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

# MSSM neutral - report and plan

WG3 MSSM neutral subgroup

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**Meeting of the LHC Higgs XS WG**

Geneva – October 2016

DESY

HELMHOLTZ | GEMEINSCHAFT

# Outline

1. Status of the MSSM neutral subgroup
2. MSSM Higgs mass calculation
3. Transverse momentum of the Higgs boson in gluon fusion
4. Conclusions

MSSM Higgs sector is a 2HDM with fields $\Phi_{1,2}$ with $\Phi_i = (\phi_i^+, \phi_i^0)$ (no FCNCs!):

$$\begin{aligned} V =& m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] \\ &+ \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ &+ \left\{ \tfrac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)\right] (\Phi_1^\dagger \Phi_2) + \text{h.c.} \right\} \end{aligned}$$

SUSY relations fix almost all parameters:

$$\lambda_1 = \lambda_2 = \tfrac{1}{4}(g^2 + g'^2),\ \lambda_3 = \tfrac{1}{4}(g^2 - g'^2),\ \lambda_4 = -\tfrac{1}{2}g^2,\ \lambda_i = 0,\ m_{12}^2 = m_A^2 s_\beta c_\beta$$

In the rMSSM the CP-even tree-level Higgs masses

$$m_{h,H}^2 = \tfrac{1}{2}\left\{ m_A^2 + m_Z^2 \mp \sqrt{(m_A^2 + m_Z^2)^2 - 4 m_Z^2 m_A^2 c_{2\beta}^2} \right\}$$

are predicted as a function of $m_A$ and $\tan\beta = t_\beta$.
$\leftrightarrow$ Benchmark scenarios with 2D planes of $(m_A, t_\beta)$.
Upper bound on tree-level Higgs mass: $m_h < m_Z |c_{2\beta}|$
Large radiative corrections needed to obtain $m_h \sim 125$ GeV.

MSSM benchmark scenarios provided as ROOT files:

| 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] |
| $m_h^{\rm max}$ | $90 - 2000$ | $0.5 - 60$ | $13, 14$ | [Carena et al. '13] |
| $m_h^{\rm mod+}$, $\mu \in \mu^{\rm val}$ | $90 - 2000$ | $0.5 - 60$ | $8, 13, 14$ | [Carena et al. '13] |
| $m_h^{\rm mod-}$ | $90 - 2000$ | $0.5 - 60$ | $13, 14$ | [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] |
| $\tau$-phobic | $90 - 2000$ | $0.5 - 50$ | $13, 14$ | [Carena et al. '13] |

$\mu \in \mu^{\rm val} = \{-1000, -500, -200, 200, 500, 1000\}$ 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 $m_\phi$ ($h$ (mostly) compatible with SM Higgs $\sim 125$ GeV)
- ✓ Gluon fusion XS
- ✓ $bb\phi$ XS in 4FS/5FS and Santander-matched XS (✗ New matched XS!)
- ✓ Branching ratios
- ✓ Scale and PDF$+\alpha_s$ uncertainties
- ✓ Charged Higgs information: $m_{H^\pm}$, $t \to H^+ b$, ($H^+ \to tb$)
- ✓ Add charged Higgs cross sections (thanks to Panu Keskinen/Semi Lehti).

Work on/extension of/update of the ROOT files:

✓ up to $m_A = 2\,$TeV.

✓ with $H^\pm$ information, i.e. BR($H^\pm$) and BR($t \to H^\pm b$) for charged Higgs searches with low mass $m_{H^\pm} < m_t$.

✓ with $H^\pm$ XS relevant for $m_{H^\pm} > 200\,$GeV by reweighting the XS from the "MSSM charged" group (thanks to Panu Keskinen), to be included in next update (if possible with $m_{H^\pm} = 150 - 200\,$GeV [Degrande et al.]).

✗ Again: We plan (since one year...) to redo the ROOT files with new SM input and N$^3$LO top contribution for the light Higgs boson.

$\alpha_s(m_Z) = 0.119 \leftrightarrow 0.118$
$m_b(m_b) = 4.16\,$GeV $\leftrightarrow 4.18\,$GeV
PDF sets: MSTW2008 $\leftrightarrow$ PDF4LHC15 $\to$ special sets for bb$\phi$!

Reasons why we were lazy:

1. Expected differences are small.
2. $750\,$GeV resonance would have changed the picture.
3. New Higgs mass calculations released in 2016 (not only for EFT scenarios)

$\to$ Lower $m_h$ asks for new scenarios!

✗ inclusion of $p_T$ distributions for heavy Higgs bosons
(thanks to Rene Caspart and Yuta Takahashi).

# Outline

[Disclaimer: Subsequent slides from Pietro's talk at HDays 2016!]

