Report on 2HDM issues

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1. Sushi <-> 2HDMC cross sections
2. H width
3. Benchmarks

SusHi cross sections with 2HDMC

- SusHi: Harlander, Liebler, Mantler [1212.3249]
  Cross sections for neutral Higgs production (gg/bb fusion) in the 2HDM up to NNLO QCD
  http://sushi.hepforge.org
  -> See talk by Robert at previous meeting

- 2HDMC: Eriksson, Rathsman, Stål [0902.0851]
  Different 2HDM parametrizations, theoretical constraints, Neutral and charged Higgs branching ratios (leading QCD corrections).
  http://2hdmc.hepforge.org
  -> See talk by me at previous meeting

SusHi cross sections with 2HDMC

- "Official" interface between the two codes:

  1. Set up of cross section calculation using SusHi
  2. Specification of 2HDM parameters in SusHi input
  3. Linking to 2HDMC for calculation of physical masses and mixings, theoretical constraints, and branching ratios (output)
  4. Calculation of bb/gg->h/H/A cross sections with SusHi

Proposed interface uses **linking** between the two codes, final results in SusHi output file, intermediate 2HDMC results can also be saved in separate file

SusHi cross sections with 2HDMC

```
Block SUSHI
  1   2         # model: 0 = SM, 1 = MSSM, 2 = 2HDM
  2   2         # 0 = light Higgs (h), 1 = pseudoscalar (A), 2 = heavy Higgs (H)
  3   0         # collider: 0 = p-p, 1 = p-pbar
  4   8000.d0   # center-of-mass energy in GeV
  5   2         # order ggh: -1 = off, 0 = LO, 1 = NLO, 2 = NNLO
  6   2         # order bbh: -1 = off, 0 = LO, 1 = NLO, 2 = NNLO
  7   1         # electroweak cont. for ggh:
                # 0 = no, 1 = light quarks at NLO, 2 = SM EW factor
Block THDMC #
  1 1                   # parametrization of 2HDM
  2 2                   # 2HDM type (1=I,2=II,3=III,4=IV)
  3 10.                 # tanb
  4 100.                 # m12
  11 .1
  12 .2
  13 .3
  14 .4
  15 .5
  16 0.
  17 0.
```

SusHi cross sections with 2HDMC

```
Block THDMC
        1     1    # parametrization of 2HDM
        2     2    # 2HDM type
        3      1.00000000E+01   # tan(beta)
        4      1.00000000E+02   # m12
       11      1.00000000E-01   # lambda1
       12      2.00000000E-01   # lambda2
       13      3.00000000E-01   # lambda3
       14      4.00000000E-01   # lambda4
       15      5.00000000E-01   # lambda5
       16      0.00000000E+00   # lambda6
       17      0.00000000E+00   # lambda7
Block MINPAR
        3      1.00000000E+01   # tan(beta)
Block ALPHA # Higgs mixing parameter
         -3.20858689E-02   # alpha
Block MASS
       35      2.65871615E+02   # Heavy Higgs mass
```

