Tools for Charged Higgs bosons

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Prospects for Charged Higgs discovery at colliders

Uppsala

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In behalf of the tool

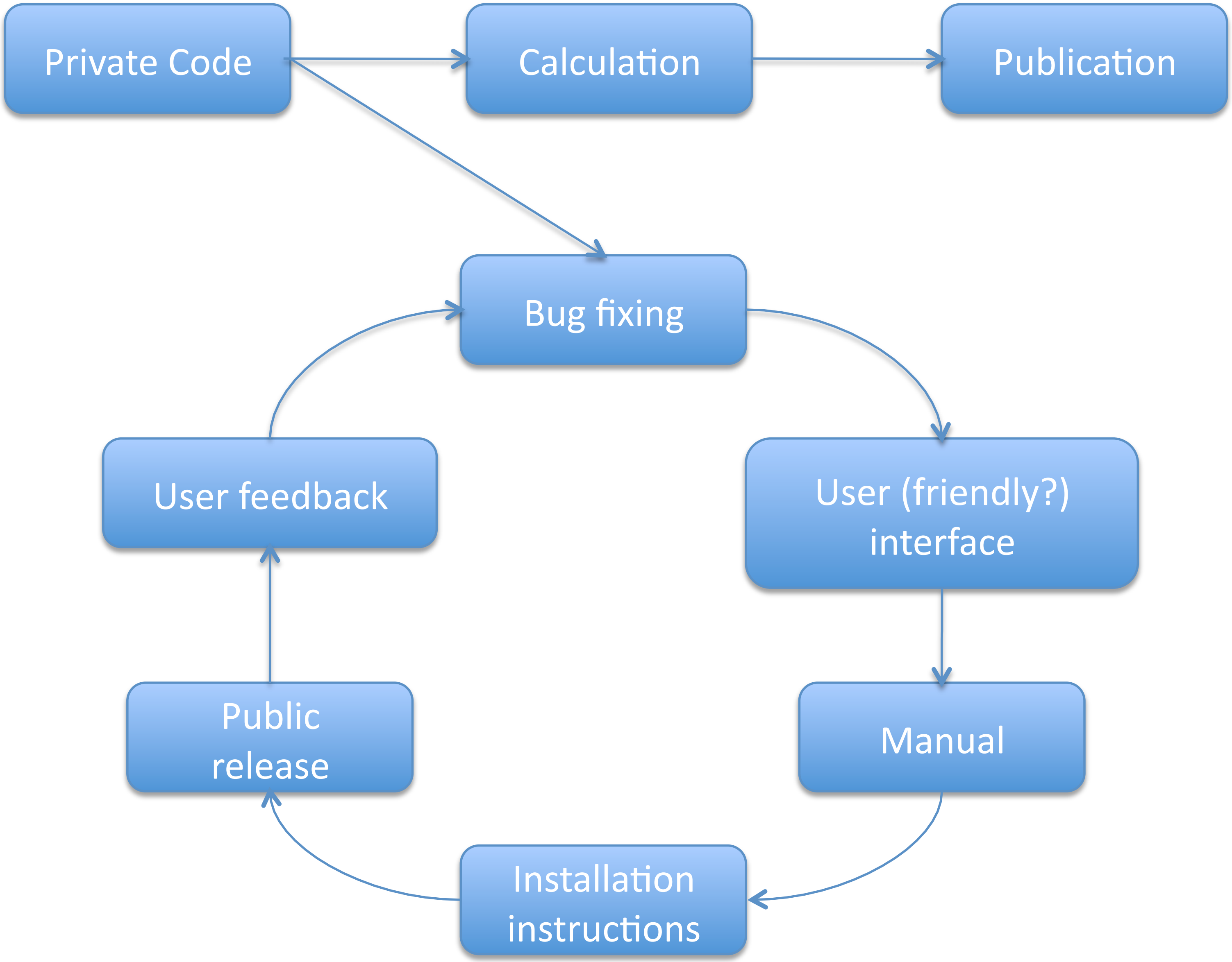
- Man the tool-maker: The ability to make and use tools is a defining characteristic of our species.

K. Oakley, 1949

- 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.

The software tool cycle



Models with charged Higgs bosons

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

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

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

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

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1^+ \\ v_1 + \phi_1^0 \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_2^+ \\ v_2 + \phi_2^0 \end{pmatrix}$$

$$G^\pm = \phi_1^\pm \cos\beta + \phi_2^\pm \sin\beta$$

$$H^\pm = -\phi_1^\pm \sin\beta + \phi_2^\pm \cos\beta$$

- Not many tools dealing with H^+ exotica
  → 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.

