

# SusHi $\oplus$ 2HDMC

R. Harlander  
with S. Liebler and O. Stål

26 Jun 2013

# 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, Rathsmann, 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

# 2HDM

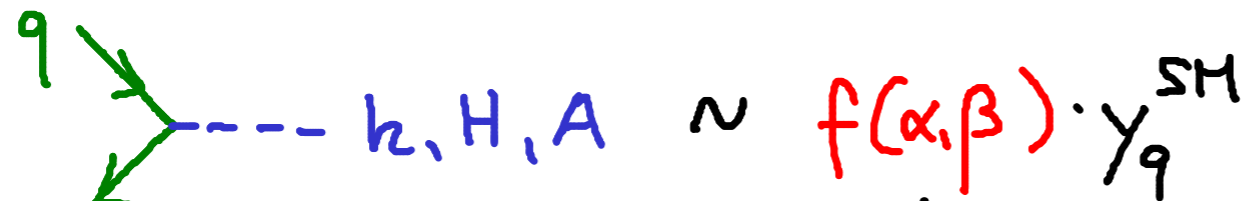
- Higgs sector  $\hat{=}$  generalized MSSM:

MSSM:  $M_A, \tan\beta$

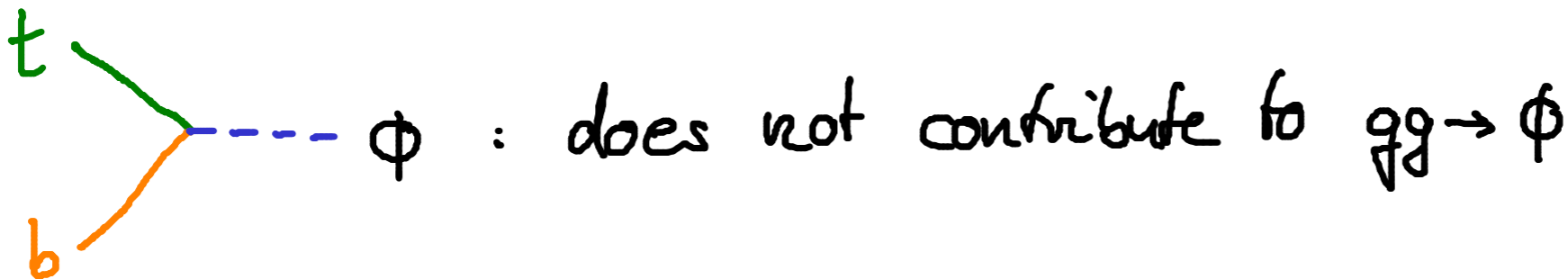
2HDM: + 5 (7) more parameters, e.g.

$M_h, M_H, M_{H^\pm}, \sin(\beta-\alpha), m_{12}^2$   
( $\lambda_6, \lambda_7$ )

- 2HDM Yukawa couplings:



↑ implemented in SusHi



# SusHi input file: 2HDM w/o 2HDMC

```
Block SUSHI
 1  2      # model: 0 = SM, 1 = MSSM, 2 = 2HDM
 2  0      # 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 2HDM # 2HDM version according to arxiv:1106.0034
 2          # (1=I,2=II,3=III,4=IV)
Block SMINPUTS # Standard Model inputs
 1  1.27934000e+02 # alpha_em^(-1)(MZ) SM MSbar
 2  1.16637000e-05 # G_Fermi
 3  1.17200000e-01 # alpha_s(MZ) SM MSbar
 4  9.11876000e+01 # m_Z(pole)
 5  4.20000000e+00 # m_b(m_b)
 6  1.73300000e+02 # m_t(pole)
 8  1.27500000e+00 # m_c(m_c)
Block MINPAR
 3  5.d0      # tanb
Block ALPHA
-5.0e-01     # mixing in Higgs sector
Block MASS
25  125.00000d0 # Higgs mass h
35  150.00000d0 # Higgs mass H
36  300.00000d0 # Pseudoscalar Higgs mass A
```

