Tools for Charged Higgs bosons

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Prospects for Charged Higgs discovery at colliders

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In behalf of the tool

• Man the tool-maker: The ability to make and use tools is a defining characteristic of our species.

• Without tools, the level of charged Higgs physics would not be very advanced.

• Fortunately, owing to the great work of many people, a large variety of tools stand at our disposal.

K. Oakley, 1949
The software tool cycle

Private Code → Calculation → Publication

Bug fixing

User feedback → Public release

User (friendly?) interface

Installation instructions → Manual
Models with charged Higgs bosons

• No charged Higgs boson in the SM
  Charged scalar eaten by W

\[ \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} G^+ \\ v + \phi^0 + iG^0 \end{pmatrix} \]

• \( \rho = 1 \) \( \rightarrow \) Need custodial symmetry
  Charged Higgs from SU(2) singlet (Zee model) or doublet(s)

• By far most popular is the 2HDM
  - Supersymmetry -

\[ G^\pm = \phi_1^\pm \cos \beta + \phi_2^\pm \sin \beta \]
\[ H^\pm = -\phi_1^\pm \sin \beta + \phi_2^\pm \cos \beta \]

\[ \Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1^+ \\ v_1 + \phi_1^0 \end{pmatrix} \]
\[ \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_2^+ \\ v_2 + \phi_2^0 \end{pmatrix} \]

• Not many tools dealing with \( H^+ \) exotica
  \( \rightarrow \) Only 2HDM in this talk

\[ \tan \beta = \frac{v_2}{v_1} \]
### Pheno toolbox for charged Higgs

| Task / Model       | 2HDM | rMSSM | cMSSM | NMSSM | Other |
|--------------------|------|-------|-------|-------|-------|
| Spectrum           |      |       |       |       |       |
| Decays             |      |       |       |       |       |
| Cross sections     |      |       |       |       |       |
| Collider limits    |      |       |       |       |       |
| Flavor limits      |      |       |       |       |       |
| Event generation   |      |       |       |       |       |
| Other              |      |       |       |       |       |

- **Selection bias unavoidable. Remedy at the end.**
MSSM: FeynHiggs

T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. Weiglein
http://www.feynhiggs.de

• “Canonical” Fortran code for the computation of Higgs masses, mixings and much more in the MSSM

• Real or complex parameters (CP violating MSSM)

• Complete set of one-loop corrections + known two-loop corrections in FD approach.

• Tree-level Higgs mass parameter renormalized on shell:

  - $m_A$ as input $\rightarrow$ Corrections to $m_{H^+}, m_h, m_H$ (usual in real case)
  - $m_{H^+}$ as input $\rightarrow$ Corrections to $m_A, m_h, m_H$ (complex case)
**FeynHiggs: Charged Higgs decays**

- Charged Higgs decay modes (and $t \rightarrow bH^+$) including QCD corrections and leading SUSY corrections ("$\Delta b$ corrections")

\[
m_b \tan \beta \rightarrow m_b \frac{\tan \beta}{1 + \Delta_b} = m_b \frac{\tan \beta}{1 + \epsilon_b \tan \beta}
\]

\[
\epsilon_b = \frac{2 \alpha_s}{3\pi} m_\tilde{g}\mu \times F(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_\tilde{g}) + \frac{y_t^2}{16\pi^2} A_t \mu \times F(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)
\]
Non-SUSY models: General 2HDM

- General potential for two identical $Y=1$ Higgs doublets

$$\mathcal{V}_{2\text{HDM}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[ m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \frac{1}{2} \lambda_1 \left( \Phi_1^\dagger \Phi_1 \right)^2$$

$$+ \frac{1}{2} \lambda_2 \left( \Phi_2^\dagger \Phi_2 \right)^2 + \lambda_3 \left( \Phi_1^\dagger \Phi_1 \right) \left( \Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left( \Phi_1^\dagger \Phi_2 \right) \left( \Phi_2^\dagger \Phi_1 \right)$$

$$+ \left\{ \frac{1}{2} \lambda_5 \left( \Phi_1^\dagger \Phi_2 \right)^2 + \left[ \lambda_6 \left( \Phi_1^\dagger \Phi_1 \right) + \lambda_7 \left( \Phi_2^\dagger \Phi_2 \right) \right] \left( \Phi_1^\dagger \Phi_2 \right) + \text{h.c.} \right\}$$

- Parameter count: 11 (with CP violation) : 8 (CP conserved)

+ $\tan \beta$ which defines a basis in the Higgs doublet space

$$\left\{ \lambda_1 - \lambda_7, m_{12}^2 \right\}$$

$$\left\{ m_h, m_H, m_A, m_{H^+}, \sin(\beta - \alpha), \lambda_6, \lambda_7, m_{12}^2 \right\}$$

- MSSM

$$\lambda_1 = \lambda_2 = \frac{g^2 + g'^2}{4} \quad \lambda_3 = \frac{g^2 - g'^2}{4} \quad \lambda_4 = -\frac{g^2}{2}$$

$$\lambda_5 = \lambda_6 = \lambda_7 = 0 \quad m_{12}^2 = m_A^2 \cos \beta \sin \beta$$
2HDM Yukawa sector

