LHC Higgs Cross Section WG:
More Progress for MSSM Branching Ratios

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1. MSSM issues and solutions

2. The MSSM BRs

3. Discussion points / future plans

1. MSSM issues and solutions

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_L \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_L \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^0_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets $\Leftarrow$ focus here!

Problem in the MSSM: many scales

Problem in the MSSM: complex phases

$\Leftarrow$ agreement: focus on rMSSM first

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) + \underbrace{\frac{g'^2 + g^2}{8}}(H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2(\tan\beta + \cot\beta)$$

MSSM issues and solutions (I):

Input parameters: M_A and $\tan\beta$

⇒ all other masses and mixing angles are predicted!

Needed:

Input

MT	173.3
MB	4.2
MW	80.4
MZ	91.1
MSusy	975
MA0	200
Abs(M_2)	332
Abs(MUE)	980
TB	50
Abs(At)	-300
Abs(Ab)	1500
Abs(M_3)	975

Computercode →

Output

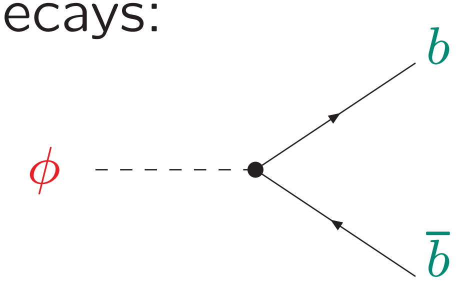
```
------------------- HIGGS MASSES -------------------
| Mh0    =   116.022817
| MHH    =   199.943497
| MA0    =   200.000000
| MHp    =   216.973920
| SAeff  =  -0.02685112
| ZHiggs =   0.99999346  -0.00361740   0.00000000 \
|            0.00361740   0.99999346   0.00000000 \
|            0.00000000   0.00000000   1.00000000

-------------- ESTIMATED UNCERTAINTIES -------------
| DeltaMh0   =  1.591957
| DeltaMHH   =  0.004428
| DeltaMA0   =  0.000000
| DeltaMHp   =  0.152519
  ...
```

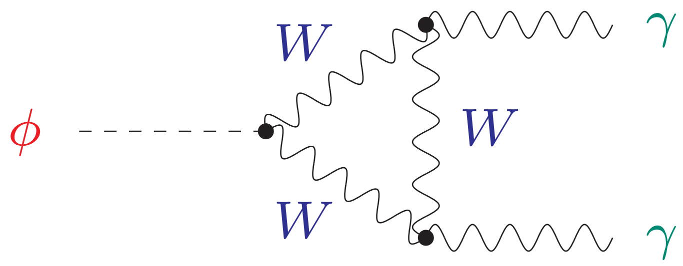
Solution (in the rMSSM): use FeynHiggs for masses and couplings

⇒ crucial: agreement with XS group!

MSSM issues and solutions (II):

Higgs decays:



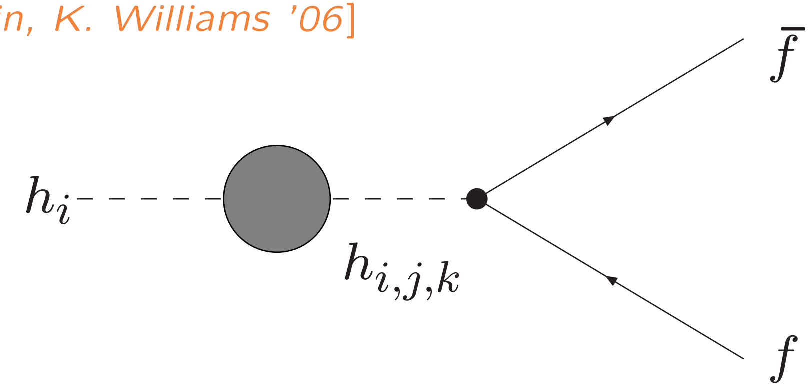


$\Rightarrow$ important to ensure on-shell properties of external Higgs boson

Correct on-shell amplitude with external Higgs h_i :

[M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein, K. Williams '06]

$$A(h_i) = \sqrt{Z_i}\left(\Gamma_{h_i} + Z_{ij}\Gamma_{h_j} + Z_{ik}\Gamma_{h_k}\right)$$



$\sqrt{Z_i}$: ensures that the residuum of the external Higgs boson is set to 1

Z_{ij} : describes the transition from $i \to j$

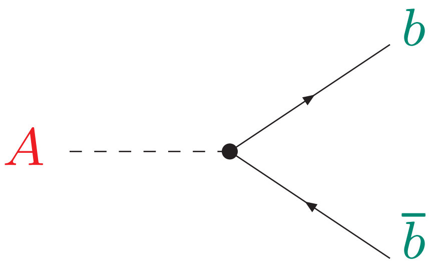
Written more compact with the $\mathbf{Z}$ matrix : $\mathbf{Z}_{ij} = \sqrt{Z_i}\, Z_{ij}$

$\Rightarrow$ evaluation clear; application not always clear . . .