# SusHi input file: 2HDM w/o 2HDMC

specify model

```
Block SUSHT
 1  2      # model: 0 = SM, 1 = MSSM, 2 = 2HDM
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 3  0      # collider: 0 = p p, 1 = e e, 2 = e p
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 5  4.20000000e+00 # m_b(m_b)
 6  1.73300000e+02 # m_t(pole)
 8  1.27500000e+00 # m_c(m_c)

Block MINPAR
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specify h,H,A

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Block MINPAR
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Block MASS
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```

specify h,H,A

specify 2HDM

# SusHi input file: 2HDM w/o 2HDMC

specify model

```
Block SUSHT
1 2 # model: 0 = SM, 1 = MSSM, 2 = 2HDM
2 0 # 0 = light Higgs (h), 1 = pseudoscalar (A), 2 = heavy Higgs (H)
3 0 # collider: 0 = p p, 1 = p p-bar, 2 = e+ e-
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 2HDM # 2HDM version according to arxiv:1106.0034
2 # (1=I,2=II,3=III,4=IV)

Block SMINPUTS # Standard Model inputs
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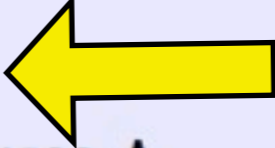
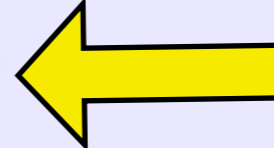
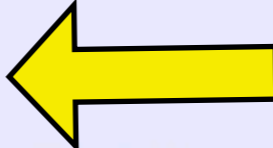
Block MINPAR
3 5.d0 # tanb

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specify h,H,A

specify 2HDM





# SusHi input file: 2HDM with 2HDMC

```
Block SUSHI
 1  2      # model: 0 = SM, 1 = MSSM, 2 = 2HDM
 2  0      # 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 2HDMC # 2HDMC arXiv:0902.0851
 1  1      # 2HDMC key, 1=lambda basis, 2=physical basis
 2  2      # 2HDM version type according to arxiv:1106.0034
 3  10.    # tan(beta)
 4  100.d0 # m12
11  0.1d0  # lambda1
12  0.2d0  # lambda2
13  0.3d0  # lambda3
14  0.4d0  # lambda4
15  0.5d0  # lambda5
16  0.0d0  # lambda6
17  0.0d0  # lambda7
Block SMINPUTS # Standard Model inputs
 1  1.27934000e+02 # alpha_em^(-1)(MZ) SM MSbar
 2  1.16637000e-05 # G_Fermi
 3  1.17200000e-01 # alpha_s(MZ) SM MSbar
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# SusHi input file 2HDM with 2HDMC

specify model

```
Block SUSHT
 1  2      # model: 0 = SM, 1 = MSSM, 2 = 2HDM
 2  0      # 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
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```

# SusHi input file 2HDM with 2HDMC

specify model

specify h,H,A

```
Block SUSHT
 1  2      # model: 0 = SM, 1 = MSSM, 2 = 2HDM
 2  0      # 0 = light Higgs (h), 1 = pseudoscalar (A), 2 = heavy Higgs (H)
 3  0      # collider: 0 = p-p, 1 = p-pbar, 2 = e+e-
 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
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16  0.0d0  # lambda6
17  0.0d0  # lambda7
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 1  1.27934000e+02 # alpha_em^(-1)(MZ) SM MSbar
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```

# SusHi input file 2HDM with 2HDMC

```
Block SUSHT
 1  2      # model: 0 = SM, 1 = MSSM, 2 = 2HDM
 2  0      # 0 = light Higgs (h), 1 = pseudoscalar (A), 2 = heavy Higgs (H)
 3  0      # collider: 0 = p-p, 1 = p-pbar, 2 = e+e-
 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 2HDMC # 2HDMC arXiv:0902.0851
 1  1      # 2HDMC key, 1=lambda basis, 2=physical basis
 2  2      # 2HDM version type according to arxiv:1106.0034
 3  10.    # tan(beta)
 4  100.d0 # m12
11  0.1d0  # lambda1
12  0.2d0  # lambda2
13  0.3d0  # lambda3
14  0.4d0  # lambda4
15  0.5d0  # lambda5
16  0.0d0  # lambda6
17  0.0d0  # lambda7

