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DER FORSCHUNG | DER LEHRE | DER BILDUNG

Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

MSSM neutral subgroup - Status report

WG3 MSSM neutral subgroup

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CMS: Roger Wolf, Felix Frensch
TH: Michael Spira, Pietro Slavich, Stefan Liebler
Particularly active member: Sven Heinemeyer

Meeting of the LHC Higgs XS WG

Geneva - 13 January 2016

DESY

HELMHOLTZ | GEMEINSCHAFT

Outline

1. Status of the MSSM subgroup section for YR4
2. ROOT files for cross sections and branching ratios
3. Benchmark scenarios for low $\tan\beta$ in the MSSM
4. Transverse momentum of the Higgs boson in gluon fusion
5. Conclusions

✓ The MSSM subgroup section for YR4 is finished:

- Introduction ~ 2.5 pp.
- Benchmark scenarios for low $\tan\beta$ in the MSSM ~ 3 pp., $+1$ fig.

  The hMSSM approach
  The "low-tb-high" scenario
- ROOT files for cross sections and branching ratios ~ 3 pp., $+1$ table, 5 fig.

  Content of the ROOT files
  Technical details and data access
  Comparison of benchmark scenarios for low $\tan\beta$
- Ambiguities in the description of the transverse momentum of the Higgs boson in gluon fusion ~ 2.5 pp., $+1$ table, 3 fig.

  Determination of the matching scale
  Resummation frameworks
  Phenomenological analysis in the THDM

based on note LHCHXSWG-2015-002 by subgroup conveners + E. Bagnaschi, S. Heinemeyer, G. Lee, M. Mühlleitner, J. Quevillon, N. Rompotis, C. Wagner.
provided by E. Bagnaschi, R. Harlander, H. Mantler, A. Vicini, M. Wiesemann.
$\rightarrow$ All will be authors of the MSSM subgroup section.

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On the webpages we provide new ROOT files for:

scenario	m_A [GeV]	$\tan\beta$	$\sqrt{s}$ [TeV]	authors
"low-tb-high"	$150-500$	$0.5-10$	$8, 13$	[Heinemeyer '15]
hMSSM	$130-1000$	$1-60$	$8, 13$	[Maiani et al. '13; Djouadi et al. '13 '15]
$m_h^{\max}$	$90-2000$	$0.5-60$	$13, 14$	[Carena et al. '13]
$m_h^{\mathrm{mod}+}$, $\mu \in \mu^{\mathrm{val}}$	$90-2000$	$0.5-60$	$8, 13, 14$	[Carena et al. '13]
$m_h^{\mathrm{mod}-}$	$90-2000$	$0.5-60$	$13, 14$	[Carena et al. '13]
light stau	$90-2000$	$0.5-60$	$13, 14$	[Carena et al. '13]
light stop	$90-650$	$0.5-60$	$13, 14$	[Carena et al. '13]
τ-phobic	$90-2000$	$0.5-50$	$13, 14$	[Carena et al. '13]

$\mu \in \mu^{\mathrm{val}} = \{-1000, -500, -200, 200, 500, 1000\}$ GeV

The setup of the ROOT files was completely rewritten in 2015. They contain as a function of m_A and $\tan\beta$ for $\phi \in \{h, H, A\}$:

- ✓ Higgs masses m_ϕ (h (mostly) compatible with SM Higgs ~ 125 GeV)
- ✓ Gluon fusion XS
- ✓ Bottom-quark annihilation XS in 4FS/5FS and Santander-matched XS
- ✓ Branching ratios
- ✓ Scale and PDF$+\alpha_s$ uncertainties
- ✓ Charged Higgs information: $m_{H^\pm}$, $t \to H^+ b$, ($H^+ \to tb$)

YR4 contains a detailed description of how the data for the ROOT files was produced, how it can be accessed and how the input parameters were chosen.

The ROOT files are used with a C++ class+header file or a python wrapper:

▷ Usage of C++ class:

```
mssm_xs_tools mssm("scenario.root",INT,0);
mssm.COMMAND(STRING,m_A,tan β);
```

with COMMAND=mass/br/xsec, STRING="H"/"$gg \to H$"/...

▷ Discussion of SM input:

ROOT files do not always follow the recommendation LHCHXSWG-INT-2015-006!