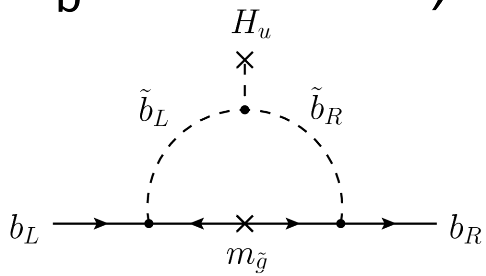
- Tree-level Higgs mass parameter renormalized on shell:

  m_A as input → Corrections to m_{H+}, m_h, m_H (usual in real case)
  m_{H+} as input → Corrections to m_A, m_h, m_H (complex case)

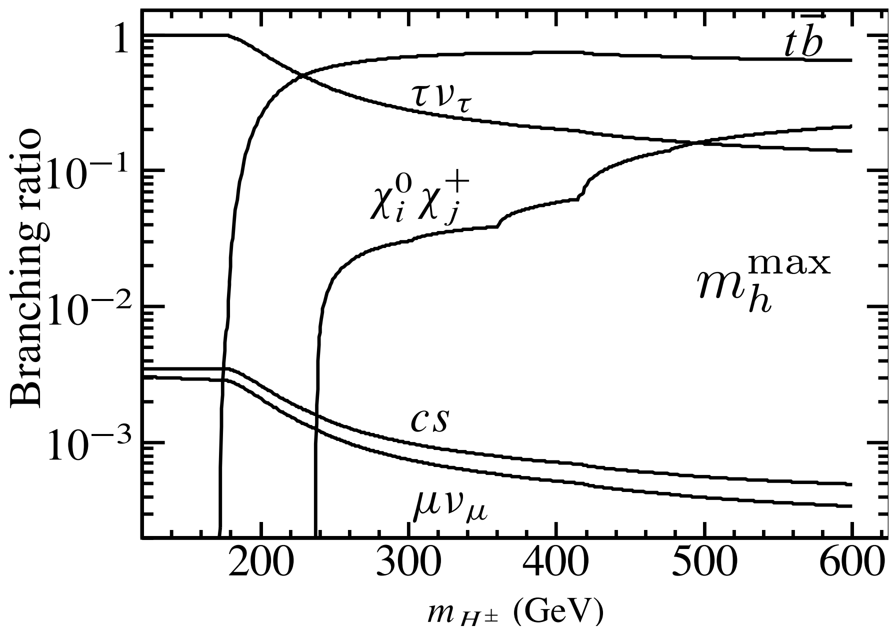
FeynHiggs: Charged Higgs decays

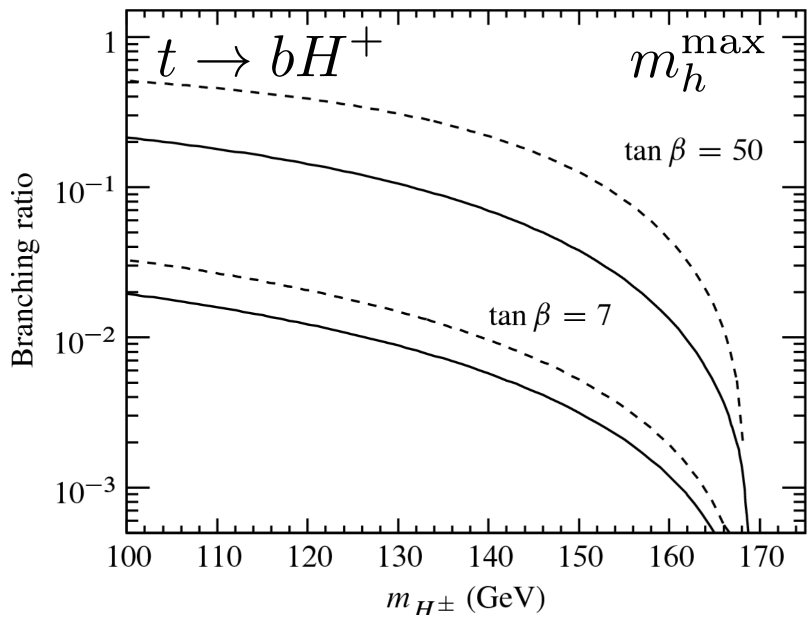
- Charged Higgs decay modes (and t → bH+) including QCD corrections and leading SUSY corrections ("Δ_b corrections")

$$m_b \tan\beta \to m_b \frac{\tan\beta}{1+\Delta_b} = m_b \frac{\tan\beta}{1+\epsilon_b \tan\beta}$$



$$\epsilon_b = \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu \times F(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{y_t^2}{16\pi^2} A_t \mu \times F(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)$$





