**Stefan Liebler**
DESY Hamburg

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

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

# MSSM status report

WG3 MSSM neutral subgroup

ATLAS: Allison McCarn
CMS: Andrew Gilbert
TH: Michael Spira, Pietro Slavich, Stefan Liebler

**13th Meeting of the LHC Higgs XS WG**

Geneva – July 2017

DESY

HELMHOLTZ | GEMEINSCHAFT

# Outline

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

$\mu \in \mu^{\text{val}} = \{-1000, -500, -200, 200, 500, 1000\}$ 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: $m_{H^\pm}$, $t \to H^+ b$, $(H^+ \to tb)$
- ✓ Charged Higgs XS (thanks to Panu Keskinen/Semi Lehti) (non-public).

# Outline

Why do we want to define new benchmark scenarios?
We anyhow need to redo the ROOT files due to:

✓ update of the SM input:

$$\alpha_s(m_Z) = 0.119 \leftrightarrow 0.118$$
$$m_b(m_b) = 4.16\,\text{GeV} \leftrightarrow 4.18\,\text{GeV}$$

PDF sets: MSTW2008 ↔ PDF4LHC15 → special sets for $bb\phi$!

✓ N$^3$LO precision in $gg \to h$ relevant for the light Higgs boson

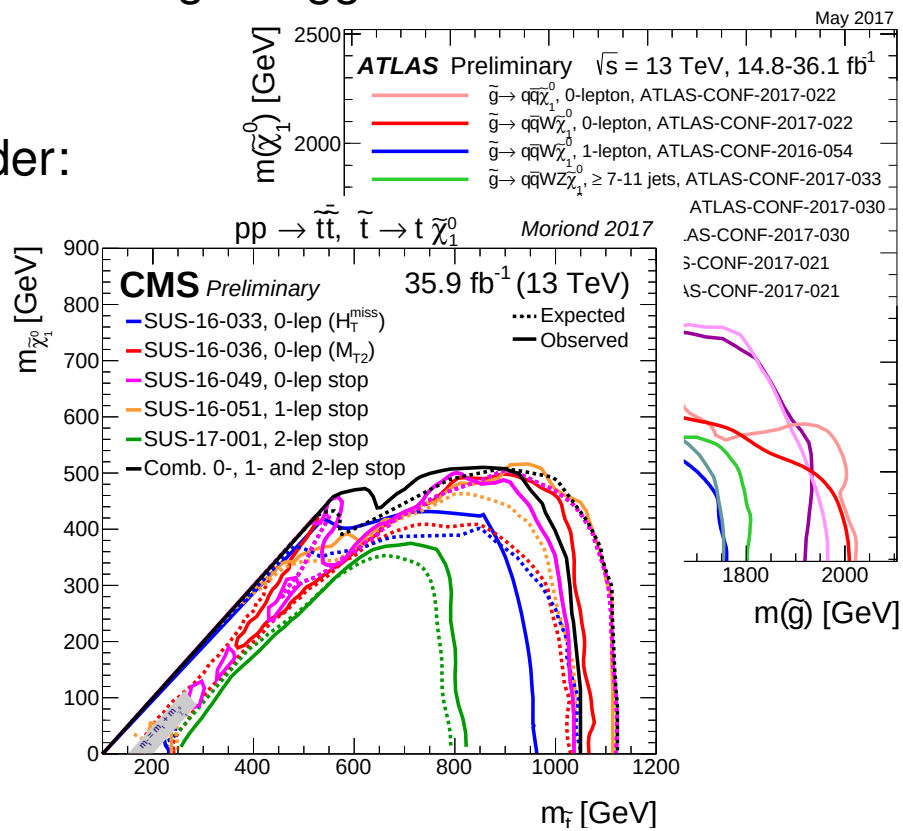
✓ new $bb\phi$ predictions

New benchmark scenarios are on order:

✓ Improvements in the calculation of the Higgs boson masses

✓ Extended sparticle exclusions (gluino and squark mass bounds)

Current scenarios: $M_3 = 1.5\,\text{TeV}$
$M_{Q_3} = M_{U_3} = M_{D_3} = 1.0 - 1.5\,\text{TeV}$
Light electroweakinos $< 500\,\text{GeV}$

