HO TOOLS FOR HIGGS PHYSICS

Michael Spira (PSI)

I HIGLU

II VV2H

III V2HV

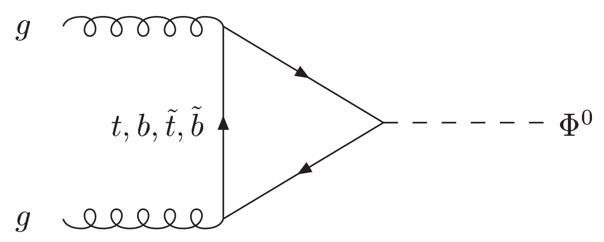
IV HQQ

V HPAIR

VI HDECAY

I *HIGLU*

- Gluon fusion: $pp \to gg \to h/H/A$ [SM + MSSM]



Georgi,...

Gamberini,...

- two-loop QCD corrections: $\sim 10 \ldots 100\%$ SDGZ
  [moderate for large tg$\beta \leftarrow b$-loop] Dawson, Kauffman

- Squark-loop corrections hidden in HIGLU

- HIGLU calculates total cxn @ LO and NLO

- recently updated MSSM subroutines [version 2.1]

- inclusion of MEs in NLO MC? [$\to$ MC@NLO?]

- MCFM: only heavy top limit

- Squark loops to be included soon...

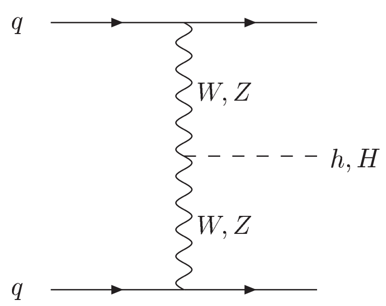
```
PROCESS:  0 = GG --> H         1 = H --> GG
=======

PROCESS  = 0
---------------------------------------------------------------
COLLIDER:   0 = P P               1 = P PBAR
========

COLLIDER = 0
---------------------------------------------------------------
TOTAL ENERGY: [TEV]
=============

ENERGY   = 14.D0
---------------------------------------------------------------
MODEL:    0 = SM   MSSM: 1 = SUBHPOLE  2 = SUBH
======                   3 = FEYNHIGGSFAST

MODEL    = 0
---------------------------------------------------------------
TAN(BETA): (MSSM)
=========

TANBETA  = 3.D0
---------------------------------------------------------------
COUPLINGS:  G_B = BOTTOM    G_T = TOP
==========  (MODEL = 0)

G_B      = 1.D0
G_T      = 1.D0
---------------------------------------------------------------
QUARK MASSES: [GEV]
=============

M_SB(1)  = 0.190D0
M_C      = 1.42D0
M_B      = 4.62D0
M_T      = 174.D0
---------------------------------------------------------------
HIGGS TYPE AND MASS [GEV]: 1 = HEAVY SCALAR 2 = PSEUDOSCALAR 3 = LIGHT SCALAR
==========================  INDIVIDU = 0: M_HIGGS = M_A

TYPE     = 3
INDIVIDU = 1
M_HIGGS  = 200.D0
---------------------------------------------------------------
SCALES: [GEV] MU = MU_1*M_HIGGS + MU_2:   RENORMALIZATION SCALE
=======        Q =  Q_1*M_HIGGS +  Q_2:     FACTORIZATION SCALE

MU_1     = 1.D0
MU_2     = 0.D0
Q_1      = 1.D0
Q_2      = 0.D0
---------------------------------------------------------------
ORDER OF ALPHA_S:  1 = LO     2 = NLO
=================

LOOP     = 2
---------------------------------------------------------------
DEFINITION OF ALPHA_S:  1 = ALPHA_S (M_Z)   2 = BY LAMBDA (N_F)
======================

CHOICE   = 1
---------------------------------------------------------------
ALPHA_S (M_Z):
==============

ALPHA_S  = 0.116D0
---------------------------------------------------------------
```



```
LAMBDA_NF: [GEV] (QCD SCALE)
==========

N_F      = 5
LAMBDA   = 0.226D0
---------------------------------------------------------------
NUMBER OF EXTERNAL LIGHT FLAVORS: (FOR H --> GG)
=================================

N_EXT    = 5
---------------------------------------------------------------
VEGAS:       ABSERR = ABSOLUTE ERROR
======       POINTS = NUMBER OF CALLS
             ITMAX  = NUMBER OF ITERATIONS
             PRINT  = PRINT OPTION FOR INTERMEDIATE VEGAS-OUTPUT
                      0            1             10
                      NO OUPUT     PRETTYPRINT   TABLE

ABSERR   = 0.D0
POINTS   = 1000
ITMAX    = 5
PRINT    = 10
--------------------------------------------------
STRUCTURE FUNCTIONS: STFUN: 0 = PDFLIB  1 = GRV
=================== SCHEME = FACTORIZATION SCHEME: 0 = MSBAR   1 = DIS

STFUN   =  1
SET     =  2
SCHEME  =  0
NGROUP  =  4
NSET    =  34
---------------------------------------------------------------
PARAMETERS: (FOR RAD. CORR. OF SUSY-COUPLINGS)
===========
            MZ   = Z-MASS [GEV]
            MSQ  = SQUARK-MASS [GEV]

GF        =  1.16639D-5
MZ        =  91.187D0
MW        =  80.41D0
MGLUINO   =  1000.D0
MSQ       =  1000.D0
MUR       =  1000.D0
MDR       =  1000.D0
M2        =  1000.D0
MU        =  100.D0
AU        =  0.D0
AD        =  0.D0
```

II $\mathcal{VV2H}$

- W/Z fusion: $pp \to W^*W^*/Z^*Z^* \to h/H$



Cahn, Dawson
Hikasa
Altarelli, Mele, Pitolli

- QCD corrections $\sigma_{tot} \leftarrow$ DIS: $\sim 10\%$

Han, Valencia,
Willenbrock

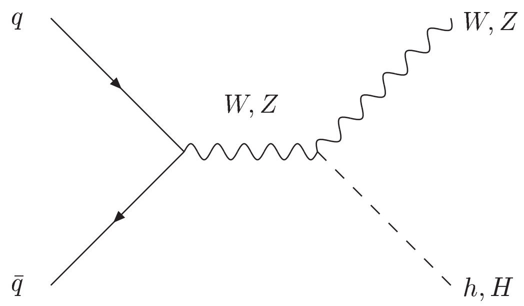
- VV2H calculates total cxn @ LO and NLO

- NLO MCs available

```
MSSM      = 0
TGBET     = 3.D0
HIGGS     = 1
MA1       = 100.D0
MA2       = 1000.D0
NA        = 10
PP/PPBAR  = 0
ENERGY    = 14000.D0

MH=0/Q=1  = 1
SCALE1    = 1.0D0
SCALE2    = 1.0D0
NSCALE    = 1
EPSILON   = 1.D-8

NGROUP    = 4
NSET      = 34
MS0/DIS1  = 0

IPOINT1   = 10000
IPOINT    = 100000
ITERAT    = 5
NPRN      = 10
SUBST12Z  = 1

MC        = 1.5D0
MB        = 5.D0
MT        = 175.D0
N0        = 5
LAMBDA    = 0.202D0
LOOP      = 2
MW        = 80.41D0
MZ        = 91.187D0
SW2       = 0.2315D0
GF        = 1.16639D-5
MPROTON   = 0.93827231D0
Q0        = 2.D0

MSQ       = 1000.D0
MUR       = 1000.D0
AT        = 0.D0
AB        = 0.D0
MU        = 0.D0
```

III $\underline{\underline{\mathcal{V}2\mathcal{H}\mathcal{V}}}$

(iii) Higgs–strahlung: $pp \to W^*/Z^* \to W/Z + h/H$



Glashow,. . .