Non-SUSY models: General 2HDM

- General potential for two identical Y=1 Higgs doublets

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

- Parameter count: 11 (with CP violation) : 8 (CP conserved) + tan β which defines a basis in the Higgs doublet space

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

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

- MSSM

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

$$\lambda_5 = \lambda_6 = \lambda_7 = 0 \qquad m_{12}^2 = m_A^2 \cos\beta \sin\beta$$

2HDM Yukawa sector

- Physical charged Higgs boson coupling

$$-\mathcal{L}_{\mathrm{Y}} = \Big[\overline{U}\big(V_{\mathrm{CKM}}\rho^{D}P_{R} - \rho^{U}V_{\mathrm{CKM}}P_{L}\big)DH^{+} + \overline{\nu}\rho^{L}P_{R}LH^{+} + \mathrm{h.c.}\Big]$$

- Off-diagonal ρ elements lead to flavour violation beyond CKM
  Worse, also to FCNC:

$$-\mathcal{L}_{\mathrm{Y}} = \frac{1}{\sqrt{2}}\overline{D}\Big[\kappa^{D}s_{\beta-\alpha} + \rho^{D}c_{\beta-\alpha}\Big]Dh + \frac{1}{\sqrt{2}}\overline{U}\Big[\kappa^{U}s_{\beta-\alpha} + \rho^{U}c_{\beta-\alpha}\Big]Uh$$

- Z_2-symmetric 2HDM "Types":

$$\kappa^{F} = \sqrt{2}\frac{M^{F}}{v}$$

	Type	U_R	D_R	L_R	ρ^U	ρ^D	ρ^L
	I	$+$	$+$	$+$	$\kappa^U \cot\beta$	$\kappa^D \cot\beta$	$\kappa^L \cot\beta$
MSSM →	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	$+$	$+$	$-$	$\kappa^U \cot\beta$	$\kappa^D \cot\beta$	$-\kappa^L \tan\beta$

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)

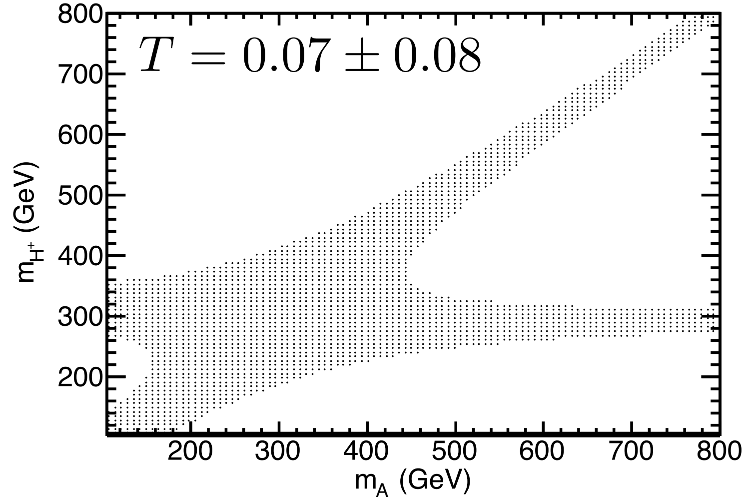
- General (CP-conserving) 2HDM
- Different 2HDM parametrizations – including physical masses
- Tree-level spectrum calculation
- Arbitrary Yukawa sector or Z_2-“types”, aligned model, etc.
- Theoretical constraints (positivity, unitarity)
- Collider mass limits (HiggsBounds 2.0, Charged Higgs)
- Oblique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