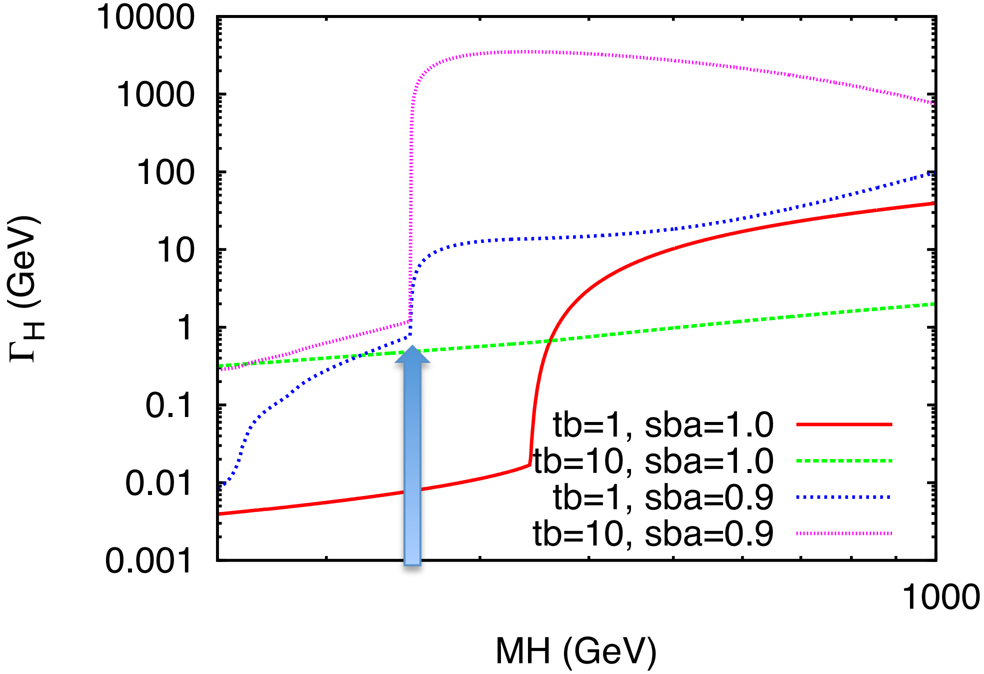
SusHi cross sections with 2HDMC

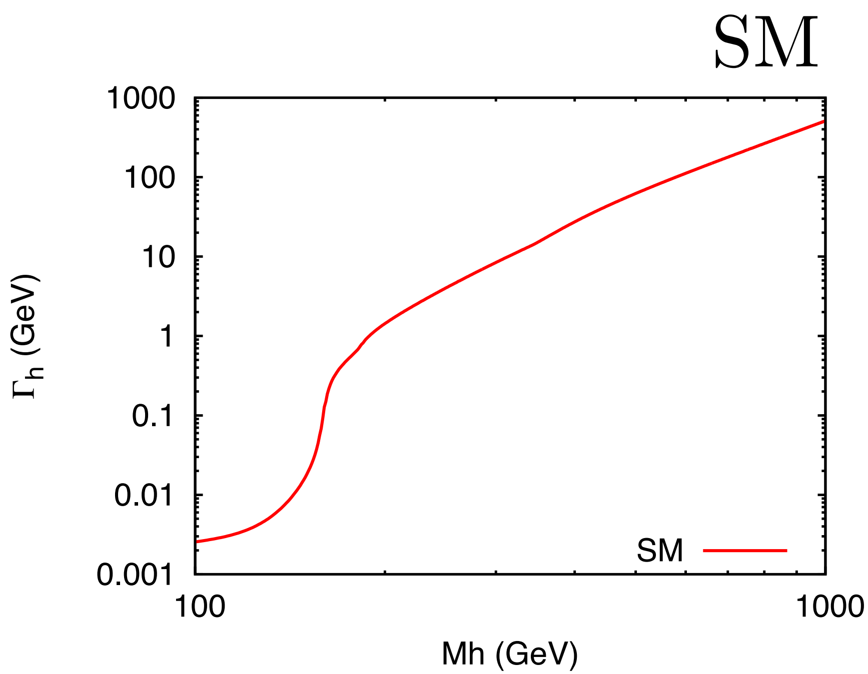
```
Block SUSHIggh # Bon appetit
         1     2.69401396E-01   # ggh XS in pb
Block SUSHIbbh # Bon appetit
         1     1.22990787E+00   # bbh XS in pb
```

- Testing on-going, public version in preparation
- Available for interested LHCXSWG members for early tests ☺

Heavy Higgs total width

$$m_{12}^2 = 9 \times 10^4 \text{ GeV}^2$$
$$m_H = m_A = m_C$$





- When sin(b-a) = 1. (h SM-like) the H width is well-behaved, but can be enhanced in the low mass range compared to SM case
- The main issue is to control H->hh when sin(b-a) < 1.
  Large width related to (non-perturbatively) large λ_i

Benchmarking Attempts

1. M_h = 125 GeV
2. M_H free parameter
3. Fix M_A and M_{H+} to be out of the way, preferably higher than M_H as limited by P, S, U (simpler case: MH=MA=MC)
4. Use tan β as a free parameter
5. Use sin($\beta-\alpha$) free parameter, "close to 1" (alt. cos($\beta-\alpha$) close to 0)
6. For given values of the inputs, determine a value for m_{12}^2 that leads to a well-behaved model (P,S,U)