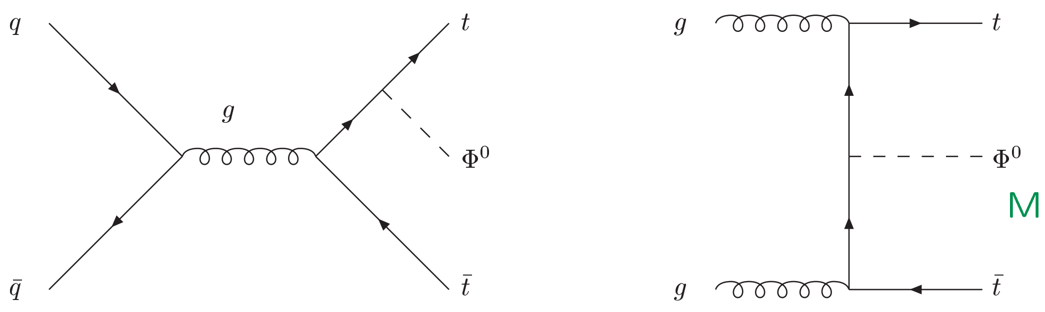
Kunszt,. . .

- QCD corrections $\leftarrow$ DY: $\sim 30\%$ Han, Willenbrock
- V2HV calculates total cxn @ LO and NLO
- included in MCFM

```
MSSM      = 0
TGBET     = 3.D0
HIGGS     = 1
MA1       = 100.D0
MA2       = 1000.D0
NA        = 10
Z=1/W=2   = 2
ENERGY    = 14000.D0
PP/PPBAR = 0

SCALE1    = 1.0D0
SCALE2    = 1.0D0
NSCALE    = 1
EPSILON   = 1.D-8

NGROUP    = 4
NSET      = 34

IPOINT    = 10000
ITERAT    = 5
NPRN      = 10

MC        = 1.5D0
MB        = 5.D0
MT        = 175.D0
N0        = 5
LAMBDA    = 0.202D0
LOOP      = 2
MW        = 80.41D0
MZ        = 91.187D0
SW2       = 0.2315D0
GF        = 1.16639D-5

MSQ       = 1000.D0
MUR       = 1000.D0
AT        = 0.D0
AB        = 0.D0
MU        = 0.D0
```

IV $\underline{\underline{\mathcal{HQQ}}}$

- Bremsstrahlung: $pp \to t\bar{t}/b\bar{b} + h/H/A$



Kunszt
Gunion
Marciano, Paige

dominant

Beenakker,...
Dawson, ...

- QCD corrections [SM]: -20% @ Tev
  $+20\%$ @ LHC
- p_T, y distributions for $t, \bar{t}, H$ available @ NLO

Beenakker,...

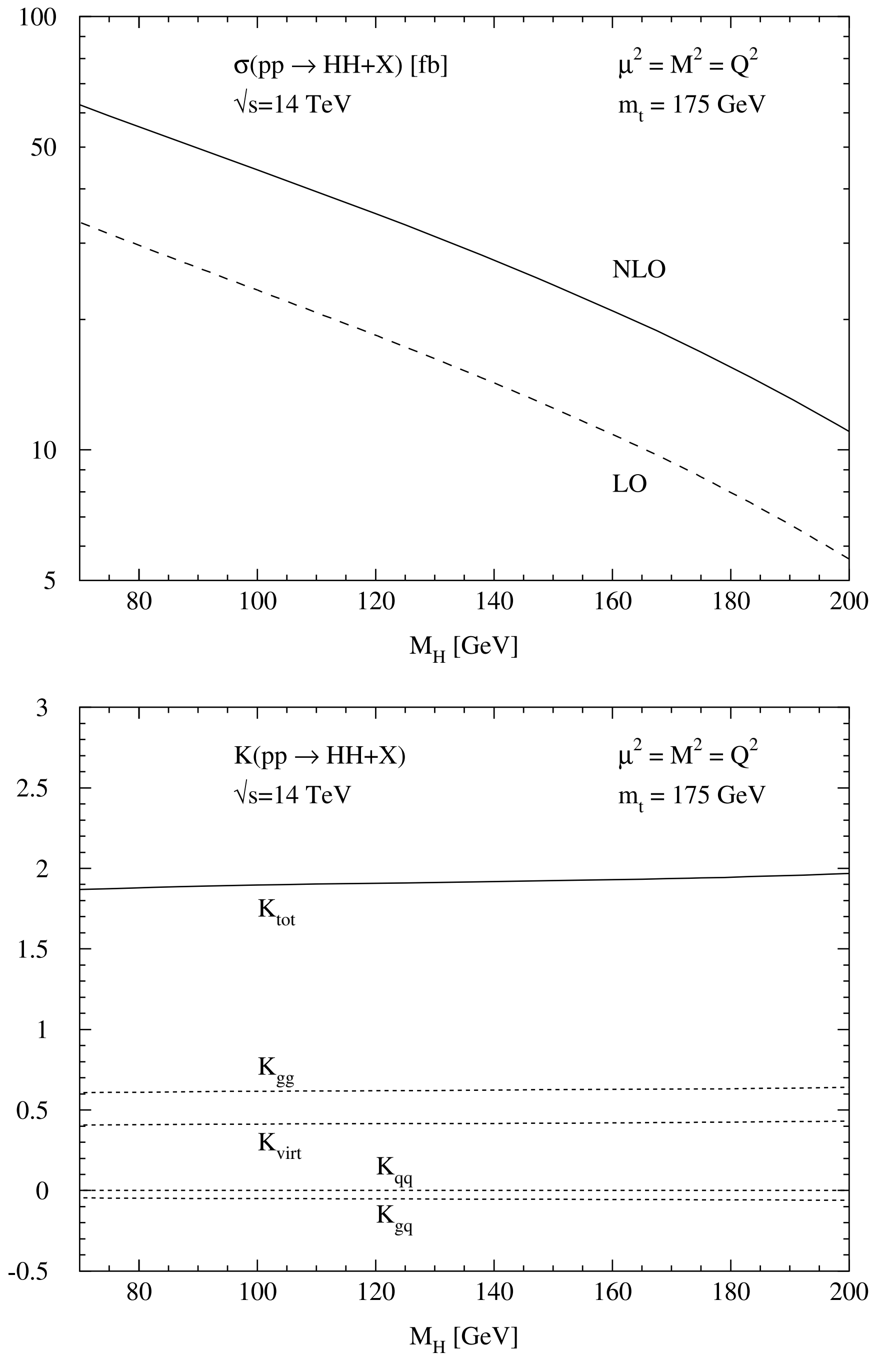
- $b\bar{b} + H/A$ dominant for large tgβ
- QCD corrections large
- HQQ calculates total cxn @ LO and with cuts in bottom rapidities/p_T
- Recently default scale choice modified to $\mu = m_Q + M_H/2$ [version 1.1]
- NLO code to come...
- NLO to $b\bar{b} \to H, bg \to Hb$ included in MCFM

```
MSSM      = 0
TGBET     = 3.D0
HIGGS     = 1
MA1       = 100.D0
MA2       = 1000.D0
NA        = 10
T=0/B=1   = 0
MQ        = 175.D0
YUKAWA    = 0
ENERGY    = 14000.D0
PP/PPBAR  = 0
PTCUT     = 0.D0
YMIN      = -100.D0
YMAX      = 100.D0

SCALE1    = 1.0D0
SCALE2    = 1.0D0
NSCALE    = 1
EPSILON   = 1.D-8

NGROUP    = 4
NSET      = 32

IPOINT    = 100000
ITERAT    = 5
NPRN      = 10

MC        = 1.5D0
MB        = 5.D0
MT        = 175.D0
N0        = 5
LAMBDA    = 0.181D0
LOOP      = 1
GF        = 1.16639D-5
MW        = 80.41D0
MZ        = 91.187D0

MSQ       = 1000.D0
MUR       = 1000.D0
AT        = 0.D0
AB        = 0.D0
MU        = 0.D0
N0        = 5
LAMBDA    = 0.202D0
```