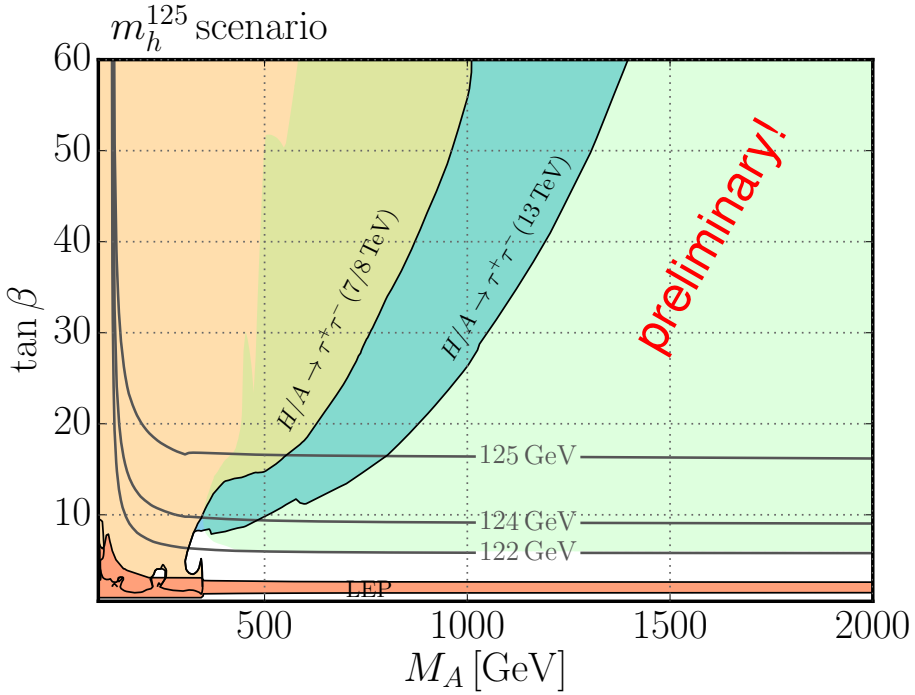


What benchmark scenarios are we aiming for?
Definition of classic scenarios (with SUSY $< 2.5$ TeV):
✓ $m_h^{125}$ scenario: 2HDM Higgs sector with SUSY properties, i.e.
SUSY $\geq 1$ TeV $\Rightarrow$ No influence on BRs of Higgs bosons $m_\phi < 2$ TeV.

$$M_{\text{SUSY}} = 2\,\text{TeV}, \quad M_{Q_3} = M_{U_3} = M_{D_3} = 1.5\,\text{TeV}, \quad \mu = 1\,\text{TeV}$$
$$M_1 = 1\,\text{TeV}, \quad M_2 = 1\,\text{TeV}, \quad M_3 = 2.5\,\text{TeV}$$
$$X_t = 2.8\,\text{TeV}, \quad A_t = A_b = A_\tau\,.$$

New setup used:
$m_\phi$ and BR: `FH 2.13.0`
$gg\phi$: `SusHi 1.7.0` (tbr)
new $bb\phi$ XS (YR4)
`HiggsBounds 5.1.0`
`HiggsSignals 2.1.0`
to check existing bounds
(up to 13 TeV $13.3\text{fb}^{-1}$, not ATLAS-CONF-2017-050)

