev. D* ***38****: 2857, 1988. C. Q. Geng and J. N. Ng*




- Conservative approach: $H^{\pm}$ contribution within experimental error
- $\tan\beta \lesssim 0.2 - 0.3$ in type I, $\tan\beta \gtrsim 5 - 10$ in type II if $m_{H^{\pm}} < 300$ GeV

# $b \rightarrow s\gamma$ decay

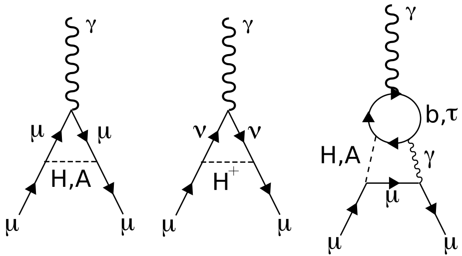
*Using Phys. Lett. B **309**: 86-90, 1993. R. Barbieri and G. F. Giudice*




- Parameters adjusted so that best SM prediction is recovered for $m_{H^\pm} \rightarrow \infty$
- Constraint in type I weaker than $B^0 - \overline{B^0}$. $m_{H^\pm} > 300$ GeV independently of $\tan\beta$ in type II

# Muon $(g-2)$

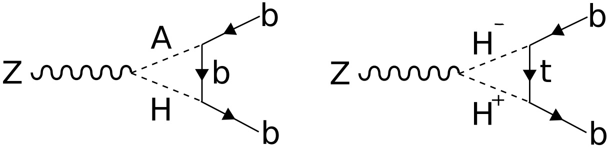
*Using hep-ph/0103223, 2001. M. Krawczyk*




- Not relevant in type I
- Data in favor of $m_{A^0} \simeq 10$ GeV and $\tan\beta \simeq 30$ in type II

# $R_b$ in $Z \to b\bar{b}$

*Using thesis hep-ph/9906332, 1999. H. E. Logan*




- Not relevant in type I
- For $\tan\beta \gtrsim 50$, $m_{A^0} > 50$ GeV if $m_{H^0} > 300$ in type II
- Less constraining than $b \to s\gamma$ for $m_{H^\pm}$ if $\tan\beta \gtrsim 1$

# Direct constraints

- $m_{h^0} \gtrsim 115$ GeV (SM Higgs constraint)
- $m_{H^0} + m_{A^0} \gtrsim 100$ GeV ($Z^{0(*)} \to H^0 A^0$)
- $m_{H^\pm}$ and $\tan\beta$ such that $BR(t \to (H^+ \to c\bar{s}, \tau^+\nu_\tau)b) \lesssim 30\%$ (Tevatron)

# Interesting scenarios ?

1. Type I: $\tan\beta \approx 0.2$

$$\begin{aligned} 10\text{GeV} &< m_{A^0} < 100\text{GeV} \\ 100\text{GeV} &< m_T < m_{h^0} \\ m_T &< m_{h^0} < 300\text{GeV} \end{aligned}$$

2. Type II: $\tan\beta \approx 30$

$$\begin{aligned} 100\text{GeV} &< m_{A^0} < 300\text{GeV} \\ m_{A^0} &< m_{h^0} < 300\text{GeV} \\ m_T &\approx 300\text{GeV} \end{aligned}$$

# Outline

# Interesting decays

1. $h^0 \to A^0 A^0$ with BRs from 0.1 to 1 depending on masses. $BR(A^0 \to \bar{b}b) \simeq 0.9$
2. $h^0 \to H^0 H^0, H^+ H^-$ if kinematically allowed, with typical BRs $\simeq 0.2 - 0.3$
3. $H^\pm \to W^\pm A^0$, $H^0 \to Z^0 A^0$ both dominant if allowed

# Possible signals

1. Type I: SM Higgs $h^0$ production and decay into $A^0A^0$, $H^0H^0$ or $H^+H^-$. 0 to 2 $W$'s or $Z$'s and 4 $b$'s (or $\tau$'s)
2. Type I: Charged Higgs production with top(s) and decay into $W^\pm A^0$. Standard top events + 2 $b$'s
3. Type II: $b\bar{b}H^0$ production and decay into $Z^0A^0$. $Z$'s and 4 $b$'s final states

# Monte-Carlo study

Exotic model + populated final states (4 to 8 particles!)

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Need for a good multipurpose MC tool . . .

# MadGraph v4

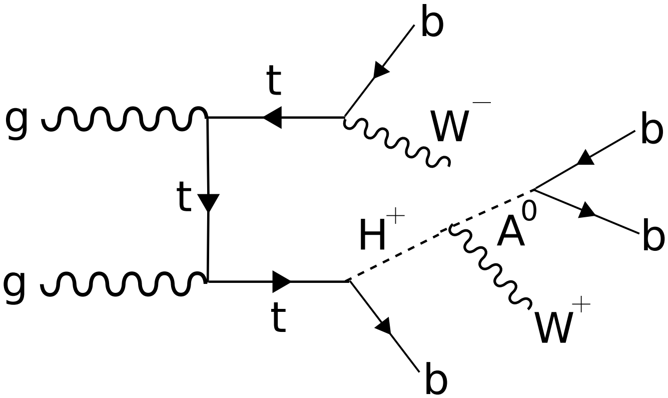
*JHEP **09**: 028 (2007). J. Alwall, P. Demin, S. de Visscher, R. Frederix, F. Maltoni, T. Plehn, D. L. Rainwater, T. Stelzer and M.H.*