V *HPAIR*

- Higgs pair production: $gg \to \phi_1\phi_2$ [SM + MSSM]

- QCD corrections: infinite top mass limit $\to \mathcal{O}(100\%)$
  $\leftarrow$ only valid for SM and small tgβ



Dawson, Dittmaier, S.

```
PROCESS:  0 = GG --> hh   1 = GG --> Hh  2 = GG --> HH
=======   3 = GG --> Ah   4 = GG --> AH  5 = GG --> AA
          6 = QQ --> Ah   7 = QQ --> AH

PROCESS  =  0
QCDCORR  =  11111
--------------------------------------------------
MODEL: 0 = SM    1 = MSSM     2 = MSSM (OLD)
=====

MODEL    =  0
--------------------------------------------------
TAN(BETA): (MSSM)
=========

TANBET   =  3.D0
--------------------------------------------------
STRUCTURE FUNCTIONS:
====================

NGROUP   =  4
NSET     =  34
--------------------------------------------------
LAMBDA_NF: [GEV]
=========

NF       =  5
LAMBDA   =  0.202D0
--------------------------------------------------
ORDER OF ALPHA_S:  1 = LO     2 = NLO
================

LOOP     =  2
BEG      =  1.D0
END      =  1.D0
NUMBER   =  1
--------------------------------------------------
TOTAL ENERGY: [GEV]
============

ENERGY   =  14000.D0
PP/PPBAR =  0
--------------------------------------------------
QUARK MASSES: [GEV]
============

MSB(1)   =  0.190D0
MC       =  1.50D0
MB       =  5.00D0
MT       =  175.D0
--------------------------------------------------
HIGGS MASS: [GEV] MABEG  = SMALLEST MASS
===========       MAEND  = LARGEST MASS
                  MULTMA = NUMBER OF HIGGS MASSES

MABEG    =  100.D0
MAEND    =  1000.D0
MULTMA   =  10
--------------------------------------------------
VEGAS:       VABSERR = ABSOLUTE ERROR
======       VPOINT  = NUMBER OF CALLS
             VITMAX  = NUMBER OF ITERATIONS
             VNPRN   = TYPE OF VEGAS-OUTPUT

VPOINT   =  10000
VITMAX   =  5
VNPRN    =  10
EPSILON  =  1.D-8
--------------------------------------------------
```



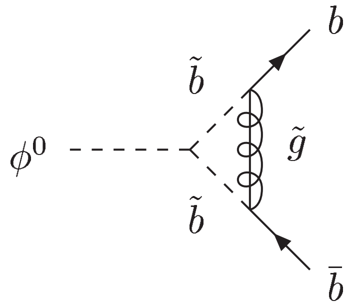
```
PARAMETERS:
==========

GF       =  1.16639D-5
ALPHA    =  137.0359895D0
MZ       =  91.187D0
MW       =  80.330D0
SW2      =  0.2315D0
MST_L    =  1000.D0
MST_R    =  1000.D0
A_U      =  0.D0
A_D      =  0.D0
MU_H     =  0.D0
GAMZ     =  2.490D0
--------------------------------------------------
```

VI *HDECAY*

• HDECAY computes Higgs widths and BRs at present theoretical status in SM and MSSM
[close to...]

• recent improvements [version 3.0]:

(i) Links to more MSSM subroutines
[e.g. FeynHiggsFast]
(ii) Extension of 2-loop RGE approach to Higgs self-interactions
(iii) Decays into gravitino + gaugino added [GMSB]
(iv) large tgβ: large MSSM corrections