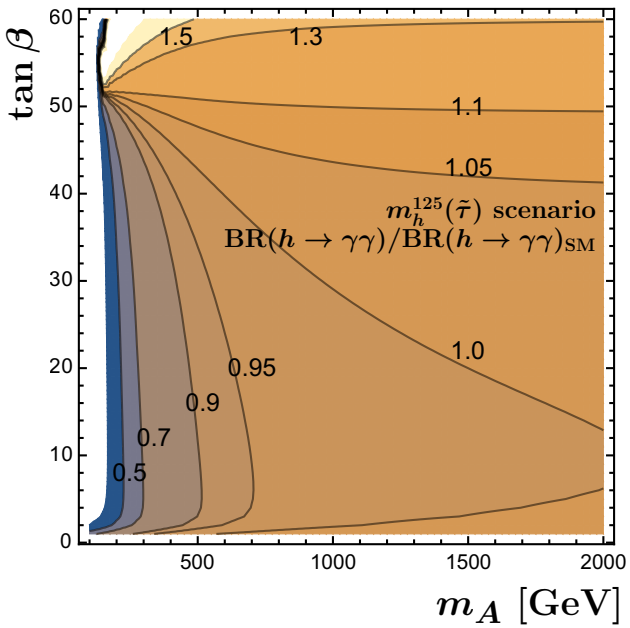
[Heinemeyer SL Slavich Stefaniak Wagner Weiglein]

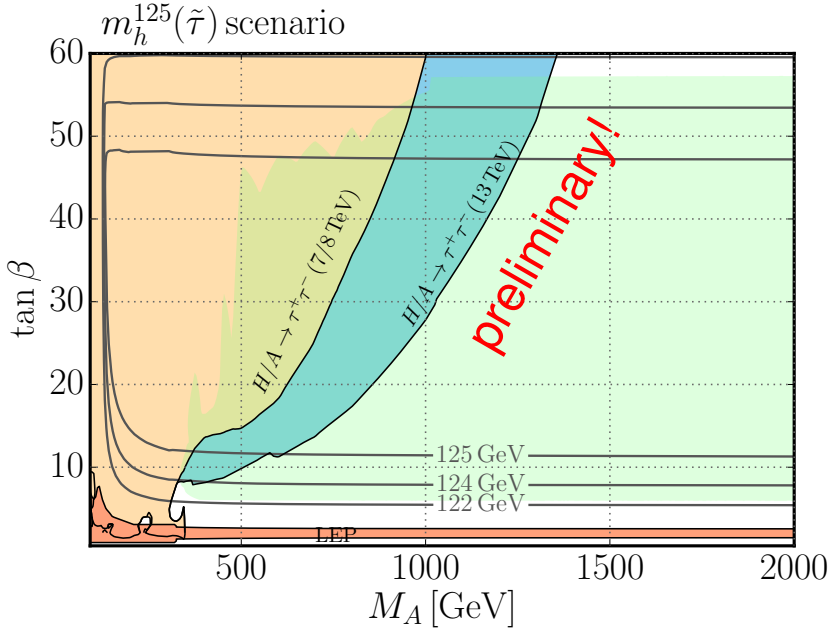


Definition of classic scenarios (with SUSY $< 2.5$ TeV):

✓ $m_h^{125}(\tilde{\tau})$ scenario: with light staus that influence $h \to \gamma\gamma$ and open BR$(H/A \to \tilde{\tau}\tilde{\tau})$ for large values of $\tan\beta$ (checked vaccum stability).

$$M_{\text{SUSY}} = 2\,\text{TeV}, \quad M_{Q_3} = M_{U_3} = M_{D_3} = 1.5\,\text{TeV}, \quad \mu = 1\,\text{TeV}$$
$$M_1 = 150\,\text{GeV}, \quad M_2 = 300\,\text{GeV}, \quad M_3 = 2.5\,\text{TeV}$$
$$M_{L_3} = 350\,\text{GeV}, \quad M_{E_3} = 350\,\text{GeV}$$
$$X_t = 2.8\,\text{TeV}, \quad A_t = A_b, \quad A_\tau = 800\,\text{GeV}\,.$$