2HDMC: Examples

- Mass constraints from T parameter

$$m_h = 117\ \mathrm{GeV}$$

$$m_H = 300\ \mathrm{GeV} \qquad \sin(\beta - \alpha) = 1$$



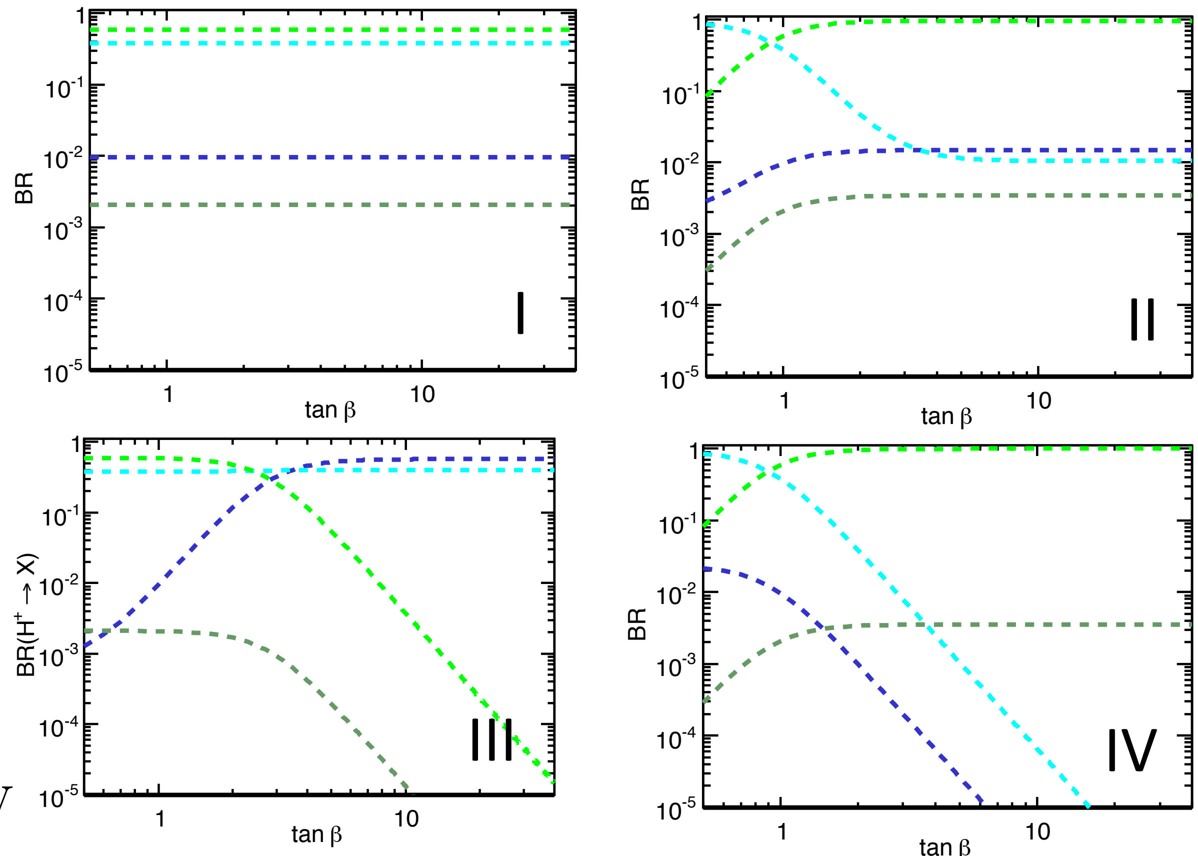
- H+ decays in 2HDM types

$H^+ \to c\bar{b}$

$H^+ \to c\bar{s}$

$H^+ \to \tau^+\nu_\tau$

$H^+ \to \mu^+\nu_\mu$



$$m_H = m_A = m_{H+} = 150\,\mathrm{GeV}$$

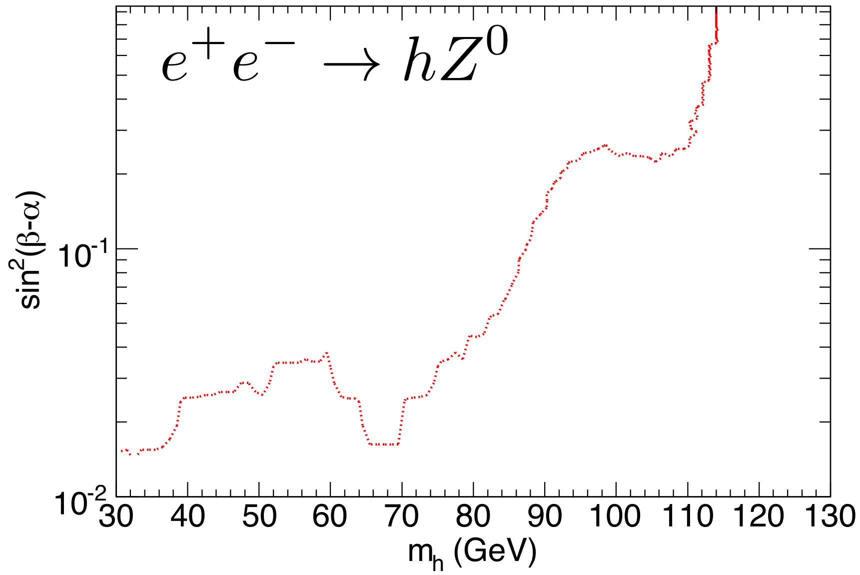
Collider limits: HiggsBounds

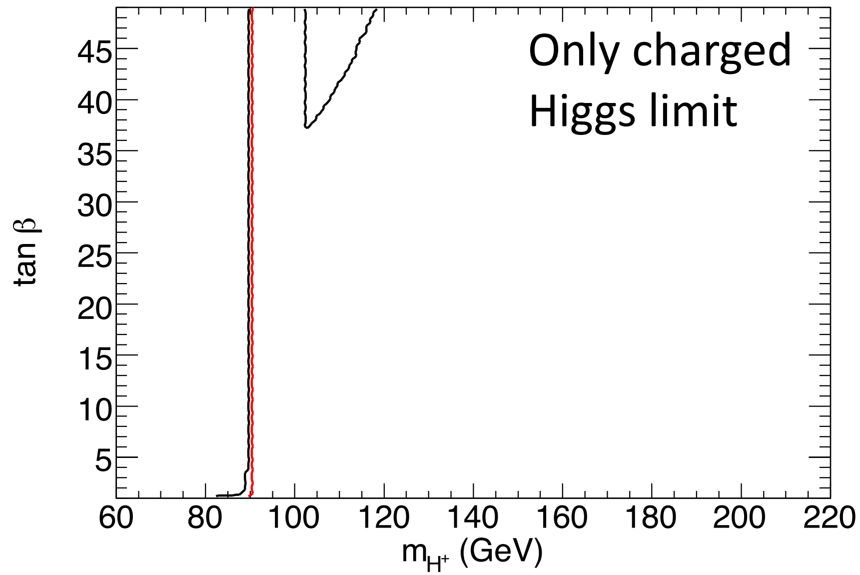
P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, K. E. Williams