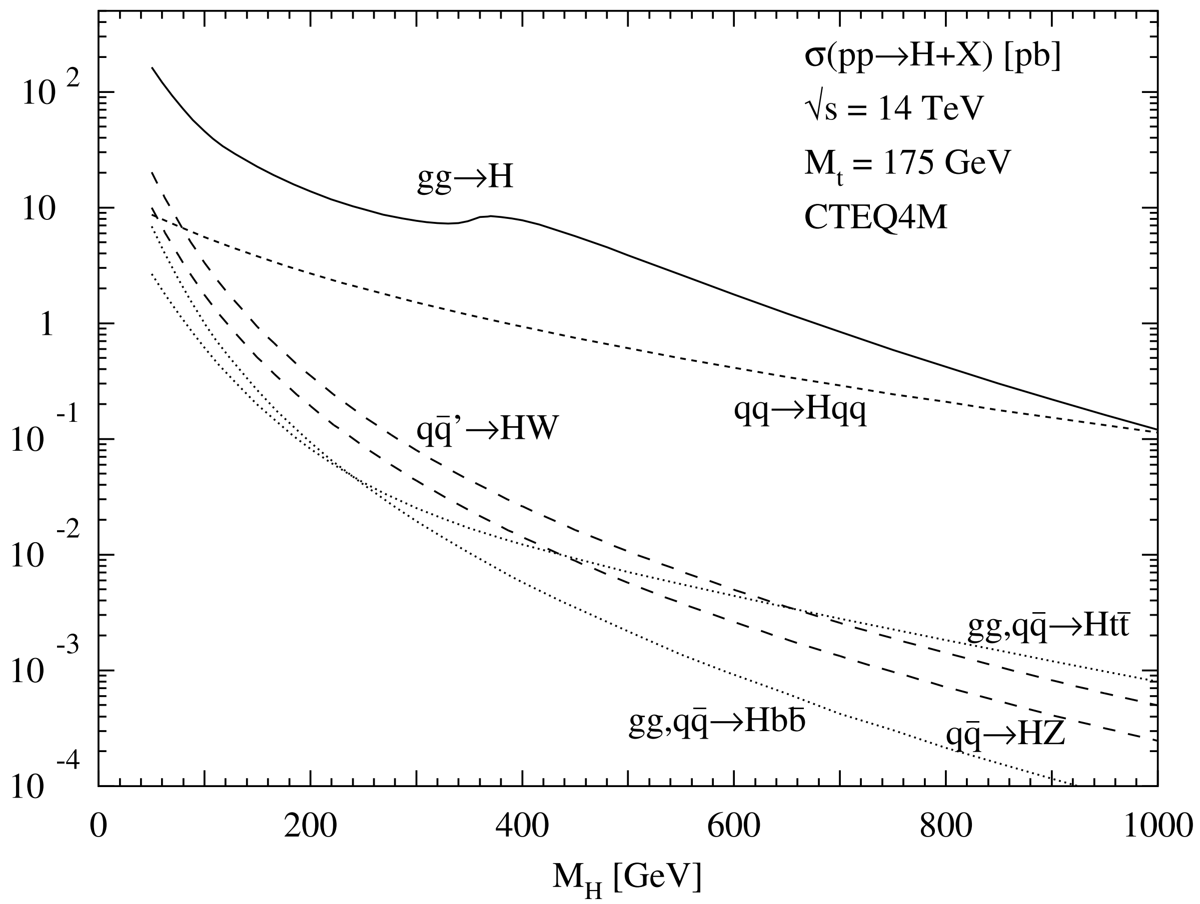


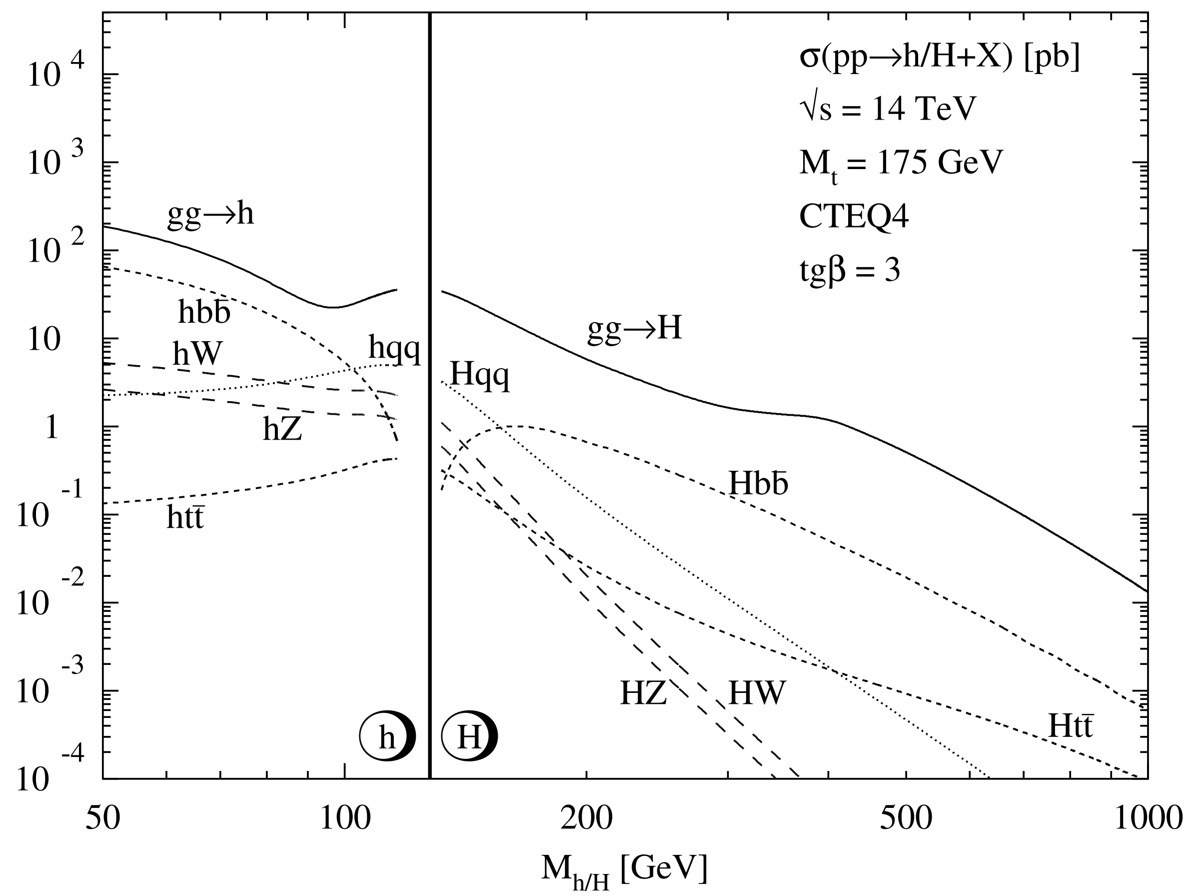
$+\cdots \qquad \propto \frac{m_{\tilde{g}}\mu\,\mathrm{tg}\beta}{m_{\tilde{b}}^2}$

Hall,...
Carena,...
...

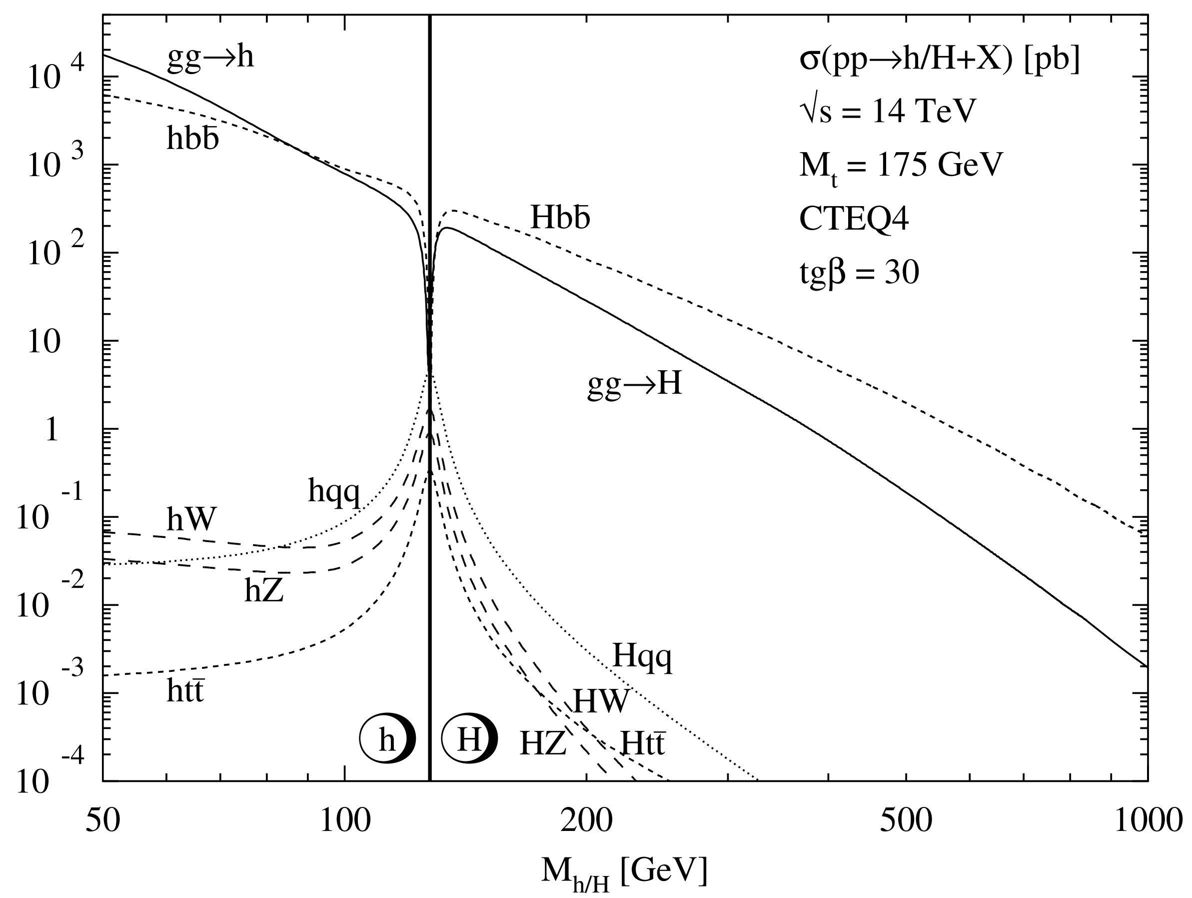
• many more improvements to come soon...

```
HIGGS     = 1
MODEL     = 1
TGBET     = 30.D0
MABEG     = 100.D0
MAEND     = 500.D0
NMA       = 5
ALS(MZ)   = 0.118D0
MSBAR(1)  = 0.190D0
MC        = 1.42D0
MB        = 4.62D0
MT        = 174.D0
MTAU      = 1.7771D0
MMUON     = 0.105658389D0
1/ALPHA   = 137.0359895D0
GF        = 1.16639D-5
GAMW      = 2.080D0
GAMZ      = 2.490D0
MZ        = 91.187D0
MW        = 80.41D0
VUS       = 0.2205D0
VCB       = 0.04D0
VUB/VCB   = 0.08D0
MU        = 300.D0
M2        = 200.D0
MGLUINO   = 1000.D0
MSL1      = 1000.D0
MER1      = 1000.D0
MQL1      = 1000.D0
MUR1      = 1000.D0
MDR1      = 1000.D0
MSL       = 1000.D0
MER       = 1000.D0
MSQ       = 1000.D0
MUR       = 1000.D0
MDR       = 1000.D0
AL        = 1500.D0
AU        = 1500.D0
AD        = 1500.D0
NNLO (M)  = 0
ON-SHELL  = 0
ON-SH-WZ  = 0
IPOLE     = 0
OFF-SUSY  = 0
INDIDEC   = 0
NF-GG     = 5
IGOLD     = 0
MPLANCK   = 2.4D18
MGOLD     = 1.D-13
```