In the limit where sin($\beta-\alpha$)=1, the values for λ_1 and λ_2 (which are sensitive to h-H splitting) can be controlled to equal the SM value

$$\lambda = m_h^2/v^2$$

by choosing

$$m_{12}^2 = m_H^2 \frac{\tan\beta}{1+\tan^2\beta}$$

```
2HDM parameters in physical mass basis:
      m_h:    125.00000
      m_H:    300.00000
      m_A:    300.00000
     m_H+:    300.00000
 sin(b-a):      1.00000
 lambda_6:      0.00000
 lambda_7:      0.00000
    m12^2:  45000.00000
tan(beta):      1.00000

2HDM parameters in generic basis:
 lambda_1:      0.25773
 lambda_2:      0.25773
 lambda_3:      0.25773
 lambda_4:      0.00000
 lambda_5:      0.00000
 lambda_6:      0.00000
 lambda_7:      0.00000
    m12^2:  45000.00000
tan(beta):      1.00000

Constraints:
 Tree-level unitarity: 1
 Perturbativity:       1
 Stability:            1
```

```
2HDM parameters in physical mass basis:
      m_h:    125.00000
      m_H:    300.00000
      m_A:    500.00000
     m_H+:    500.00000
 sin(b-a):      1.00000
 lambda_6:      0.00000
 lambda_7:      0.00000
    m12^2:   8910.89100
tan(beta):     10.00000

2HDM parameters in generic basis:
 lambda_1:      0.25774
 lambda_2:      0.25773
 lambda_3:      5.53612
 lambda_4:     -2.63919
 lambda_5:     -2.63919
 lambda_6:      0.00000
 lambda_7:      0.00000
    m12^2:   8910.89100
tan(beta):     10.00000

Constraints:
 Tree-level unitarity: 1
 Perturbativity:       1
 Stability:            1
```

Benchmarking Attempts

- Unfortunately, the preferred value for m_{12}^2 is still sensitive to changes in $\sin(\beta-\alpha)$. (Very) stringent bound on allowed values
-> significant amount of tuning required, in particular for high $\tan\beta$
- Choose m_{12}^2 value tuned for $\tan\beta$ and $\sin(\beta-\alpha)$ simultaneously?
- Fix m_{12}^2 such that Hhh vertex vanishes?
- Some different approach?

Summary

- Interface SusHi <-> 2HDMC has been set up, testing is on-going
- H width can be larger than corresponding SM Higgs width in the low mass range (tan β enhancement).

  If couplings to vector bosons are suppressed, the width will remain smaller in the high mass range provided H->hh is under control.
- To ensure control over H->hh, benchmark scenarios respecting theory sanity checks (perturbativity, unitarity, ...) should be used
- We have discussed a strategy to obtain models fulfilling these criteria in the precise limit where they are not needed...
  -> Input for benchmark discussion

General two-Higgs-doublet Model (2HDM)

- Two complex SU(2) doublets (Y=1): Φ_1, Φ_2

- General 2HDM potential:

$$V_{2\mathrm{HDM}} = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - \left[m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}\right]$$
$$+ \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right)$$
$$+ \left\{\frac{1}{2}\lambda_5\left(\Phi_1^\dagger\Phi_2\right)^2 + \left[\lambda_6\left(\Phi_1^\dagger\Phi_1\right) + \lambda_7\left(\Phi_2^\dagger\Phi_2\right)\right]\left(\Phi_1^\dagger\Phi_2\right) + \mathrm{h.c.}\right\}$$

- Complex phases on λ_5, λ_6, λ_7 and m_{12} can give rise to CP-violation
  In 2HDMC: CP-conservation only (real parameters)

- Reparametrization invariance: $\Phi_a = U_{ab}\Phi_b \quad (a = 1,2)$

S. Davidsson, H.E. Haber [hep-ph/0504050]
Review: [arXiv:1106.0034]

Physical Basis

- Introducing an explicit basis in (Φ_1, Φ_2) space: $\tan\beta = \frac{v_2}{v_1}$

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\left(G^+ \cos\beta - H^+ \sin\beta\right) \\ v\cos\beta - h\sin\alpha + H\cos\alpha + \mathrm{i}\left(G^0\cos\beta - A\sin\beta\right) \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\left(G^+ \sin\beta + H^+ \cos\beta\right) \\ v\sin\beta + h\cos\alpha + H\sin\alpha + \mathrm{i}\left(G^0\sin\beta + A\cos\beta\right) \end{pmatrix}$$