http://www.ippp.dur.ac.uk/HiggsBounds

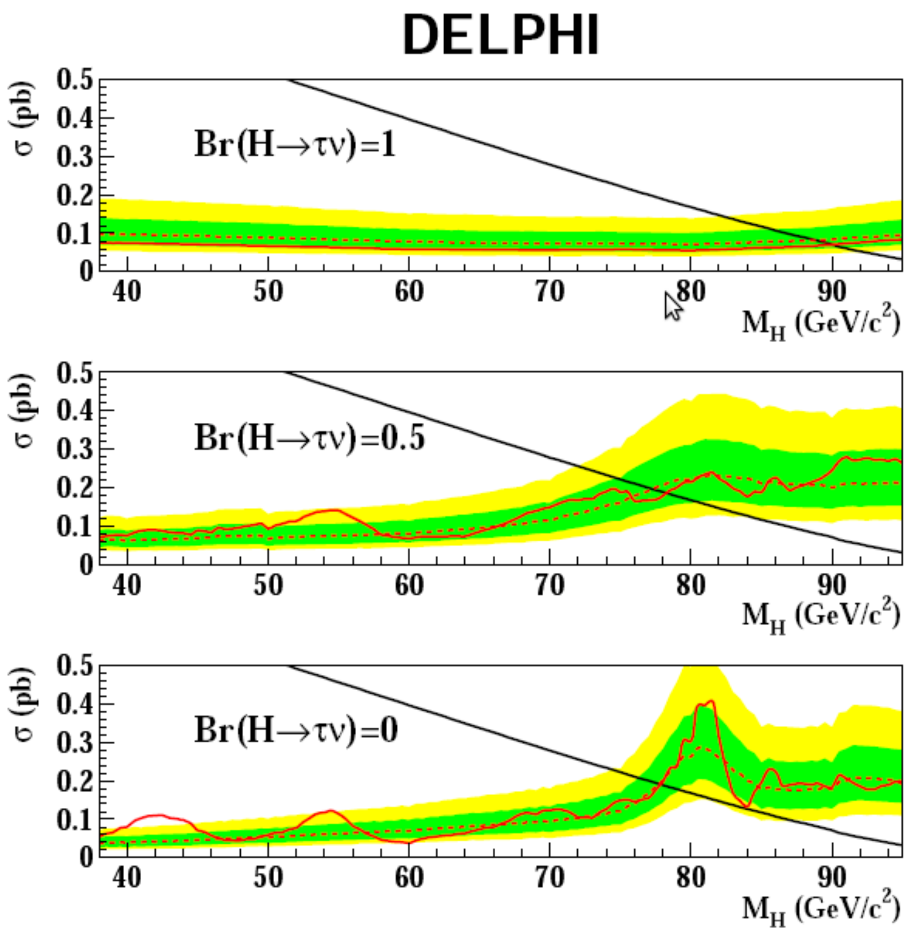
- HiggsBounds evaluates collider limits for an arbitrary Higgs sector with *N* neutral Higgses, *M* charged Higgs (new ver. 2.0)
- Two independent versions: Fortran 77 and Fortran 90
- Model-independent comparison to search signatures using published data from LEP+Tevatron experiments (soon: LHC)
- Statistically consistent limits at 95% CL obtained by considering only the channel with highest *expected* significance.