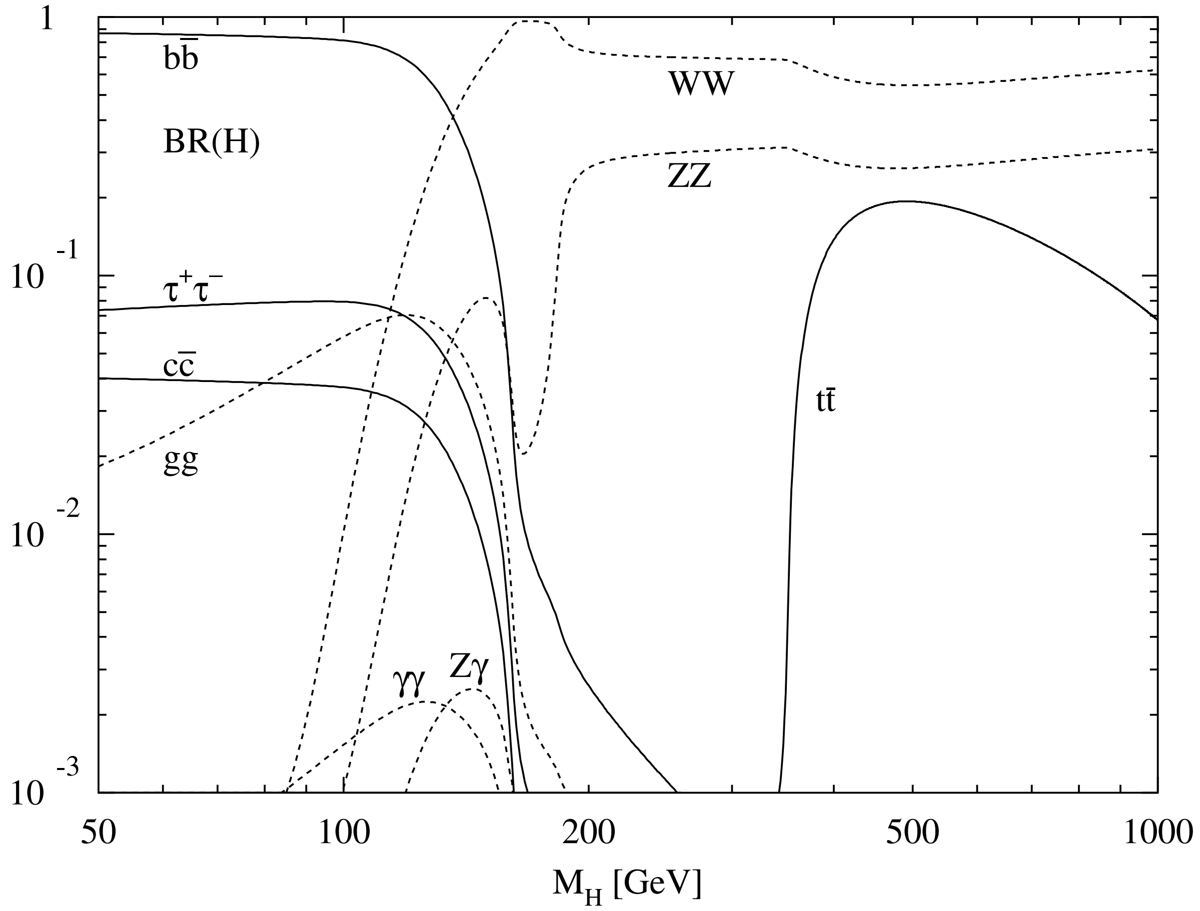

σ(pp→H+X) [pb]
√s = 14 TeV
M_t = 175 GeV
CTEQ4M
gg→H
qq→Hqq
qq̄'→HW
gg,qq̄→Htt̄
gg,qq̄→Hbb̄
qq̄→HZ
10^2
10
1
10^-1
10^-2
10^-3
10^-4
0
200
400
600
800
1000
M_H [GeV]