1. New models (HEFT, MSSM, 2HDM, ...), framework for user defined models (USRMOD)
2. Matching ME description with parton shower
3. User friendly interface (online, configuration with cards, calculators, analysis tools, . . . )
4. More is coming ! (FeynRules, Decay chains, ME techniques, new fast simulation tool, . . . )

# Generic 2HDM in MadGraph v4

1. Fully generic 2HDM with CP violation and FCNC
2. Calculator (TwoHiggsCalc) with a web interface, working both in generic and Higgs basis
3. Sufficient to reproduce nearly all possibilities of Higgs phenomenology

# $H^{\pm} \to W^{\pm} A^0$ with top(s)



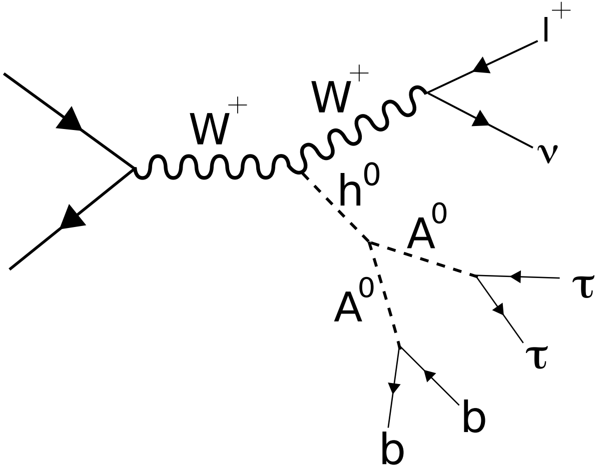
# $H^\pm \to W^\pm A^0$ with top(s)

1. For $m_{H^\pm} < 160$ GeV: $t \to H^+ b$, final state is $W^+W^-b\bar{b}b\bar{b}$. $\simeq$ 10pb at LHC and 0.1pb at Tevatron.

   *See hep-ph/0701193 R. Godbole*

2. For $m_{H^\pm} > 160$ GeV: $tH^-$, final state is $W^+W^-b\bar{b}b$. $\simeq$ 0.5pb at LHC.
3. Main background is $t\bar{t}$ + n jets, irreducible if gluon decaying into $b\bar{b}$

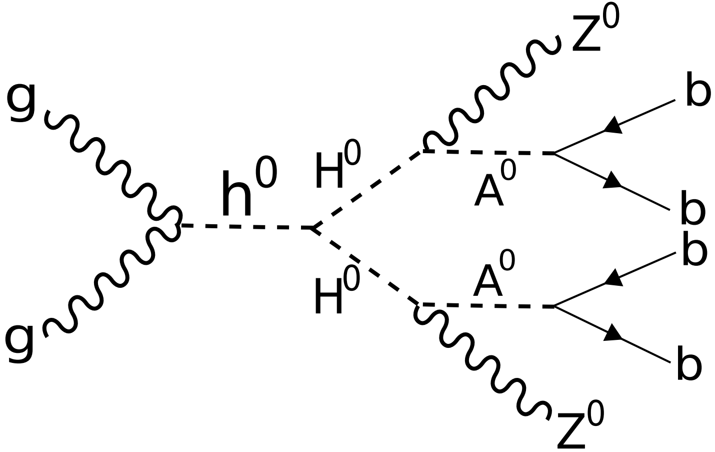
# $h^0 \to A^0 A^0$



# $h^0 \to A^0 A^0$

1. $4b$ final state only feasible at Tevatron if $h^0$ production enhanced compare to SM (Type II and large $\tan\beta$)
   *See Phys. Rev. D **75**: 077701 (2007) T. Stelzer, S. Wiesenfeldt and S. Willenbrock*
2. Associated production, $Z + 4b$, may be feasible at LHC for light $h^0$
   *See Phys. Rev. Lett. **99**:031801 (2007) K. Cheung, J. Song and Q.-S. Yan*
3. $2b2\tau$ final states may also be interesting at LHC in associated production with $Z$ or in VBF

# $H^0 \to Z^0 A^0$



# $H^0 \to Z^0 A^0$

1. From decay $h^0 \to H^0 H^0$, $2Z4b$ final state with cross section around 1pb at LHC.
2. Produced in association with $b$'s (in type II), $b\bar{b}H^0$, $Z4b$ final state with cross section around 5pb at LHC
3. Direct production at Tevatron (in type II), $gg \to H^0$, $Z2b$ final state
4. Low SM backrounds $Z$+jets and $ZZ$+jets

# Challenging analysis

1. Backgrounds ($t\bar{t}$+jets, nZ+jets and nW+jets) must be simulated carefully with matching

   *See J. Alwall, S. de Visscher and F. Maltoni, in preparation.*

2. $b$'s produced in light $A^0$ decays could be highly boosted and collinear. How well these "super $b$-jets" can be tagged ? Can $m_{A^0}$ be measured ?
3. Can Matrix Element techniques help ?

# Conclusion

1. A custodial symmetry is necessary in the Higgs sector and a twisted realization exists
2. A 2HDM with a twisted custodial symmetry is viable
3. Unusual and challenging phenomenology at hadron collider

# Perspectives

1. Possible role/consequences of a twisted custodial symmetry in more ambitious models
2. Full simulation study of the "golden" signatures
3. Detailed study of Tevatron signal(s)

# Twisting Higgs phenomenology

Higgs phenomenology does not always reduce to SM, MSSM or NMSSM-like scenarios

Stay open to more exotic possibilities