Examples: HiggsBounds

- Pure 2HDM interfaced using 2HDMC → HiggsBounds





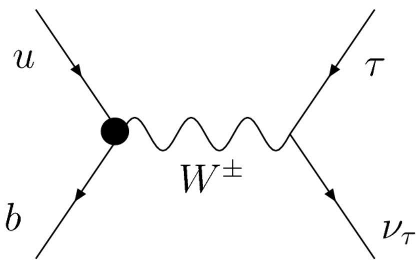


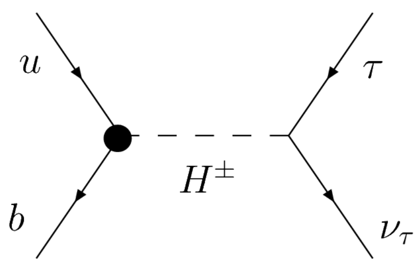
Charged Higgs in flavor physics

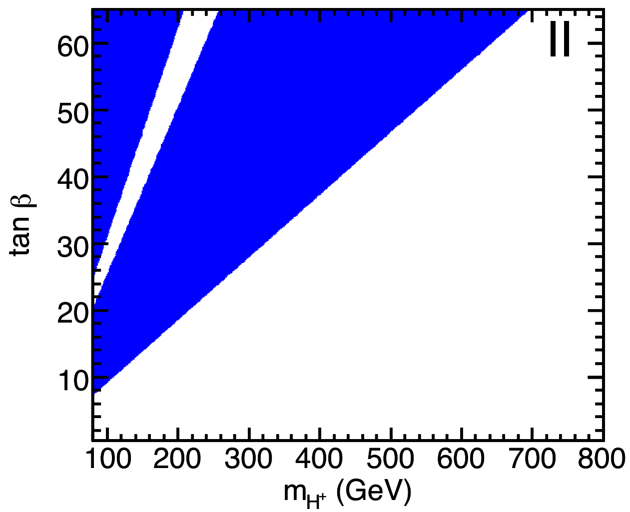
- The charged Higgs boson can give important signatures of MFV SUSY in low-energy processes → Constraints