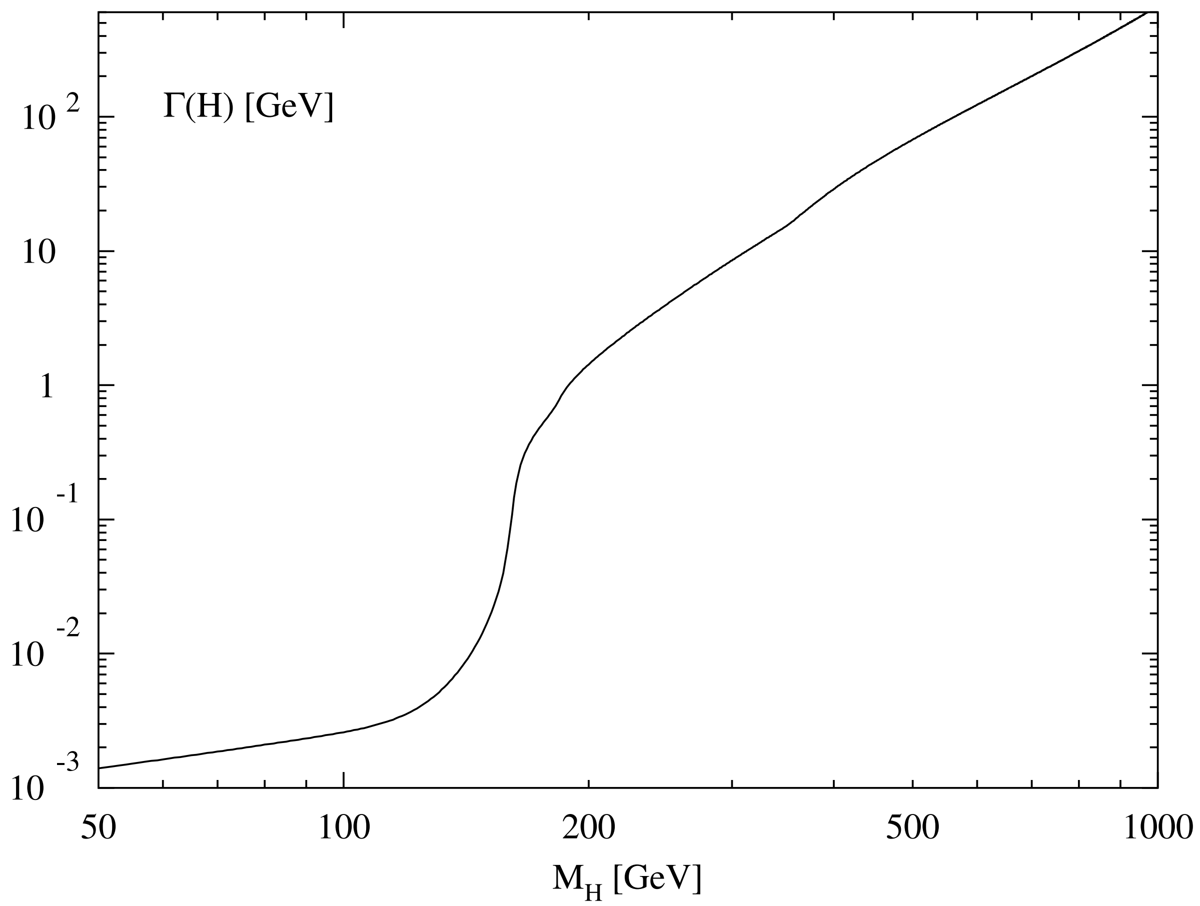


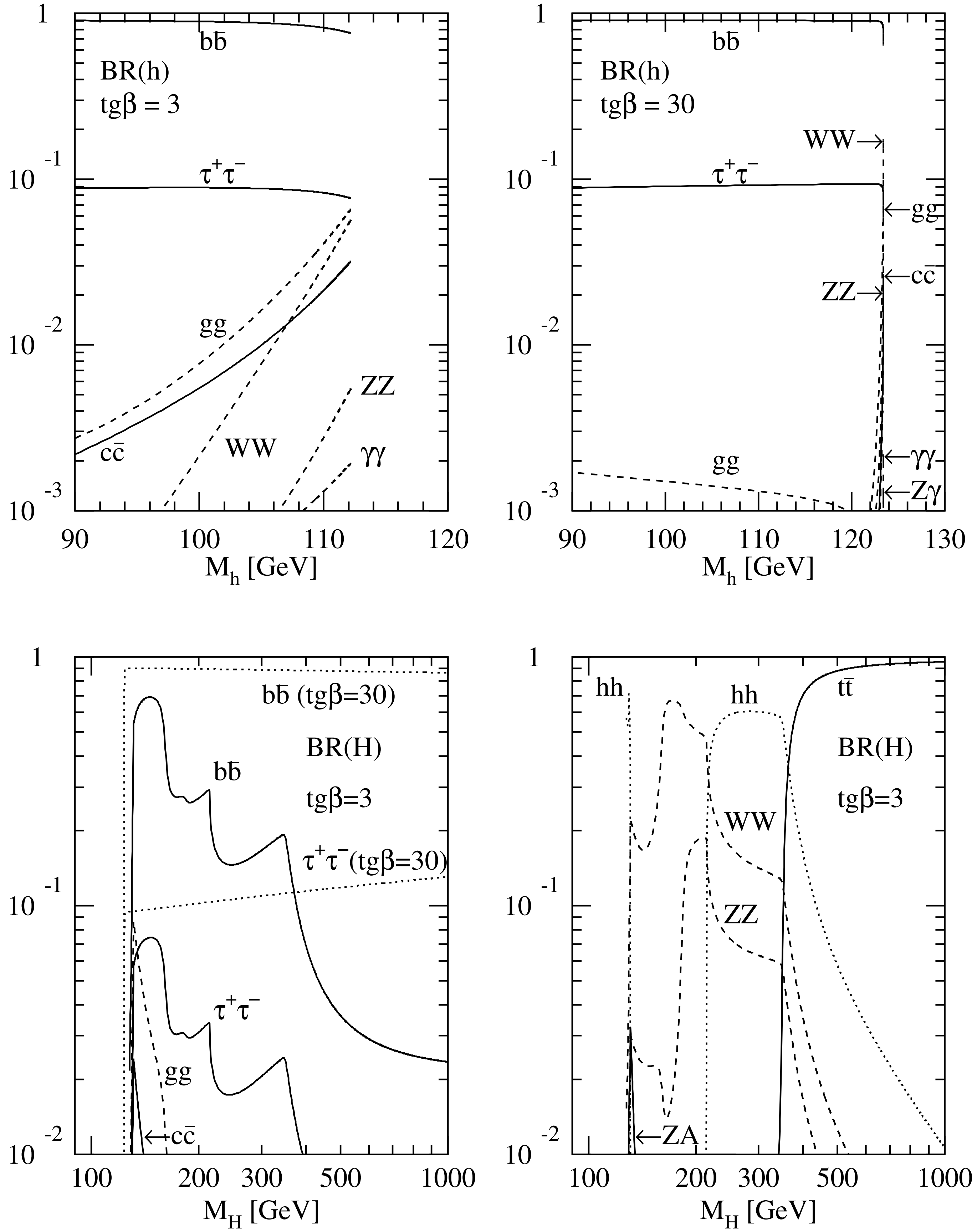
σ(pp→h/H+X) [pb]
√s = 14 TeV
M_t = 175 GeV
CTEQ4
tgβ = 3
gg→h
hbb̄
hW
hqq
hZ
htt̄
gg→H
Hqq
Hbb̄
HZ
HW
Htt̄
h
H
M_h/H [GeV]