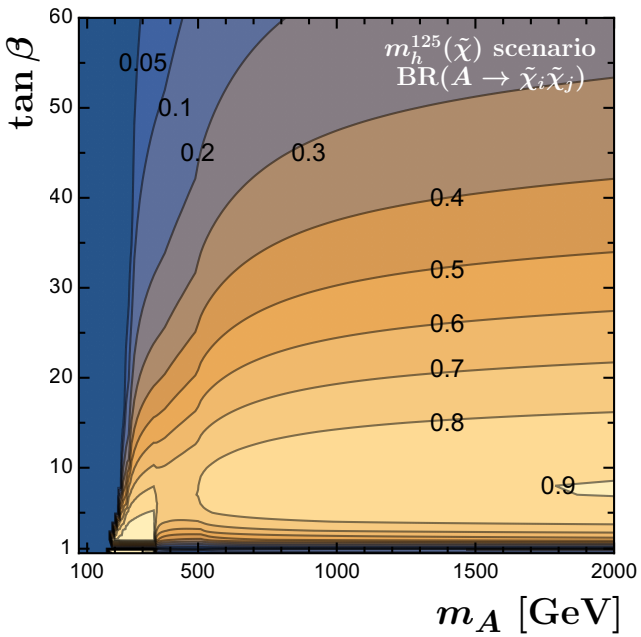
Definition of classic scenarios (with SUSY $< 2.5$ TeV):

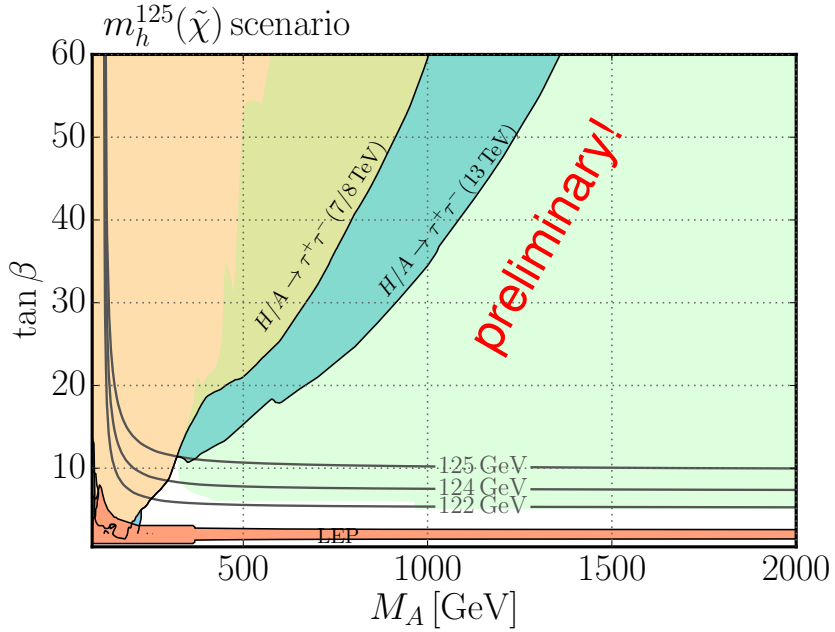
✓ $m_h^{125}(\tilde{\chi})$ scenario: with light electroweakinos that open BR$(H/A \to \tilde{\chi}_i\tilde{\chi}_j)$.

[Craig D'Eramo Draper Thomas Zhang '15, Barman Bhattacherjee Chakraborty Choudhury '16]

$$M_{\text{SUSY}} = 2\,\text{TeV}, \quad M_{Q_3} = M_{U_3} = M_{D_3} = 1.5\,\text{TeV}, \quad \mu = 180\,\text{GeV}$$
$$M_1 = 160\,\text{GeV}, \quad M_2 = 180\,\text{GeV}, \quad M_3 = 2.5\,\text{TeV}$$
$$X_t = 2.5\,\text{TeV}, \quad A_t = A_b = A_\tau\,.$$

Search for decay modes $H/A \to \tilde{\chi}_i\tilde{\chi}_j$ in the future.