- Example: $B_u \to \tau\nu_\tau$

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

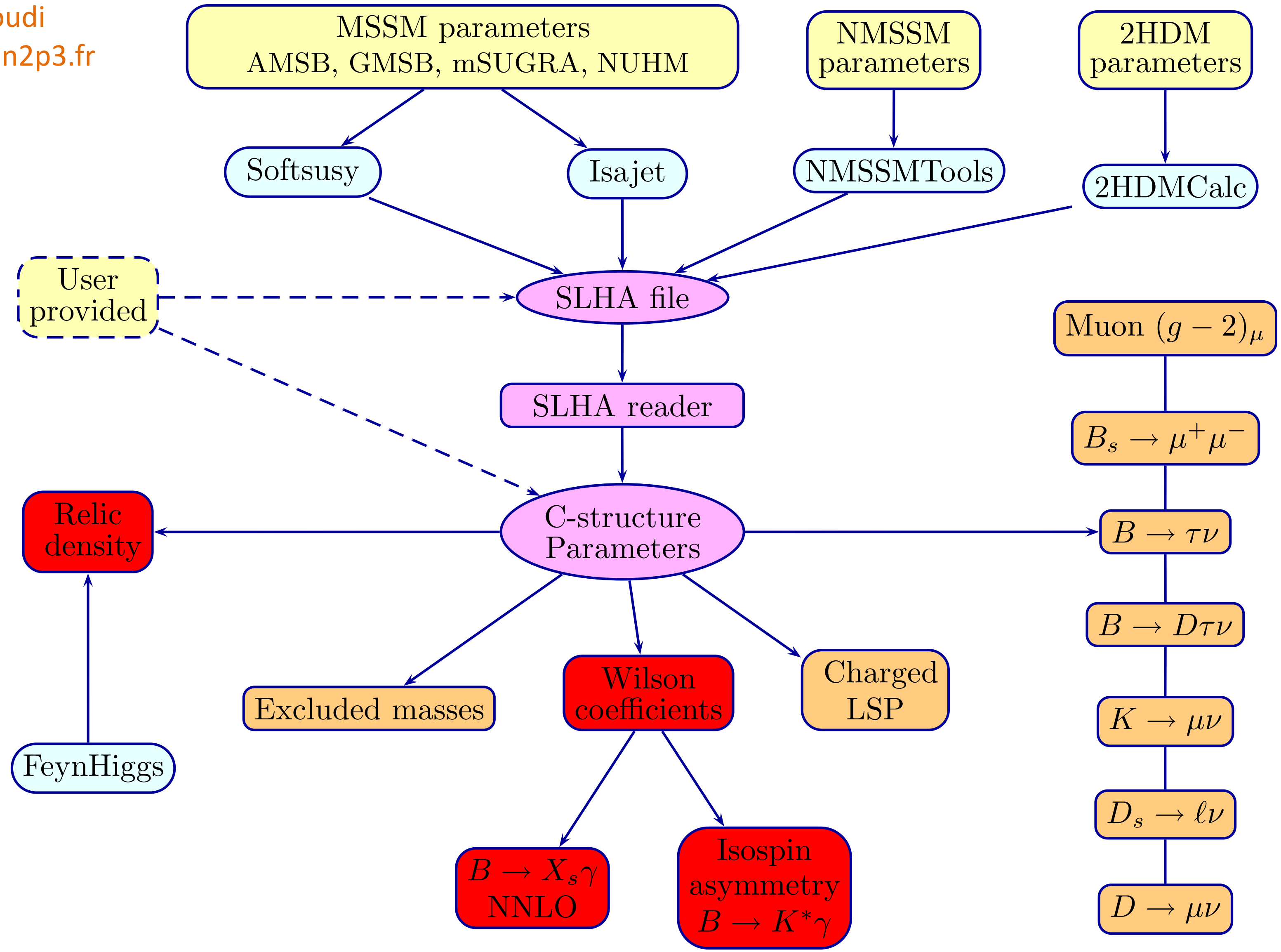






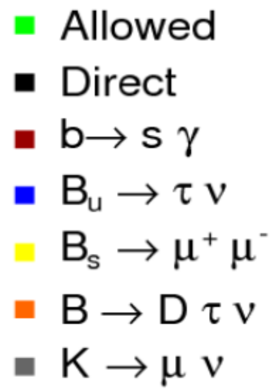
SuperIso

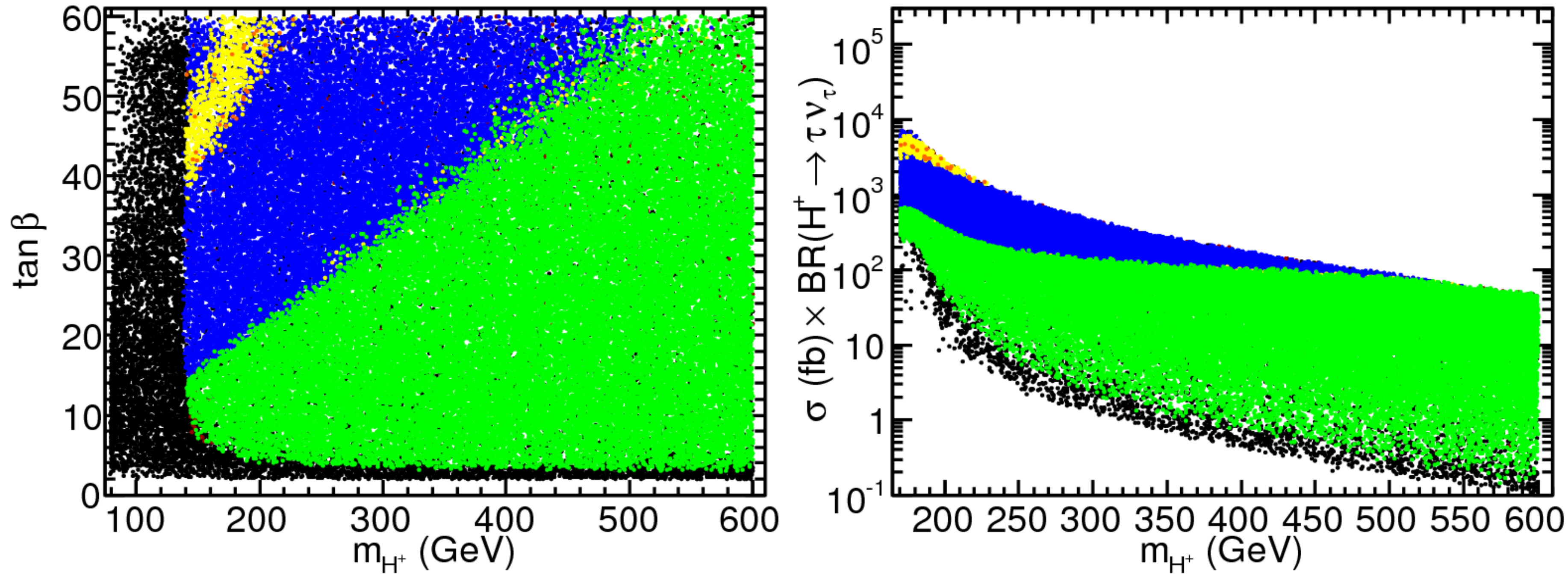
F. Nazila Mahmoudi
http://superiso.in2p3.fr