Block SMINPUTS # Standard Model inputs
 1  1.27934000e+02 # alpha_em^(-1)(MZ) SM MSbar
 2  1.16637000e-05 # G_Fermi
 3  1.17200000e-01 # alpha_s(MZ) SM MSbar
```

specify model

specify h,H,A

specify 2HDM

# SusHi input file 2HDM with 2HDMC

```
Block SUSHT
 1  2      # model: 0 = SM, 1 = MSSM, 2 = 2HDM
 2  0      # 0 = light Higgs (h), 1 = pseudoscalar (A), 2 = heavy Higgs (H)
 3  0      # collider: 0 = p-p, 1 = p-pbar, 2 = e+e-
 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 quark, 2 = heavy quark, 3 = gluon, 4 = top, 5 = bottom, 6 = charm, 7 = strange, 8 = up, 9 = down, 10 = all
          # 11 = gluon, 12 = top, 13 = bottom, 14 = charm, 15 = strange, 16 = up, 17 = down, 18 = all

Block 2HDMC # 2HDMC arXiv:0902.0851
 1  1      # 2HDMC key, 1=lambda basis, 2=physical basis
 2  2      # 2HDM version type according to arxiv:1106.0034
 3  10.    # tan(beta)
 4  100.d0 # m12
11  0.1d0  # lambda1
12  0.2d0  # lambda2
13  0.3d0  # lambda3
14  0.4d0  # lambda4
15  0.5d0  # lambda5
16  0.0d0  # lambda6
17  0.0d0  # lambda7

Block SMINPUTS # Standard Model inputs
 1  1.27934000e+02 # alpha_em^(-1)(MZ) SM MSbar
 2  1.16637000e-05 # G_Fermi
 3  1.17200000e-01 # alpha_s(MZ) SM MSbar
```

specify model

specify h,H,A

specify parametrization

specify 2HDM

# SusHi input file 2HDM with 2HDMC

```
Block SUSHT # specify model
 1  2 # model: 0 = SM, 1 = MSSM, 2 = 2HDM
 2  0 # 0 = light Higgs (h), 1 = pseudoscalar (A), 2 = heavy Higgs (H)
 3  0 # collider: 0 = p-p, 1 = p-pbar, 2 = e+e-
 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 quark, 2 = heavy quark, 3 = gluon, 4 = NNLO,
    # 5 = NNLO+
Block 2HDMC # 2HDMC arXiv:0902.0851
 1  1 # 2HDMC key, 1=lambda basis, 2=physical basis
 2  2 # 2HDM version type according to arxiv:1106.0034
 3  10. # tan(beta)
 4  100.d0 # m12
11  0.1d0 # lambda1
12  0.2d0 # lambda2
13  0.3d0 # lambda3
14  0.4d0 # lambda4
15  0.5d0 # lambda5
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Block SMINPUTS # Standard Model inputs
 1  1.27934000e+02 # alpha_em^(-1)(MZ) SM MSbar
 2  1.16637000e-05 # G_Fermi
 3  1.17200000e-01 # alpha_s(MZ) SM MSbar
```

specify model

specify h,H,A

specify parametrization

specify 2HDM

2HDMC input

# SusHi input file for 2HDM with 2HDMC

```
Block SUSHT
1 2 # model: 0 = SM, 1 = MSSM, 2 = 2HDM
2 0 # 0 = light Higgs (h), 1 = pseudoscalar (A), 2 = heavy Higgs (H)
3 0 # collider: 0 = p-p, 1 = p-pbar, 2 = e+e-
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 Higgs, 2 = heavy Higgs, 3 = pseudoscalar, 4 = NLO, 5 = NNLO