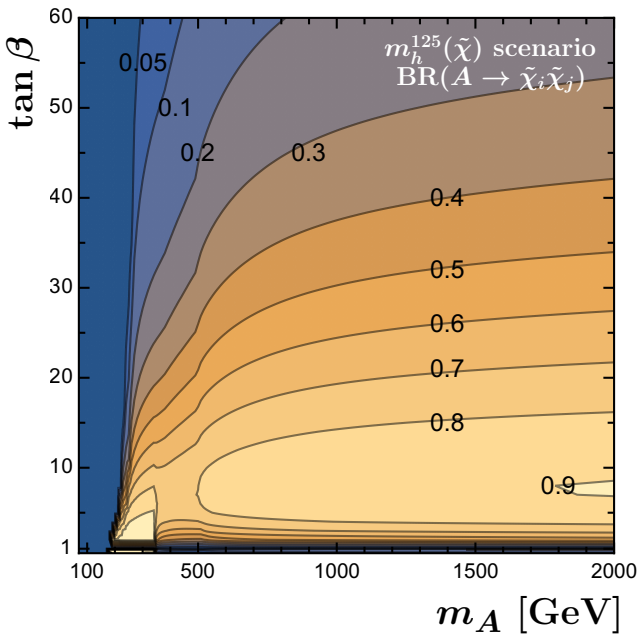
Definition of classic scenarios (with SUSY $< 2.5$ TeV):

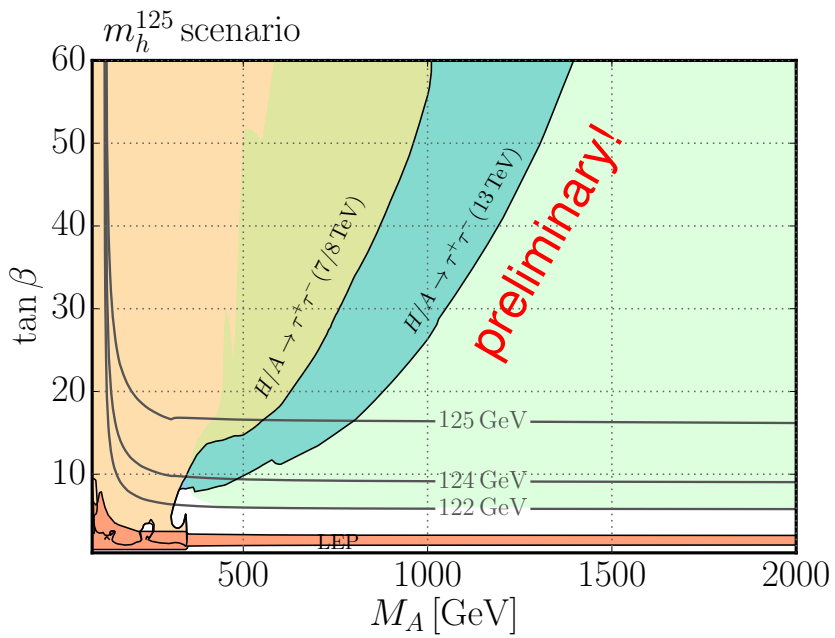
✓ $m_h^{125}(\tilde{\chi})$ scenario: with light electroweakinos that open BR$(H/A \to \tilde{\chi}_i\tilde{\chi}_j)$.

[Craig D'Eramo Draper Thomas Zhang '15, Barman Bhattacherjee Chakraborty Choudhury '16]

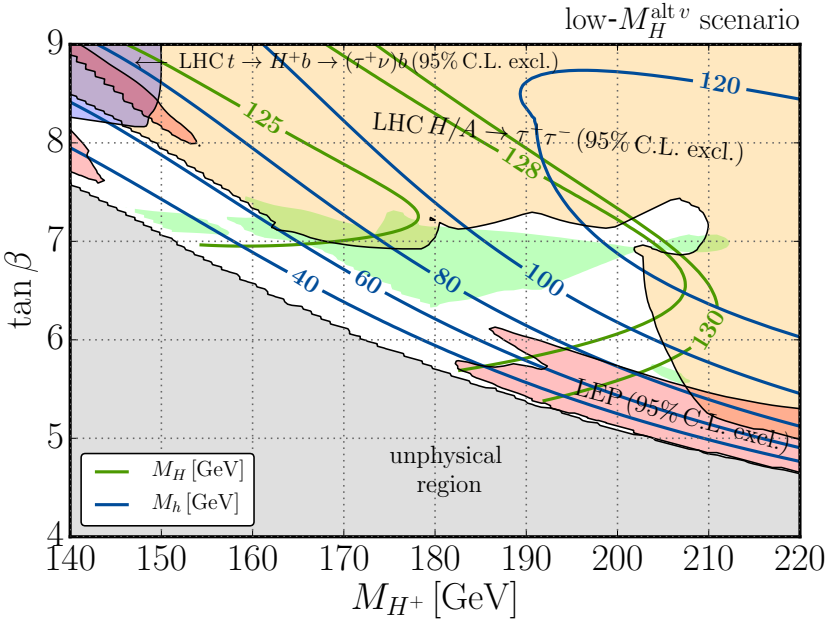
$$M_{\text{SUSY}} = 2\,\text{TeV}, \quad M_{Q_3} = M_{U_3} = M_{D_3} = 1.5\,\text{TeV}, \quad \mu = 180\,\text{GeV}$$
$$M_1 = 160\,\text{GeV}, \quad M_2 = 180\,\text{GeV}, \quad M_3 = 2.5\,\text{TeV}$$
$$X_t = 2.5\,\text{TeV}, \quad A_t = A_b = A_\tau\,.$$