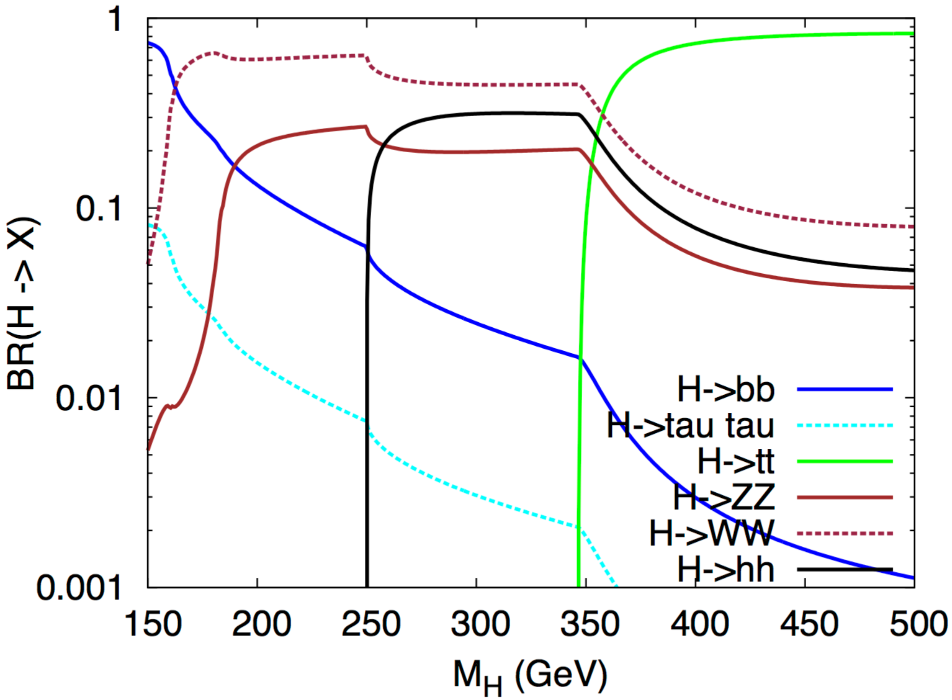
- Physical spectrum: Two CP-even scalars, h, H with $M_h < M_H$ Mass matrix diagonalized by angle α CP-odd scalar, A, and charged scalar pair $H^\pm$

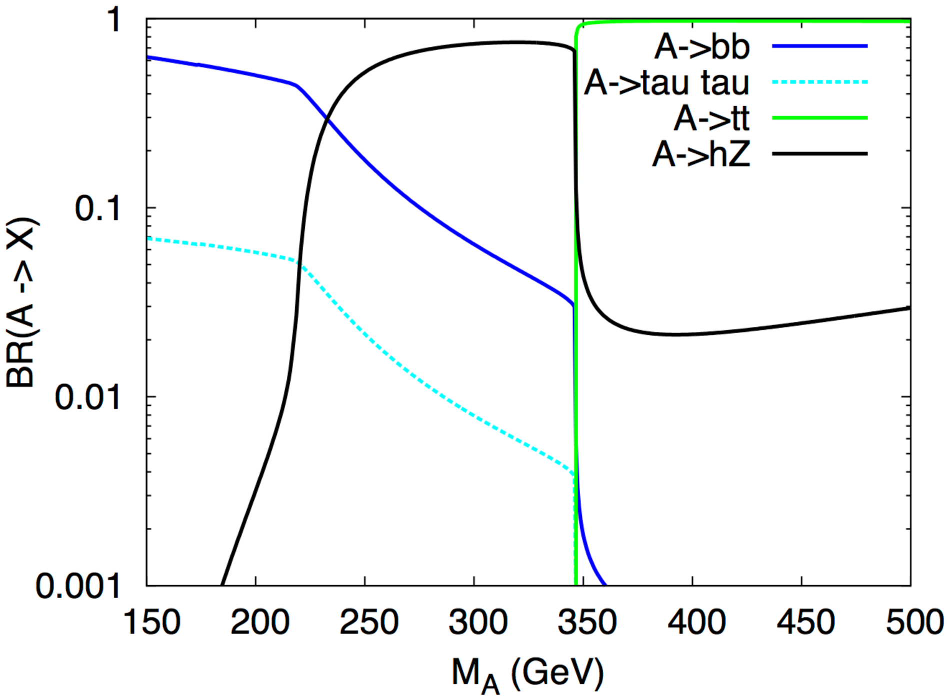
- No mass relations (unlike the MSSM). Scalar masses can be chosen independently as free parameters (like SM Higgs mass). Higgs-gauge couplings determined by $s_{\beta-\alpha} = \sin(\beta-\alpha)$
- SM-like light Higgs for $s_{\beta-\alpha} \to 1$ $c_{\beta-\alpha} = \cos(\beta-\alpha)$

Example: Heavy Higgs Decays

$$M_h = 125\,\mathrm{GeV} \qquad M_H = M_A = M_{H^\pm} \qquad m_{12}^2 = 0$$

$$\sin(\beta - \alpha) = 0.99 \qquad \tan\beta = 1 \ (\text{Type II})$$





- At low tan β, vector boson modes important even for small $c_{\beta-\alpha}$
- Higgs-to-Higgs-Higgs decays unavoidable feature in complete model