- Physical charged Higgs boson coupling
  \[ -\mathcal{L}_Y = \left[ \overline{U} \left( V_{\text{CKM}} \rho^D P_R - \rho^U V_{\text{CKM}} P_L \right) D H^+ + \overline{\nu} \rho^L P_R L H^+ + \text{h.c.} \right] \]

- Off-diagonal \( \rho \) elements lead to flavour violation beyond CKM
  Worse, also to FCNC:
  \[ -\mathcal{L}_Y = \frac{1}{\sqrt{2}} \overline{D} \left[ \kappa^D s_{\beta - \alpha} + \rho^D c_{\beta - \alpha} \right] Dh + \frac{1}{\sqrt{2}} \overline{U} \left[ \kappa^U s_{\beta - \alpha} + \rho^U c_{\beta - \alpha} \right] Uh \]

- \( Z_2 \)-symmetric 2HDM “Types”:

| Type | \( U_R \) | \( D_R \) | \( L_R \) | \( \rho^U \) | \( \rho^D \) | \( \rho^L \) |
|------|---------|---------|---------|---------|---------|---------|
| I    | +       | +       | +       | \( \kappa^U \cot \beta \) | \( \kappa^D \cot \beta \) | \( \kappa^L \cot \beta \) |
| II   | +       | -       | -       | \( \kappa^U \cot \beta \) | \( -\kappa^D \tan \beta \) | \( -\kappa^L \tan \beta \) |
| III/Y| +       | -       | +       | \( \kappa^U \cot \beta \) | \( -\kappa^D \tan \beta \) | \( \kappa^L \cot \beta \) |
| IV/X | +       | +       | -       | \( \kappa^U \cot \beta \) | \( \kappa^D \cot \beta \) | \( -\kappa^L \tan \beta \) |

\[ \kappa^F = \sqrt{2} \frac{M_F}{v} \]

MSSM →
2HDMC: Two-Higgs-Doublet Model Calculator
D. Eriksson, J. Rathsman, OS
http://www.isv.uu.se/thep/MC/2HDMC

Public version: 1.1 (2010-09-28)

- General (CP-conserving) 2HDM
- Different 2HDM parametrizations – including physical masses
- Tree-level spectrum calculation
- Arbitrary Yukawa sector or $Z_2$-“types”, aligned model, etc.
- Theoretical constraints (positivity, unitarity)
- Collider mass limits (HiggsBounds 2.0, Charged Higgs)
- Oblique EW parameters, muon g-2
- All two-body Higgs decays at tree-level (incl. FCNC)
- Leading QCD corrections
- Non-standard top decays
- $H \rightarrow VV^*$ and $H \rightarrow HV^*$ off-shell decays
- $H \rightarrow gg$ and $H \rightarrow gg$
- Model file for MG/ME to generate events
- LesHouches-style interface (SuperIso, MG/ME, ...)

NEW!
2HDMC: Examples

- Mass constraints from T parameter
  \[ m_h = 117 \text{ GeV} \]
  \[ m_H = 300 \text{ GeV} \]
  \[ \sin(\beta - \alpha) = 1 \]

- \( H^+ \) decays in 2HDM types
  - \( H^+ \rightarrow c\bar{b} \)
  - \( H^+ \rightarrow c\bar{s} \)
  - \( H^+ \rightarrow \tau^+\nu_\tau \)
  - \( H^+ \rightarrow \mu^+\nu_\mu \)

\[ m_H = m_A = m_{H^+} = 150 \text{ GeV} \]
Collider limits: HiggsBounds

P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, K. E. Williams
http://www.ippp.dur.ac.uk/HiggsBounds

• HiggsBounds evaluates collider limits for an arbitrary Higgs sector with \( N \) neutral Higgses, \( M \) charged Higgs (new ver. 2.0)

• Two independent versions: Fortran 77 and Fortran 90

• Model-independent comparison to search signatures using published data from LEP+Tevatron experiments (soon: LHC)

• Statistically consistent limits at 95% CL obtained by considering only the channel with highest expected significance.
Examples: HiggsBounds

- Pure 2HDM interfaced using 2HDMC \(\rightarrow\) HiggsBounds

\[ e^+ e^- \rightarrow hZ^0 \]

\[ \sin^2(\beta-\alpha) \]

| \( m_H \) (GeV) | \( \tan \beta \) |
|----------------|----------------|
| 30             | 60             |
| 40             | 80             |
| 50             | 100            |
| 60             | 120            |
| 70             | 140            |
| 80             | 160            |
| 90             | 180            |
| 100            | 200            |
| 110            | 220            |

\[ \sqrt{s} \]

\[ \text{DELPHI} \]

Only charged Higgs limit

\[ \text{Br}(H \rightarrow \tau \nu) = 1 \]

\[ \text{Br}(H \rightarrow \tau \nu) = 0.5 \]

\[ \text{Br}(H \rightarrow \tau \nu) = 0 \]
Charged Higgs in flavor physics

• The charged Higgs boson can give important signatures of MFV SUSY in low-energy processes → Constraints