Block 2HDMC # 2HDMC arXiv:0902.0851
1 2 # 2HDMC key, 1=lambda basis, 2=physical basis
2 2 # 2HDM version type according to arxiv:1106.0034
3 10. # tan(beta)
4 100.d0 # m12
21 125.d0 # mh
22 300.d0 # mH
23 250.d0 # mA
24 270.d0 # mC
25 0.99 # sin(beta-alpha)
26 0.d0 # lambda6
27 0.d0 # lambda7

Block SMINPUTS # Standard Model inputs
1 1.27934000e+02 # alpha_em^(-1)(MZ) SM MSbar
2 1.16637000e-05 # G_Fermi
3 1.17200000e-01 # alpha_s(MZ) SM MSbar
```

specify model

specify h,H,A

specify parametrization

specify 2HDM

2HDMC input

# Output:

```
Block SUSHIggh # Bon appetit
      1      2.52176640E+01 # ggh XS in pb
Block SUSHIbbh # Bon appetit
      1      3.09348402E-02 # bbh XS in pb
```

```
Block 2HDMCOUT # 2HDMC results for
      1      1 # stability, 0=failed, 1=ok
      2      1 # perturbativity, 0=failed, 1=ok
      3      1 # unitarity, 0=failed, 1=ok
      4     -3.20858689E-02 # alpha (Higgs mixing angle)
      5      1.00000000E+01 # tan(beta)
     25      1.13644566E+02 # Mh in GeV
     35      2.65871615E+02 # MA in GeV
     36      3.16464535E+02 # MH in GeV
```

in addition: full 2HDMC output file



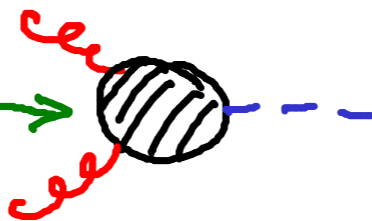
- link between SusHi and 2HDMC works
- private version available for checks
- lambda-basis and physical basis available
- implementation of “Higgs-basis” in progress

# Appendix

SusHi includes:

total inclusive Xsec for  $gg \rightarrow \phi$ :

- exact LO  $t+b + \overset{\text{MSSM}}{\underbrace{(\tilde{t} + \tilde{b})}_{\text{only}}}$
- exact NLO  $t+b$
- NLO  $\tilde{t} + \tilde{b}$  for  $M_\phi \lesssim 1\text{TeV}$   
(+  $\tilde{g}$ ) MSSM only
- NNLO  $t$  (eff. th., i.e.  $M_\phi \lesssim 2m_t$ ;  $gg \rightarrow \phi$  NNLO)
- approx. NNLO  $\tilde{t}$  (see [hep-ph/0308210]) MSSM only
- $\Delta_b$ -corrections (large  $\tan\beta$ ), resummation schemes,  
MSSM only scale variation, etc.



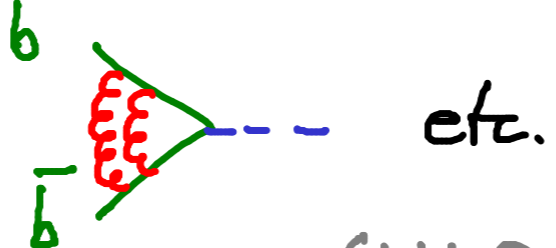
differential ( $p_T, \gamma$  cuts and distributions):

$\mathcal{O}(\alpha_s^3)$ , i.e. LO for  $p_T \neq 0$

NLO for  $p_T = 0$

Sustfi includes:

total inclusive Xsec for  $b\bar{b} \rightarrow \phi$ :

- through NNLO 

( $\Delta_b$ -corrections, MSSM only scale variation, etc.) (bbh@nnlo)

differential (cuts on  $p_T, \gamma$ )

$\mathcal{O}(\alpha_s)$ , i.e. LO for  $p_T \neq 0$   
NLO for  $p_T = 0$