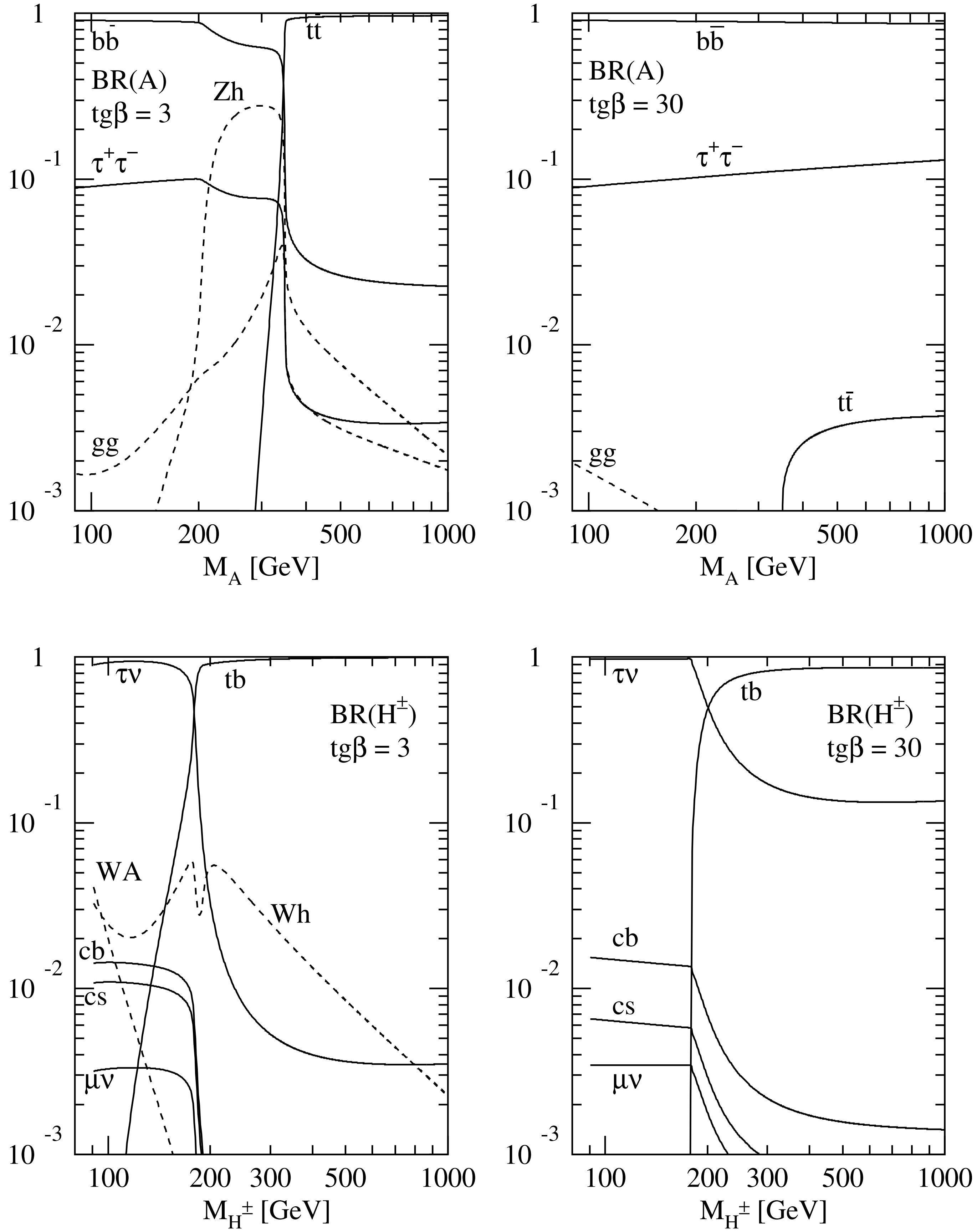


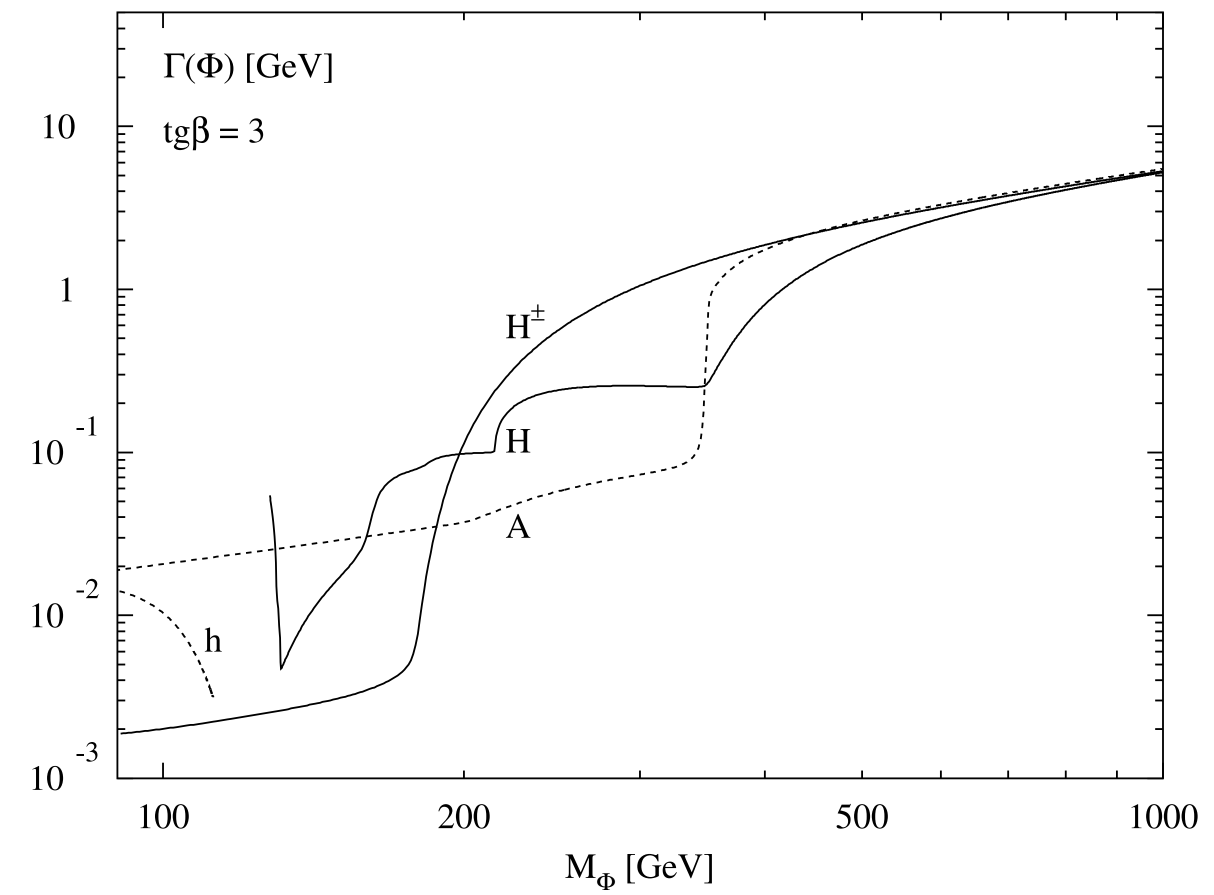
σ(pp→h/H+X) [pb]
√s = 14 TeV
M_t = 175 GeV
CTEQ4
tgβ = 30
gg→h
hbb̄
Hbb̄
gg→H
hW
hqq
hZ
htt̄
Hqq
HW
HZ
Htt̄
h
H
M_h/H [GeV]