• Example: $B_u \rightarrow \tau \nu_{\tau}$

\[
\text{BR}(B \rightarrow \tau \nu) = \frac{G_F^2 f_B^2 |V_{ub}|^2}{8\pi \Gamma_B} m_B m_{\tau}^2 \left(1 - \frac{m_{\tau}^2}{m_B^2}\right)^2 \left[1 - \frac{m_B^2}{m_{H^+}^2} \tan^2 \beta\right]
\]
SuperIso

F. Nazila Mahmoudi
http://superiso.in2p3.fr

- MSSM parameters
  - AMSB, GMSB, mSUGRA, NUHM
- NMSSM parameters
- 2HDM parameters
- User provided
- Softsusy
- Isajet
- NMSSMTools
- SLHA file
- SLHA reader
- C-structure
- Parameters
- Relic density
- Excluded masses
- Wilson coefficients
- Charged LSP
- FeynHiggs
- $B \to X_s \gamma$
  - NNLO
- $B \to K^* \gamma$
- Isospin asymmetry
- $B_s \to \mu^+ \mu^-$
- $B \to \tau \nu$
- $B \to D \tau \nu$
- $K \to \mu \nu$
- $D_s \to \ell \nu$
- $D \to \mu \nu$
- Muon $(g-2)_\mu$
Combined MSSM $H^{+}$ limits

- **SoftSUSY:** RGE running, spectrum calculation
- **Hdecay:** Higgs decays
- **FeynHiggs:** More Higgs decays, production
- **SuperIso:** Flavour physics, muon $g-2$

D. Eriksson, F. Mahmoudi, OS, JHEP0811:035 (2008)
Behind the scenes: tools talking

• A complete phenomenological project often involves running of many different tools → Standardize communication

• SLHA: SUSY LesHouches accord (current ver. 2) SUSY spectrum and observables (incl. RPV, NMFV, NMSSM)
  P. Skands et al, [hep-ph/0311123], [arXiv:0801.0045]

• FLHA: Flavour LesHouches accord
  Quantities relevant for flavour physics calculations
  CKM matrix elements, Wilson coefficients, lattice, …
  F. Mahmoudi et al, [arXiv:1008.0762]

• Common standards necessary for streamlined comparisons.
Charged Higgs production

- Heavy charged Higgs produced in association with t quark
- Experimental studies up to now: (LO MC) x K factor
- Complication in LO description: gg/bg matching → MATCHIG
  - Full NLO calculations available
    - 5FS: Zhu; Plehn; Berger, Han, Jiang, Plehn
    - 4FS: Dittmaier, Kramer, Spira, Walser
- Essential with $\Delta_b$ corrections to $H^+tb$ coupling at large $\tan \beta$
MC@NLO for H⁺t production
C. Weydert, S. Frixione, M. Herquet, M. Klasen, E. Laenen, T. Plehn, G. Stavenga, C. D. White, EPJC67:617 (2010)

• Work initiated as a result of Charged Higgs conference 2006

• MC@NLO is a generic framework for combining NLO matrix elements with parton shower MC (HERWIG).

NLO: Reliable normalization, reduced scale dependence, exact kinematic description of hardest emission

MC: Resummation of soft and collinear emissions through parton shower, output of complete unweighted events

• Public MC@NLO code for Charged Higgs production should be available ~now?
## Summary of tools for charged Higgs

| Task / Model          | 2HDM          | rMSSM         | cMSSM         | NMSSM         |
|-----------------------|---------------|---------------|---------------|---------------|
| Spectrum              | 2HDMC         | SoftSUSY      | CPSuperH      | NMSSMTools    |
|                       |               | Spheno        | FeynHiggs     |               |
|                       |               |               |               |               |
| Decays                | 2HDMC         | FeynHiggs     | CPSuperH      | NMSSMTools    |
|                       |               | HDecay        | FeynHiggs     |               |
| Cross sections        | (MC@NLO)      | MC@NLO        | MC@NLO        | (MC@NLO)      |
|                       | (Prospino)    | FeynHiggs     | FeynHiggs     | (Prospino)    |
|                       |               | Prospino      | Prospino      |               |
| Collider limits       | HiggsBounds   | HiggsBounds   | HiggsBounds   | HiggsBounds   |
|                       | (2HDMC)       |               |               | NMSSMTools    |
| Flavor physics        | SuperIso      | SuperIso      | CPSuperH      | SuperIso      |
|                       |               | SUSYBsg       |               |               |
|                       |               | FeynHiggs     |               |               |
| Event generation      | MG/ME (MC@NLO)| MC@NLO        | MC@NLO        | (MC@NLO)      |
|                       |               |               |               | WHIZARD       |
Final words, requests

• Development of tools for charged Higgs physics has prospered since the previous workshop in 2008.

• Major achievements:
  - MC@NLO for $H^+t$ production
  - HiggsBounds for model independent collider limits
  - 2HDMC for phenomenology in general 2HDM
  - Continuous updates and improvements to most other codes

• The pheno community is well-equipped with tools to meet the LHC data, and there might be still some time for improvements.

• What else would you have us do?