MSSM issues and solutions (III):

Cancellations between XS and BR

Most prominent example: Δ_b in $pp \to \phi \to \tau^+\tau^-$



$$y_b \quad \longrightarrow \quad y_b \, \frac{\tan\beta}{1+\Delta_b}$$

At large $\tan\beta$: either $H \approx A$ or $h \approx A$

$$\Delta_b = \frac{2\alpha_s}{3\,\pi} m_{\tilde{g}}\, \mu \tan\beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{\alpha_t}{4\,\pi} A_t\, \mu \tan\beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu) + \ldots$$

$\Rightarrow$ other parameters enter $\Rightarrow$ strong μ dependence

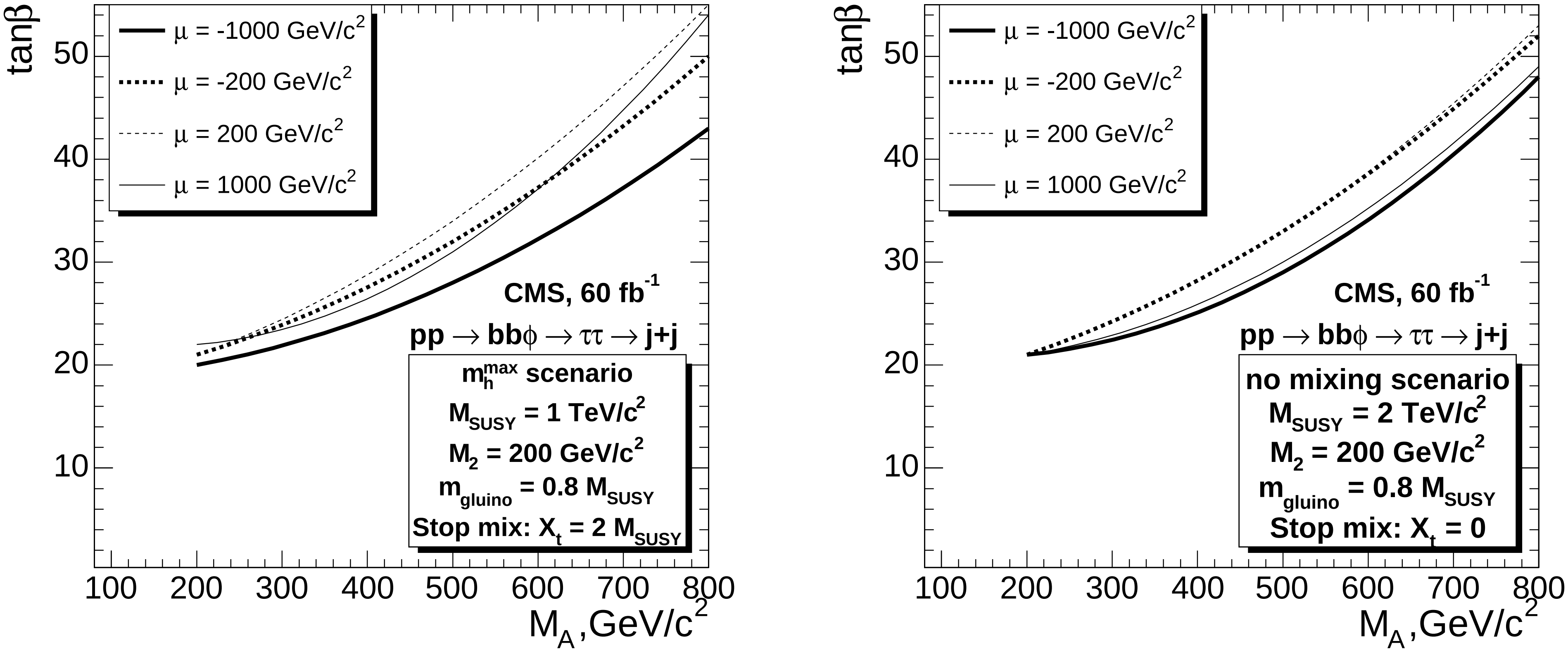
$\Rightarrow$ partial cancellation in $gg/b\bar{b} \to \phi$ and $\phi \to \tau^+\tau^-$

$\Rightarrow$ crucial: same Δ_b in production and decay

Other example: production and decay cannot be treated separately if large H/A mixing occurs (cMSSM)

Dependence of LHC wedge from $b\bar{b} \to H/A \to \tau^+\tau^- \to 2\,$jets on μ:

[*S.H., A. Nikitenko, G. Weiglein et al. '06*]



$\Rightarrow$ non-negligible variation with the sign and absolute value of μ

(despite numerical compensations in production and decay)

MSSM issues and solutions (IV):

tree-level: two parameters: M_A, $\tan\beta$

loop-level: 10-20 relevant parameters, possibly more
most relevant: $\tilde{t}/\tilde{b}$ sector, μ, $M_{1,2,3}$, ...