▷ Most prominent differences:

$$\alpha_s(m_Z) = 0.119 \leftrightarrow 0.118$$

$$m_b(m_b) = 4.16\,\text{GeV} \leftrightarrow 4.18\,\text{GeV}$$

PDF sets: MSTW2008 $\leftrightarrow$ PDF4LHC15 $\to$ bbh talk by Marius!

▷ Reason: ROOT files were produced before LHCHXSWG-INT-2015-006 release and were already used, e.g. in [ATLAS 1509.00672 JHEP 1511 (2015) 206].

$\to$ For documentation they have to be kept!

$\to$ Idea is to produce new scenarios with new SM input.

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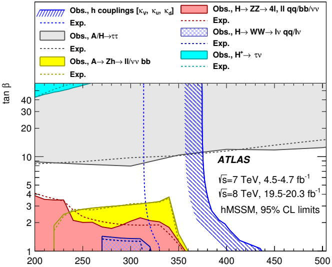
Why is the low $(\tan\beta, m_A)$ region of interest?
Low m_A yields low mass states $A, H, H^{\pm}$.
At low $\tan\beta$ no exclusion from $H, A \to \tau\tau$.
$\to$ Non decoupling effects in $H \to hh$,
$H \to WW/ZZ$, $A \to Zh$.

Problem: Requires very large stop masses to get $m_h \approx 125\,\text{GeV}$.
$\to$ Resummation of large logs in an EFT.



[ATLAS 1509.00672]

Different approaches:

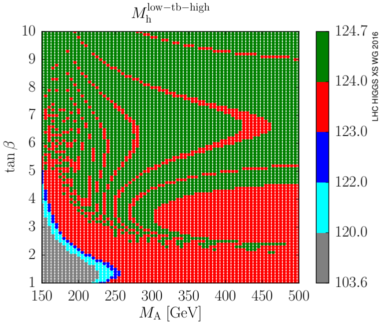
- ▷ `FeynHiggs` approach: fixed-order calculation of `FeynHiggs` with partial resummation of large logs $\to$ “low-tb-high” scenario [Heinemeyer]
- ▷ hMSSM approach: Trade the knowledge of m_h for the element of the Higgs mass matrix where large logs arise, obtain formulae for m_H and α.
  [Maiani et al., 1305.2172; Djouadi et al., 1307.5205 and 1502.05653]
- ▷ safe approach: Effective THDM with heavy SUSY
  [Haber Hempfling, early 90s, Lee Wagner 1508.00576]

YR4 provides an introduction to low $\tan\beta$ scenarios.

The "low-tb-high" scenario: [Heinemeyer]
based on `FeynHiggs` $\geq$ `2.10.0`
with NLL resummation
Low $(m_A, \tan\beta)$ scenario with heavy sfermions and gluino, but TeV-scale EW-inos:

$$m_{\tilde{f}} = M_3 = M_S, \quad 0 \leq X_t/M_S \leq 2$$
$$M_2 = 2\,\text{TeV}, \quad \mu = 1.5\,\text{TeV}$$

M_S and X_t are adjusted such that $m_h \approx 125 \pm 3\,$GeV.



Comparison to the EFT approach with heavy SUSY and intermediate m_A:
[Lee Wagner 1508.00576]
m_h is about $2(5)(10)$ GeV lower for $\tan\beta > 5.5 (\tan\beta < 3.5) (\tan\beta < 2)$
Discreprancies in α, m_H reach $10-12\%$ at low $\tan\beta < 1.5$ and $m_A < 200$ GeV.
$\rightarrow$ Discreprancies still need to be resolved.

The hMSSM approach: [Maiani et al. '13; Djouadi et al. '13 '15]
Mass matrix for the neutral CP-even states ($s_x/c_x = \sin x/\cos x$):

$$\mathcal{M}^2_{\mathrm{hMSSM}} = \begin{pmatrix} m_A^2 s_\beta^2 + m_Z^2 c_\beta^2 & -(m_A^2 + m_Z^2) s_\beta c_\beta \\ -(m_A^2 + m_Z^2) s_\beta c_\beta & m_A^2 c_\beta^2 + m_Z^2 s_\beta^2 \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & \Delta M_{22}^2 \end{pmatrix}$$

Assumptions:
- ▷ Observed Higgs is the light scalar h.
- ▷ Of the radiative corrections only ΔM_{22}^2 is of relevance.
- ▷ All SUSY particles are heavy.

