Flashback in 94

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

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

\[ \hat{\rho} \equiv \frac{M_W^2}{\hat{c}_Z^2 M_Z^2} \not= 1 \]

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

\[
\Delta_{H} \hat{\rho} = - \frac{3 \alpha}{16 \pi \hat{c}_{W}^{2}} \left( \log \frac{m_{h}^{2}}{m_{W}^{2}} + \frac{1}{6} + \frac{1}{\hat{s}_{W}^{2}} \log \frac{m_{W}^{2}}{m_{Z}^{2}} \right)
\]

but only logarithmic so

\[
m_{t}^{\text{pred}} = 149^{+16}_{-18} \text{ GeV for } m_{h} = 60 \text{ GeV} \\
m_{t}^{\text{pred}} = 186^{+16}_{-18} \text{ GeV for } m_{h} = 1 \text{ TeV}.
\]
Why not quadratic in $m_\Phi$?

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

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

$$\phi^\dagger \phi = \pi_1^2 + \pi_2^2 + \pi_3^2 + \sigma_0^2$$

if $\phi = \left( \begin{array}{c} \pi_1 + i\pi_2 \\ \sigma_0 + i\pi_3 \end{array} \right)$

$\langle \sigma_0 \rangle = v$, $SO(4)$ 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 $g_Y \to 0$ or $g_L \to 0$

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

- **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

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

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

Generic 2HDM potential (14 parameters):
\[
V = -m_1 \hat{A} - m_2 \hat{B} - m_{12} \hat{C} - \tilde{m}_{12} \hat{D} + \lambda_1 \hat{A}^2 + \lambda_2 \hat{B}^2 + \lambda_3 \hat{C}^2 + \lambda_4 \hat{D}^2 \\
+ \lambda_5 \hat{A} \hat{B} + \lambda_6 \hat{A} \hat{C} + \lambda_7 \hat{A} \hat{D} \\
+ \lambda_8 \hat{B} \hat{C} + \lambda_9 \hat{B} \hat{D} + \lambda_{10} \hat{C} \hat{D}
\]
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

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

\[
M_1 \equiv \frac{1}{\sqrt{2}} (\sigma_0 \mathbb{I} + i \pi a \tau^a)
\]

\[ M_1 \rightarrow U_L M_1 U_R^\dagger \]

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 → 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

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

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

$$\hat{C}' \equiv \frac{1}{2} \text{Tr}(M_1 XM_2^\dagger) = \cos\left(\frac{\gamma}{2}\right) \hat{C} + \sin\left(\frac{\gamma}{2}\right) \hat{D}$$

are invariants of this generic custodial symmetry

Imposing it: $14 \rightarrow 9$ free parameters
We can choose

\[
(CP)\phi_1(t, \vec{r})(CP)\dagger = \phi_1^*(t, -\vec{r})
\]

\[
(CP)\phi_2(t, \vec{r})(CP)\dagger = \phi_2^*(t, -\vec{r}).
\]

\(\hat{A}, \hat{B}\) and \(\hat{C}\) are \(CP\)-even while \(\hat{D}\) is \(CP\)-odd

→ 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 custodinal + $CP$ 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

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

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

\[ m_{h^0}^2 = 4\Lambda_S v^2 \]
\[ m_{H^0}^2 = m_{H^\pm}^2 = \frac{2\mu_{12}}{\sin(2\beta)} \equiv m_T^2 \]
\[ m_{A^0}^2 = m_T^2 - 4\Lambda_{AS} v^2 \]
Yukawa couplings: Type I

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

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

- $h^0$ 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

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

1. 2HDM with a twisted custodial symmetry
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Light pseudoscalar hypothesis

\[ m_{h^0}, m_T > m_{A^0} \]
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 $|\Lambda_{S,AS}| < \pi$

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


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

Muon \((g - 2)\)


- Not relevant in type I
- Data in favor of \(m_{A^0} \approx 10\) GeV and \(\tan \beta \approx 30\) in type II
$R_b$ in $Z \rightarrow b\bar{b}$


- 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 $b \rightarrow s\gamma$ 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 ($Z^0(\ast) \rightarrow H^0A^0$)
- $m_{H^\pm}$ and $\tan \beta$ such that $BR(t \rightarrow (H^+ \rightarrow c\bar{s}, \tau^+\nu_\tau)b) \lesssim 30\%$ (Tevatron)
Interesting scenarios?

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

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

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

   $100\text{GeV} < m_{A^0} < 300\text{GeV}$
   $m_{A^0} < m_{h^0} < 300\text{GeV}$
   $m_T \approx 300\text{GeV}$
Outline

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Interesting decays

1. \( h^0 \rightarrow A^0 A^0 \) with BRs from 0.1 to 1 depending on masses. \( BR(A^0 \rightarrow \bar{b}b) \approx 0.9 \)

2. \( h^0 \rightarrow H^0 H^0, H^+ H^- \) if kinematically allowed, with typical BRs \( \approx 0.2 - 0.3 \)

3. \( H^\pm \rightarrow W^\pm A^0, H^0 \rightarrow Z^0 A^0 \) 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!)

= Need for a good multipurpose MC tool ...
MadGraph v4


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, ...)

M. Herquet (CP3 - UCL)  |  Twisted Higgs Phenomenology  |  Fermilab
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
$H^\pm \rightarrow W^\pm A^0$ with top(s)
$H^\pm \rightarrow W^\pm A^0$ with top(s)

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

2. For $m_{H^\pm} > 160$ GeV: $tH^-$, final state is $W^+ W^- b\bar{b}b$. $\approx 0.5$ pb at LHC.

3. Main background is $t\bar{t} + n$ jets, irreducible if gluon decaying into $b\bar{b}$

See hep-ph/0701193 R. Godbole
$h^0 \rightarrow A^0 A^0$
$h^0 \rightarrow A^0 A^0$

1. 4$b$ final state only feasible at Tevatron if $h^0$ production enhanced compared to SM (Type II and large tan $\beta$)


2. Associated production, $Z+4b$, may be feasible at LHC for light $h^0$


3. 2$b2\tau$ final states may also be interesting at LHC in associated production with $Z$ or in VBF
$H^0 \rightarrow Z^0 A^0$
$H^0 \rightarrow Z^0 A^0$

1. From decay $h^0 \rightarrow H^0 H^0$, $2Z4b$ 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), $gg \rightarrow H^0$, $Z2b$ final state.

4. Low SM backgrounds $Z$+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