Twisted Higgs Phenomenology at Hadron Colliders

Michel Herquet

UC Davis HEP Theory Seminar
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Flashback in 94

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PDG value, best fit of all indirect EW data

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First top candidate events:

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

Top mass prediction

In Standard Model, at one loop

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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

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

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

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

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

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

Custodial symmetry breaking in SM

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

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

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- 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

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Generic 2HDM

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

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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

Phys. Rev. D ***72****: 035004, 2005, S. Davidson and H. E. Haber*

Arbitrary (ϕ_1, ϕ_2) basis:

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

+ redefinition of m_i's and λ_i's

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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 ϕ_1:

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

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

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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:

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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

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

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Imposing it: $14 \to 9$ 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

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- 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 $\gamma = \pi$

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Twisted custodial symmetry $\gamma = \pi$

- Custodial and CP symmetries must be imposed since $\hat{C}' = \hat{D} \to 6$ 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:

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

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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

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

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

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

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

Yukawa couplings: Type I

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

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

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$\tan\beta \to 0$: 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:

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

Yukawa couplings: Type II

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

- 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 $\Lambda_S > \Lambda_{AS}$

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

ρ parameter

1. Exact twisted custodial symmetry :
   SM-like correction $\simeq \log(m_{h^0}^2)$, $m_{h^0} \lesssim 250$ GeV

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2. If slightly broken, $m_{H^\pm} \neq m_{H^0}$ and

$$\Delta\rho \simeq \frac{\alpha}{16\pi m_W^2 s_W^2} \left(\frac{m_{H^\pm}^2 - m_{H^0}^2}{2} \right) + \Delta\rho_{SM}(m_{h^0})$$

Phys. Lett. B496 :195-205, 2000. P. H. Chankowski, T. Farris, B. Grzadkowski, J. F. Gunion, J. Kalinowski, M. Krawczyk

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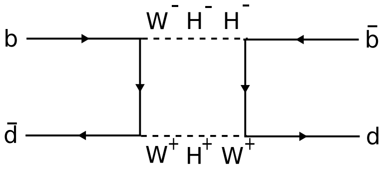
*Phys. Lett. B**496** :195-205, 2000. P. H. Chankowski, T. Farris, B. Grzadkowski, J. F. Gunion, J. Kalinowski, M. Krawczyk*

3. Can accommodate $m_{h^0} \simeq 350$ GeV with a 10% breaking

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

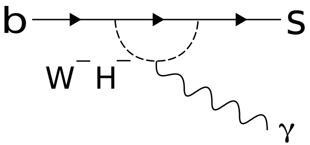
Using Phys. Rev. D ***38****: 2857, 1988. C. Q. Geng and J. N. Ng*



- 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

$b \to s\gamma$ decay

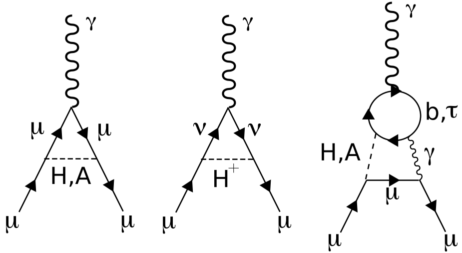
*Using Phys. Lett. B **309**: 86-90, 1993. R. Barbieri and G. F. Giudice*



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

Muon $(g-2)$

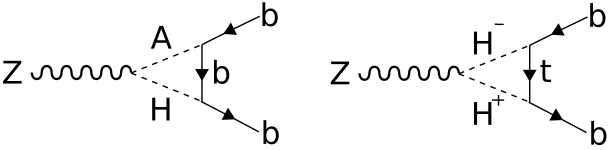
Using hep-ph/0103223, 2001. M. Krawczyk



- Not relevant in type I
- Data in favor of $m_{A^0} \simeq 20$ GeV and $\tan\beta \simeq 30$ in type II

R_b in $Z \to b\overline{b}$

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

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- $m_{H^0} + m_{A^0} \gtrsim 150$ GeV ($Z^{0(*)} \to H^0 A^0$ at LEPII)

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- $m_{h^0} \gtrsim 115$ GeV (SM Higgs constraint)
- $m_{H^0} + m_{A^0} \gtrsim 150$ GeV ($Z^{0(*)} \to H^0 A^0$ at LEPII)
- $m_{H^\pm}$ 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: $\tan\beta \approx 0.2$

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

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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. $BR(A^0 \to \bar{b}b) \simeq 0.9$

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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 τ's)

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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 τ'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

Monte-Carlo study

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

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Need for a new MC tool . . .