$\rightarrow$ Trade ΔM_{22}^2 for m_h and obtain m_H and α:

$$m_H^2 = \frac{(m_A^2 + m_Z^2 - m_h^2)(m_Z^2 c_\beta^2 + m_A^2 s_\beta^2) - m_A^2 m_Z^2 c_{2\beta}^2}{m_Z^2 c_\beta^2 + m_A^2 s_\beta^2 - m_h^2}$$

$$\tan\alpha = -\frac{(m_Z^2 + m_A^2) c_\beta s_\beta}{m_Z^2 c_\beta^2 + m_A^2 s_\beta^2 - m_h^2}$$

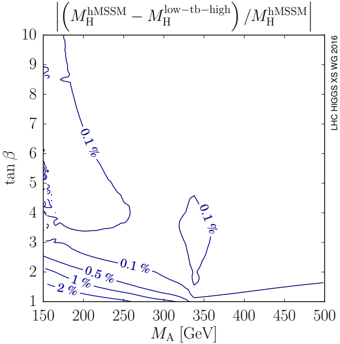
Additional contribution to $\lambda_{Hhh} = \lambda_{Hhh,\mathrm{tree}} + 3\Delta M_{22}^2 s_\alpha c_\alpha^2/s_\beta/m_Z^2$.

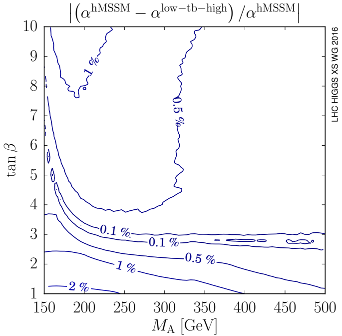
Comparison to the EFT approach with heavy SUSY and intermediate m_A:
[Lee Wagner 1508.00576]
Agreement within a few % with exact results for m_H and α if $\mu X_t/M_S^2 \lesssim 1$.

Comparison of the ROOT files for "low-tb-high" scenario and hMSSM (in YR4):

▷ "low-tb-high" ROOT files: m_h, m_H and α from FeynHiggs
$gg\phi$ and $b\bar{b}\phi$ XS with SusHi (THDM + Δ_b)
Widths with FeynHiggs+Prophecy4f+HDECAY

▷ hMSSM ROOT files: $m_h = 125$ GeV, m_H and α from hMSSM formulae
$gg\phi$ and $b\bar{b}\phi$ XS with SusHi (THDM), Widths with HDECAY
Comparison of "validation" ROOT files with same m_h (from "low-tb-high" sc.):

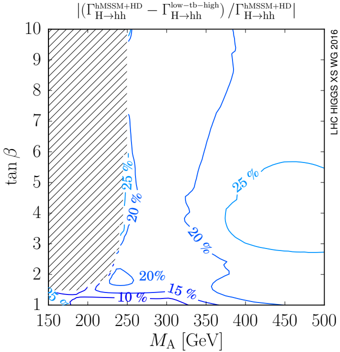




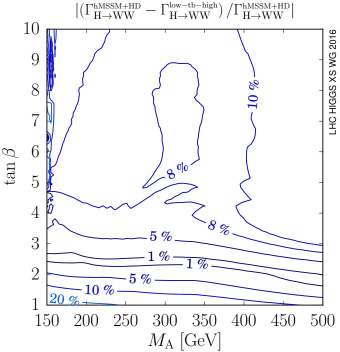
→ Agreement of $(0.1 - 1)\%$ for m_H and α except at very low $\tan\beta$

Discreprancies about $(10-20)\%$ only in some widths from different accuracy of calculations, see e.g. $H \to hh$ and $H \to W^+W^-$:

"low-tb-high" files:
FeynHiggs (with log resummation)
hMSSM files:
HDECAY (LO with eff. Hhh coup.)