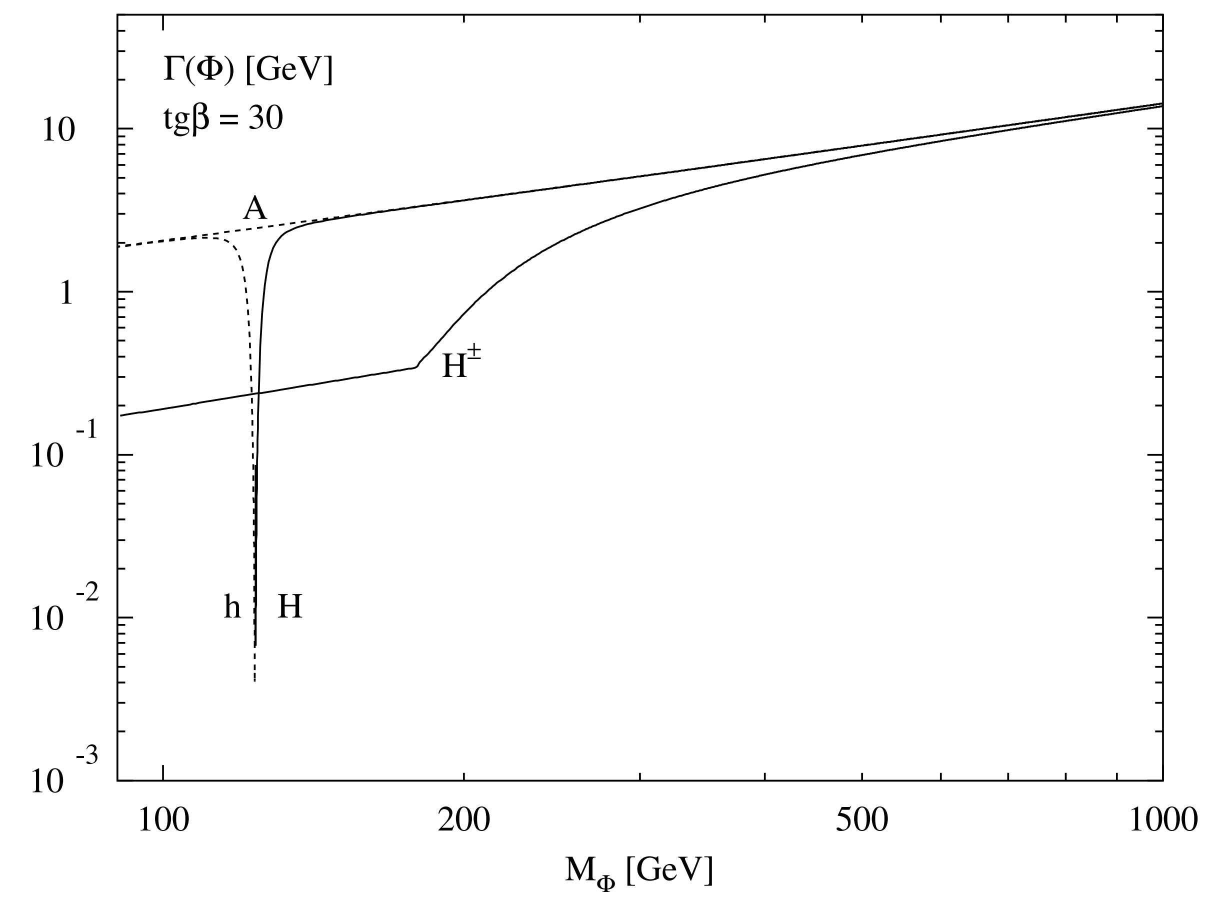

1
bb̄
BR(H)
WW
ZZ
10 -1
τ+τ−
cc̄
tt̄
gg
10 -2
γγ
Zγ
10 -3
50
100
200
500
1000
M_H [GeV]

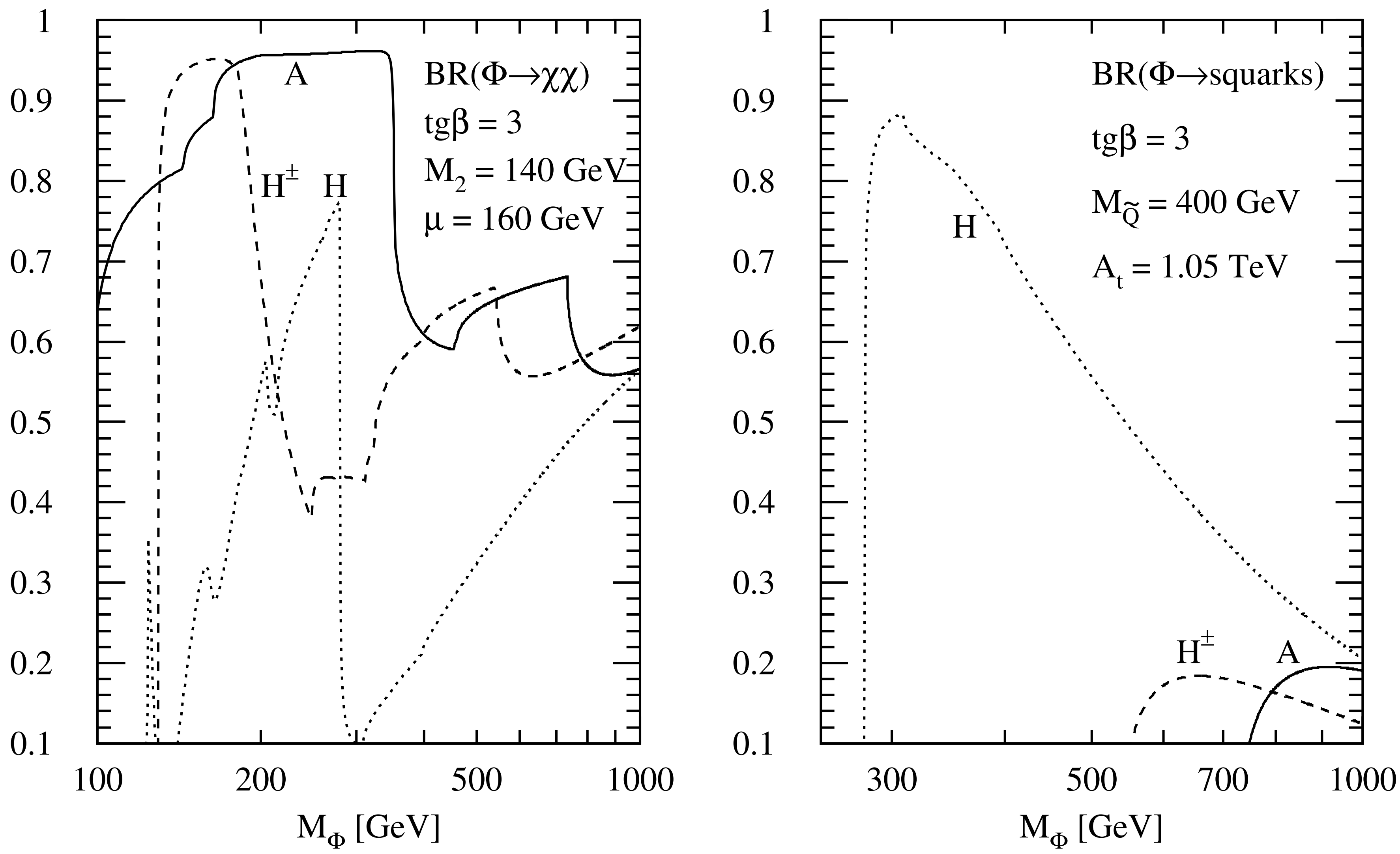

Γ(H) [GeV]
10 2
10
1
10 -1
10 -2
10 -3
50
100
200
500
1000
M_H [GeV]


BR(h)
tgβ = 3
$b\bar{b}$
$\tau^+\tau^-$
gg
$c\bar{c}$
WW
ZZ
γγ
M_h [GeV]
BR(h)
tgβ = 30
$b\bar{b}$
$\tau^+\tau^-$
WW→
←gg
←$c\bar{c}$
ZZ→
gg
←γγ
←Zγ
M_h [GeV]
$b\bar{b}$ (tgβ=30)
BR(H)
$b\bar{b}$
tgβ=3
$\tau^+\tau^-$(tgβ=30)
$\tau^+\tau^-$
gg
←$c\bar{c}$
M_H [GeV]
hh
hh
$t\bar{t}$
BR(H)
WW
tgβ=3
ZZ
←ZA
M_H [GeV]


1
$b\bar{b}$
$t\bar{t}$
BR(A)
tgβ = 3
Zh
10^{-1}
$\tau^+\tau^-$
10^{-2}
gg
10^{-3}
100
200
500
1000
M_A [GeV]
1
$b\bar{b}$
BR(A)
tgβ = 30
10^{-1}
$\tau^+\tau^-$
10^{-2}
$t\bar{t}$
gg
10^{-3}
100
200
500
1000
M_A [GeV]
1
τν
tb
BR($H^{\pm}$)
tgβ = 3
10^{-1}
WA
Wh
cb
10^{-2}
cs
μν
10^{-3}
100
200
300
500
1000
$M_{H^{\pm}}$ [GeV]
1
τν
tb
BR($H^{\pm}$)
tgβ = 30
10^{-1}
cb
10^{-2}
cs
μν
10^{-3}
100
200
300
500
1000
$M_{H^{\pm}}$ [GeV]


Γ(Φ) [GeV]
tgβ = 3
H±
H
A
h
10
1
10 -1
10 -2
10 -3
100
200
500
1000
MΦ [GeV]


Γ(Φ) [GeV]
tgβ = 30
A
H±
h
H
10
1
10 -1
10 -2
10 -3
100
200
500
1000
MΦ [GeV]



BR(Φ→χχ)
tgβ = 3
M2 = 140 GeV
μ = 160 GeV
A
H±
H
BR(Φ→squarks)
tgβ = 3
MQ̃ = 400 GeV
At = 1.05 TeV
H
H±
A
MΦ [GeV]
MΦ [GeV]