Dominant corrections to Higgs masses through top quarks and squarks:

$$(\Delta m_h^2)^{\text{1-loop}} \sim \frac{3m_t^4}{2\pi^2 v^2}\left(\ln\frac{m_S^2}{m_t^2} + \frac{X_t^2}{m_S^2} - \frac{X_t^4}{12 m_S^4}\right) - \frac{y_b^4 \mu^4 t_\beta^4 v^2}{32\pi^2 m_S^4}$$

(Decoupling limit, $m_S$ =averaged stop mass, $X_t = A_t - \mu\cot_\beta$ = stop mixing)

✓ "Maximal-mixing" scenarios ($X_t \sim \sqrt{6}m_S$) work with stops around the TeV scale (for large $t_\beta$ and $m_A$)

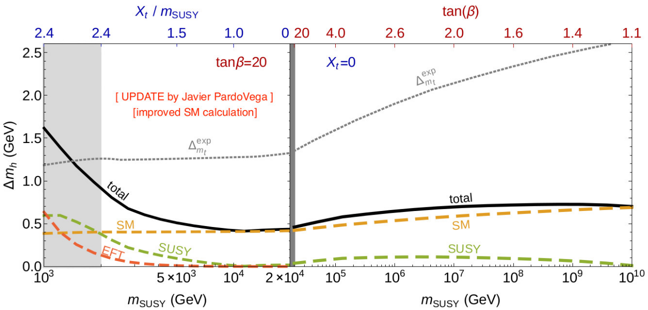
✓ Small mixing ($X_t \ll m_S$) or small $t_\beta$ (or $m_A$) require multi-TeV stops masses
$\rightarrow$ resummation of large logarithms

"fixed-order" codes
(`SuSpect`, `SPheno/SARAH`, `SoftSUSY/FlexibleSUSY`, `FeynHiggs`, `H3m`,...)

"hybrid" codes
(`FeynHiggs` $\geq$ `2.10`, `FlexibleEFTHiggs`)

"EFT" codes
(`SusyHD`, `MhEFT`, `HSSUSY`)
new in 2016!

Details of state-of-the-art EFT calculations: Pietro's talk at HDays 2016.
Focus here: Uncertainties in EFT calculations
[PardoVega Villadoro (SusyHD) 1504.05200]




SM uncertainty: mostly from missing higher order QCD effects
SUSY uncertainty: estimated varying SUSY matching scale by factor $1/2$ or $2$
EFT uncertainty: estimated replacing $\Delta\lambda \to \Delta\lambda(1 + v^2/m_S^2)$
Note the large uncertainty associated to $\Delta m_t^{\rm exp}$!

Comparison of EFT calculations: $m_S(m_S) = 10$ TeV, $X_t(m_S) = 0$, $t_\beta = 20$

| Calculation | $m_h$ [GeV] |
|---|---|
| Bagnaschi et al. [1407.4081] | 123.6 |
| SusyHD [1504.05200] | 123.6 |
| MhEFT [1508.00576] | 123.8 |
| HSSUSY [1609.00371] | 123.6 |
| FlexibleEFTHiggs [1609.00371] | 123.8 |
| FeynHiggs 2.10.0 [1312.4937] | 126.5 |
| FeynHiggs 2.12.0 [1608.01880] | 124.3 |

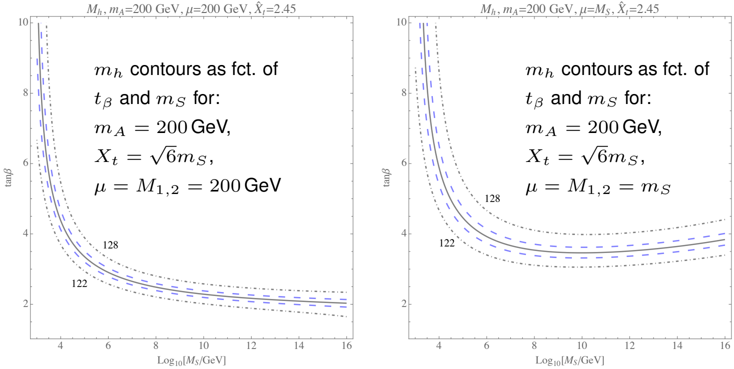
Main source of discrepancy:
Determination of top Yukawa coupling

Full 1-loop
+ 2/3-loop QCD

Partial 1-loop [QCD+$\mathcal{O}(Y_t^2)$]

Full 1-loop + 2-loop QCD

New EFT codes (MhEFT, FlexibleSUSY/HSSUSY) (Effective 2HDM with heavy SUSY) allow to check the validity of hMSSM approach: Reopened the low $(m_A, t_\beta)$ region with very heavy SUSY.