"low-tb-high" files:
Prophecy4f (scaled to MSSM)
hMSSM files:
HDECAY (LO)



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p_T distributions in gluon fusion diverge for $p_T \to 0$ at fixed order!
Thus: Need for resummation of Sudakov logarithms $\sim \log(p_T/m_\phi)$

✓ NNLL+NNLO in the heavy top-limit
[Catani et al. '88, Yuan '92, Kauffman '92, Bozzi et al. '03 '05, Cao et al. '09, de Florian et al. '11, Catani Grazzini '11, Wang et al. '12]; in the context of SCET [Idilbi et al. '05, Gao et al. '05, Mantry et al. '10, Becher et al. '10 '12, Stewart et al. '11 '13] + Works from 2015

✓ Top-quark mass effects at NLL+NLO in SM
Bottom-quark contributions recently at NLL+NLO in SM (with $\log(p_T/m_b)$)
[Bagnaschi Degrassi Slavich Vicini '11, Mantler Wiesemann '12, Grazzini Sargsyan '13, Banfi Monni Zanderighi '13]
$\to$ Matching to the resummed result
$\to$ Momentum ("matching") scales $(\mu_t, \mu_b, \mu_{\text{int}})$ for individual contributions:

$$\frac{d\sigma}{dp_T^\phi} = \left.\frac{d\sigma_t}{dp_T^\phi}\right|_{\mu_t} + \left.\frac{d\sigma_b}{dp_T^\phi}\right|_{\mu_b} + \left.\frac{d\sigma_{\text{int}}}{dp_T^\phi}\right|_{\mu_{\text{int}}}$$

Determination of scales:
▷ Bagnaschi-Vicini (BV): [Bagnaschi Vicini '15]
resummation when the collinear limit is a good approximation/partonic level
▷ Harlander-Mantler-Wiesemann (HMW): [Harlander Mantler Wiesemann '14]
recover the NLO behavior sufficiently fast for $p_T \geq m_\phi$/hadronic level

Resummation frameworks in extended Higgs sectors (like the 2HDM, MSSM):

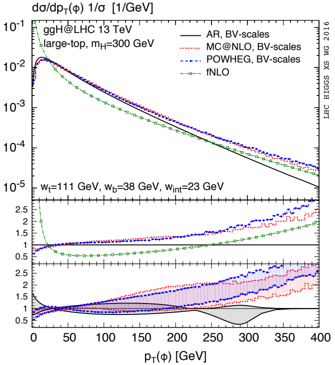
▷`POWHEG` (gg_H_MSSM, gg_H_2HDM) - Resummation through parton shower
[Bagnaschi Degrassi Slavich Vicini '11, Bagnaschi Vicini '15]

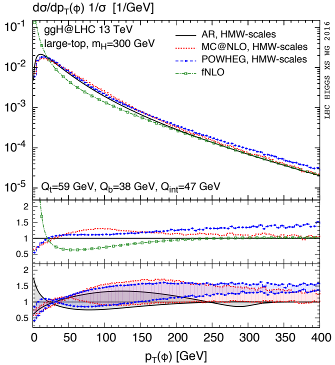
(`POWHEG-SusHi` [Mantler unpublished])

▷`aMCSusHi` - `SusHi` amplitudes to `MG5_aMC@NLO` [Alwall et al. '14]
[Mantler Wiesemann '15]

▷`MoRe-SusHi (Momentum-Resummed SusHi)` - Analytic resummation
[Harlander Mantler Wiesemann '14]

YR4 contains a description of the approaches and main results of comparison:





see also [Bagnaschi Harlander Mantler Vicini Wiesemann '15]

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Conclusion:

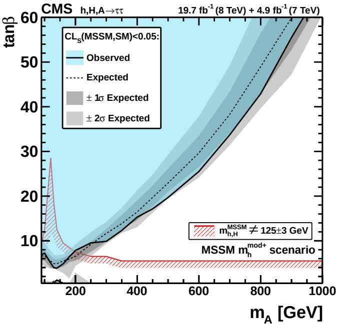
The MSSM subgroup section of the YR4 is finished!

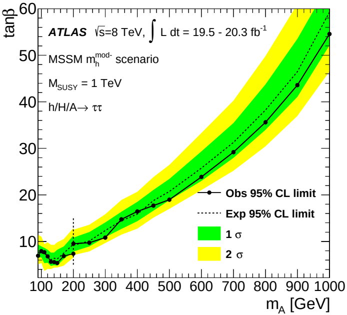
Future projects:

We are looking forward to new scenarios (with maybe new physics?!).

We need to keep the XS and BR predictions compatible with SM predictions.

Thanks for your attention.





[CMS: 1408.3316, ATLAS: 1409.6064]