MadGraph v4

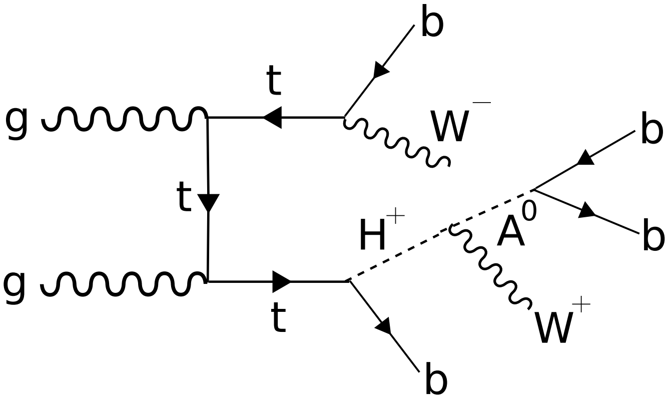
JHEP ***09**: 028 (2007). J. Alwall, P. Demin, S. de Visscher, R. Frederix, F. Maltoni, T. Plehn, D. L. Rainwater, T. Stelzer and M.H.*

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)

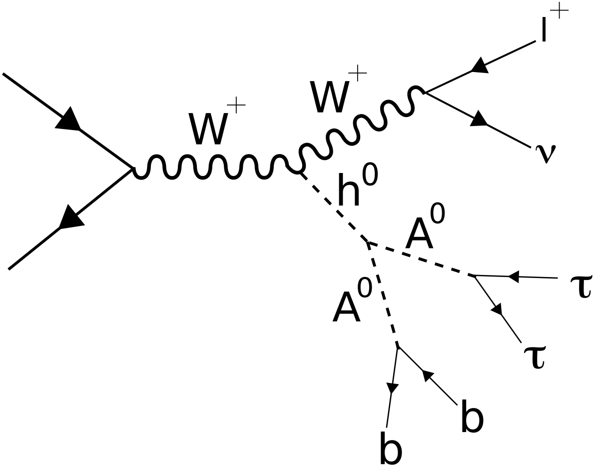
1. For $m_{H^\pm} < 160$ GeV: $t \to H^+ b$, final state is $W^+ W^- b\bar{b}b\bar{b}$. $\simeq$ 10pb at LHC and 0.1pb at Tevatron.

   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 $\tan\beta$)

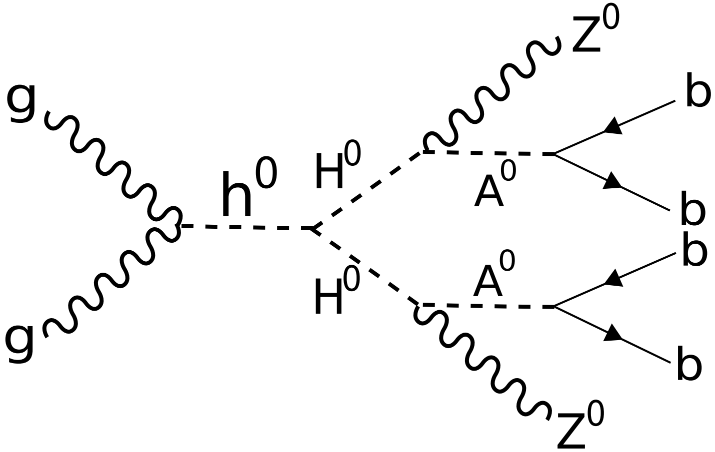
   *See Phys. Rev. D **75**: 077701 (2007) T. Stelzer, S. Wiesenfeldt and S. Willenbrock*

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.

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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

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Stay open to more exotic possibilities