[Lee Wagner 1508.00576]

Conclusion: $m_h = 125$ GeV cannot be reached at all for low $m_A$ and $t_\beta$. Moreover, the low-tb-high scenario can be superseded with proper EFT scenario.

Comparison of standard scenario:
$t_\beta = 20$, SUSY masses $= 1$ TeV, $X_t$ varied to maximize $m_h$

| Calculation | $m_h$ [GeV] |
|---|---|
| `SPheno 3.3.8` | 126.3 |
| `SuSpect 2.43` | 125.8 |
| `SoftSUSY 3.7.0` | 124.3 |
| `NMSSMTools 4.9.1` | 124.6 |
| `FeynHiggs 2.11.2` | 129.8 |
| `FeynHiggs 2.11.3` | 128.1 |
| `FeynHiggs 2.12.0` | 126.3 |

Main source of discrepancy:
Determination of top Yukawa coupling

same $\overline{\text{DR}}$ calculation of Higgs mass
differences in determination of top Yukawa

OS calculation of Higgs mass
running $m_t$ at NLO

running $m_t$ at NNLO

resummation $+\ m_t$ with EW effects

Running current benchmark scenarios with new `FeynHiggs` version would provide too low values for $m_h$.
$\rightarrow$ New benchmark scenarios should be defined. $\rightarrow$ Sven's talk.

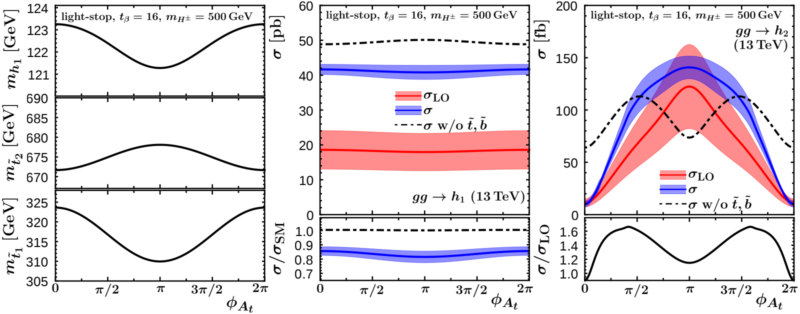
New directions for what concerns benchmark scenarios:

✓ Low-$m_h$ scenario with $m_h < 125$ GeV and $m_H = 125$ GeV → Sven's talk.

✓ CP-violation in the Higgs sector:

Mixing of $\{h, H, A\}$ to three mass eigenstates $h_i$ through phases in Higgsino parameter $\mu$, gaugino masses $M_i$ or trilinear couplings $A_f$.

Example cross sections obtained with SusHiMi: [SL Patel Weiglein '16?!]




Setup available: FeynHiggs and SusHiMi

to be discussed: inclusion of large interferences [Fuchs Weiglein]

# Outline

$p_T$ 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 (N$^3$LL+N$^3$LO since 2016) 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] + Huge progress in 2015/2016

✓ Light-quark contributions and top-quark mass effects at NLL+NLO in SM
[Bagnaschi Degrassi Slavich Vicini '11, Mantler Wiesemann '12, Grazzini Sargsyan '13, Banfi Monni Zanderighi '13]
+ Corrections beyond NLO since 2016: [Melnikov et al., Caola et al.; Frederix et al.; Neumann et al.]

Current procedure: Resummation scales ($\mu$) for individual contributions:

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

Resummation frameworks in extended Higgs sectors:

▷ (m) POWHEG (gg_H_MSSM, gg_H_2HDM) - Resummation through parton shower ($\mu = h$)
[Bagnaschi Degrassi Slavich Vicini '11, Bagnaschi Vicini '15]

(POWHEG-SusHi [Mantler unpublished])

▷aMCSusHi - SusHi amplitudes to MG5_aMC@NLO [Alwall et al. '14] ($\mu = Q^{\text{shower}}$)
[Mantler Wiesemann '15]

▷MoRe-SusHi - Analytic resummation ($\mu = Q^{\text{res}}$)
[Harlander Mantler Wiesemann '14]

Determination of scales (see also arXiv:1510.08850 by authors listed below):

▷ Bagnaschi-Vicini (BV): [Bagnaschi Vicini '15]