$\Rightarrow$ no "final" results possible as in the SM

Numerical results:

only as an example in the m_h^{max} scenario

General set-up:

"Machinery" that can produce results for any parameter

$\Rightarrow$ eventually ONE machinery for XS and BR!

2. The MSSM BRs

As in the SM:

$\Rightarrow$ select best code for each decay width

only that in the MSSM things are much more involved...

Most relevant right now in the MSSM: BR($\phi \to \tau^+\tau^-$)

(i) $\Gamma(\phi \to \tau^+\tau^-)$

Evaluated by FeynHiggs

– full one-loop

– Z factors automatically ok

– no problem with masses and couplings

(ii) $\Gamma(\phi \to b\bar{b})$

Hdecay:

– Δ_b: leading one-loop corrections and two-loop QCD corrections included
– SM QCD corrections beyond 2-loop included
– SUSY QCD corrections at 1-loop
– no EW corrections
– Z-factors in the $p^2 = 0$ approximation (α_{eff})
– Masses and couplings (org. from 'improved subhpole') from FeynHiggs

FeynHiggs:

– full one-loop calculation (i.e. including EW corrections)
– Δ_b: full one-loop included;
two-loop QCD (as taken over from Hdecay) is there, but not active yet (because of a remaining problem with the subtraction of the double counting.) By definition we have the Δ_b corrections as in $b\bar{b} \to \phi$ or in the bottom loop of $gg \to \phi$
– SM QCD corrections only up to two-loop
– full Z-factors included
– Masses and couplings from FeynHiggs

(ii) $\Gamma(\phi \to b\bar{b})$ (cont.)

$\Rightarrow$ both codes have several advantages and disadvantages, which are difficult to disentangle

Proposal to follow for now:
Evaluate $\Gamma(\phi \to b\bar{b})$ with both codes, check uncertainties etc. Overlap?
Issues of cancellation of Δ_b cancellations between production and decay will have to be investigated

To start an investigation of the size of several higher-order corrections we will look at four points in the m_h^{max} scenario:

$$\tan\beta = 3, 50, \quad M_A = 120, 300 \text{ GeV}$$

For these four points we will try to see the effects of
– SM QCD corrections beyond 2L
– Δ_b corrections at 2L
– Cancellation in production and decay ??

$\to$ SLHA files from Hdecay, should be ready somewhen after Easter

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$\to$ SLHA files from Hdecay, sent yesterday :-)

(iii) $\Gamma(\phi \to VV^{(*)})$

The two proposals were discussed:
(1) Take the LO result (incl. $\alpha_{\rm eff}$) and fold with the two Breit-Wigners
(2) Take the NLO result from Prophecy4f and apply the Higgs coupling correction factor from SM to MSSM Higgs (incl. $\alpha_{\rm eff}$)

Effectively this boils down to
(1') Take the LO result from Prophecy4f and apply the Higgs coupling correction
(2') Take the NLO result from Prophecy4f and apply the Higgs coupling correction

$\rightarrow$ still under discussion

(iv) $\Gamma(\phi \to gg)$

not discussed yet; possibly as for Higgs production cross section?

(v) $\Gamma(\phi \to \gamma\gamma)$

not discussed yet; possibly as for Higgs production cross section?

A few more words on the 'machinery':

We will need at least a combination of Hdecay and FeynHiggs

A relatively easy to implement way is
(1) feed input parameter to Hdecay
(2) Hdecay produced an SLHA file
(3) FeynHiggs calculates Higgs masses and couplings, output into a new SLHA file
(4) this new SLHA file can then be used by other codes for further evaluation

Steps (1,2) could be omitted once FeynHiggs can generate its own SLHA files, but this will not be ready within a few weeks from now.

It has to be kept in mind that Hdecay requires $\overline{\text{DR}}$ input, whereas FeynHiggs requires On-Shell input, which in principle should be handled by the SLHA procedure.

For the m_h^{max} scenario the above description should work without major problems, since a $\overline{\text{DR}}$ version of the m_h^{max} scenario is defined.

3. Discussion points / future plans

1. First data: low M_A, large $\tan\beta$
   First analyses: exclusion limits? benchmarks? XS $\times$ BR limits?
   SUSY parameter dependences (Δ_b, μ dependence, . . .)
   $\Rightarrow$ important for interpretation

2. Phenomenology in the MSSM can differ strongly from the SM

   Possible deviations:

   – $\phi \to$ SUSY
   – SUSY $\to \phi +$ SUSY
   – $\phi \to$ invisible, e.g. $\phi \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$
   – several Higgses with similar masses
   – . . . with relatively large width
   – very light Higgs bosons with $m_\phi < 114.4$ GeV
   – . . .

3. Can we always achieve decoupling to the SM limit?
   Example for the problem: some SM corrections that are known can possibly not be implemented into the SUSY calculation. Then decoupling to the SM limit cannot be reached

4. For which part of the MSSM parameter space should the code be reliable/optimized?
   SM-limit?
   Or where one expects large differences between SM and MSSM?

5. . . .


Higgs Days at Santander 2011
Theory meets Experiment
19.-23. September
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