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]

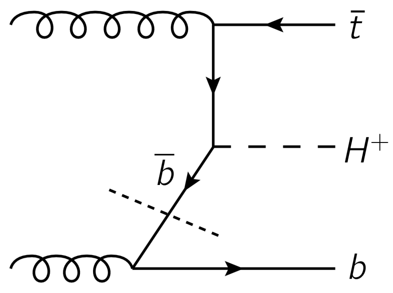
- FLHA: Flavour LesHouches accord
  Quantities relevant for flavour physics calculations
  CKM matrix elements, Wilson coefficients, lattice, …

  F. Mahmoudi et al, [arXiv:1008.0762]

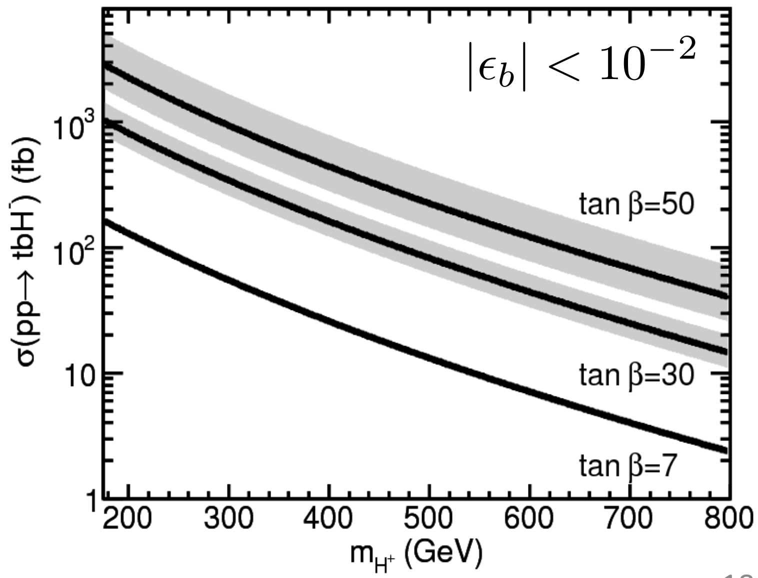
- Common standards necessary for streamlined comparisons.

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 Alwall, Rahtsman
- Full NLO calculations available
  5FS Zhu; Plehn; Berger, Han, Jiang, Plehn
  4FS Dittmaier, Kramer, Spira, Walser



- Essential with Δ_b corrections to H^+tb coupling at large tan β

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 Spheno FeynHiggs	CPSuperH FeynHiggs	NMSSMTools
Decays	2HDMC	FeynHiggs HDecay	CPSuperH FeynHiggs	NMSSMTools
Cross sections	(MC@NLO) (Prospino)	MC@NLO FeynHiggs Prospino	MC@NLO FeynHiggs Prospino	(MC@NLO) (Prospino)
Collider limits	HiggsBounds (2HDMC)	HiggsBounds	HiggsBounds	HiggsBounds NMSSMTools
Flavor physics	SuperIso	SuperIso SUSYBsg FeynHiggs	CPSuperH	SuperIso
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?