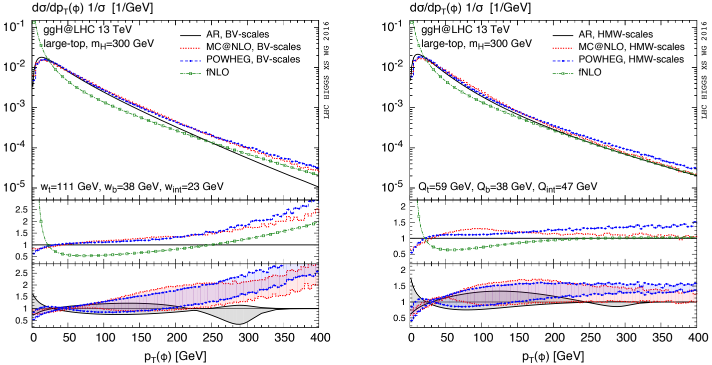
partonic level, low $p_T$,

apply resummation when the collinear limit is a good approximation

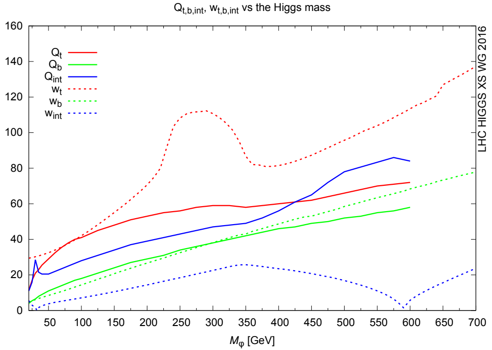
▷ Harlander-Mantler-Wiesemann (HMW): [Harlander Mantler Wiesemann '14]

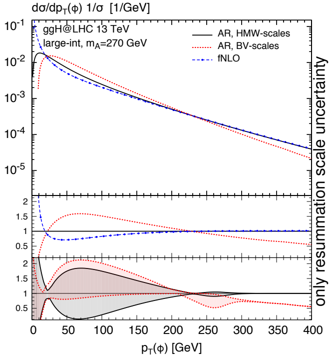
hadronic level, high $p_T$, recover the NLO behavior sufficiently fast for $p_T \geq m_\phi$

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



Main result of [arXiv:1510.08850]:
Variation of resummation scales within $(\mu/2, 2\mu)$ and addititional variation of renormalization and factorization scales gives comparable results between the different codes. Uncertainties capture differences of order $\mathcal{O}(50)$%! Both scale choices ($w$ =BV and $Q$ =HMW) are then acceptable.



Conservative procedure to obtain uncertainties (discussed in August meeting):

0. Pick one tool and one scale setting approach.
1. Calculate the three contributions for $t$, $b$ and int for three choices of $\mu^{\text{res}}$ ($9$ curves: $d\sigma_{t,b,\text{int}}/dp_T(\mu^{\text{res}})$) keeping $(\mu_{\text{R}},\mu_{\text{F}})$ fixed.
2. Calculate the three contributions for $t$, $b$ and int for seven (three?) choices of $(\mu_{\text{R}},\mu_{\text{F}})$ ($21$ curves: $d\sigma_{t,b,\text{int}}/dp_T(\mu_{\text{R}},\mu_{\text{F}})$) keeping $\mu^{\text{res}}$ fixed.
3. Reweight curves from $\text{2HDM}$ (with e.g. $t_\beta = 15$) to $\text{MSSM}$.
4. Obtain the maximal and minimal curves from all combinations of curves in 1. and 2. individually and calculate the absolute errors for both:

$$\Delta\sigma(p_T) = \frac{\sigma^{\max}(p_T) - \sigma^{\min}(p_T)}{2} \qquad \text{with} \qquad \sigma(p_T) = \left.\frac{d\sigma}{dp_T}\right|_{p_T}$$

Add the errors in quadrature (Assumption: Uncorrelated!):

$$\Delta\sigma(p_T) = \sqrt{(\Delta\sigma^{\mu^{\text{res}}}(p_T))^2 + (\Delta\sigma^{(\mu_{\text{R}},\mu_{\text{F}})}(p_T))^2}$$

Note: Steps 3.+4. can be performed on the fly within the ROOT files given we store the curves from 1.+2. as a function of the Higgs mass $m_H/m_A$.

# Outline

**Status of the subgroup:**
After ICHEP the MSSM is well.
**Short term:** (summer 2017)
Wait for/define new benchmark scenarios for new ROOT files:
✓ Update of classic scenarios (due to new Higgs mass calculations).
✓ Proper EFT scenario with effective 2HDM.
✓ Extension to CP-violating scenario(s) (FeynHiggs and SusHiMi).
✓ New low-$m_H$ scenario? $\rightarrow$ Sven's talk.
The new ROOT files should include new SM input, $\mathrm{N^3LO}$ top contributions for light Higgs, $H^\pm$ information (XS and BRs $\leftrightarrow$ charged Higgs subgroup), new $bb\phi$ matched predictions and ultimately distributions (not only for $gg\phi$ but also $bb\phi$ $\leftrightarrow$ bbh subgroup).
Specific official note on distributions?!

**Possible future directions:**
✗ classify deviations for the light Higgs boson cross sections and branching ratios, i.e. trying to classify deviations due to delayed decoupling, SUSY particles, etc.

✗ add other production mechanisms to ROOT files.