Search for decay modes $H/A \to \tilde{\chi}_i\tilde{\chi}_j$ in the future.



Definition of classic scenarios:
Under investigation: Low-$m_H$ scenario.
Scenario with heavy CP-even Higgs $H$ being the SM-like Higgs boson.
[see Sven's talk at the 12th meeting of the LHCHXSWG!]
based on [Bechtle, Haber, Heinemeyer, Stål, Stefaniak, Weiglein, Zeune '16]




Small parameters space strongly under tension from current searches!

CP-violating scenario: [Fuchs SL Patel Weiglein]
Mixing of $\{h, H, A\}$ to three mass eigenstates $h_i$ through phases in Higgsino parameter $\mu$, gaugino masses $M_i$ or trilinear couplings $A_f$.
Setup: `SusHiMi` [SL Patel Weiglein '16] and `FeynHiggs`

Stick to narrow-width approximation, but add additional interference factor:

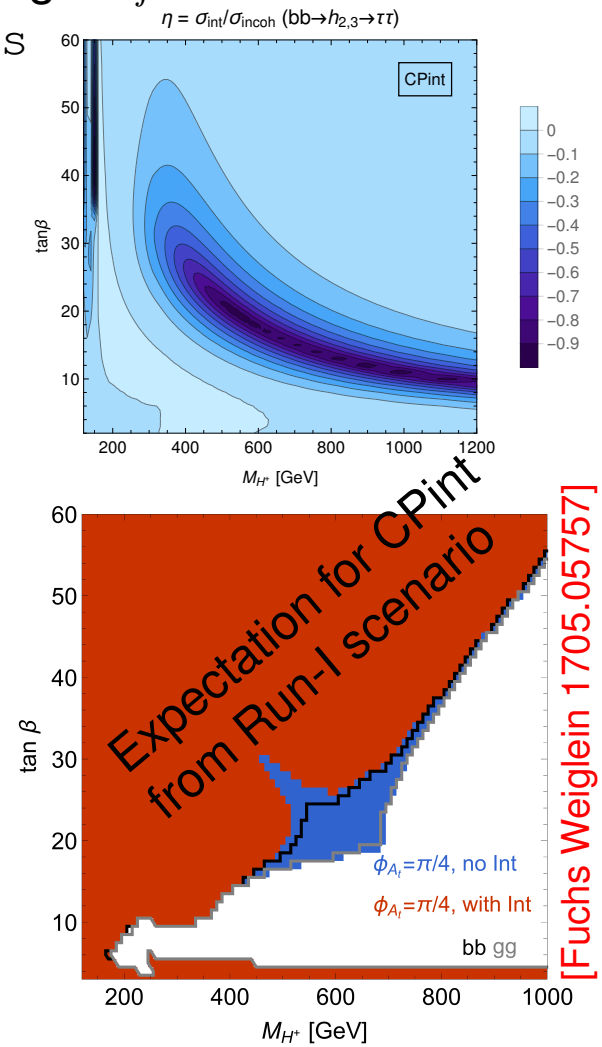
$$\eta_{\text{IF}} = \frac{2\text{Re}[A_{h_2} A_{h_3}^*]}{|A_{h_2}|^2 + |A_{h_3}|^2}$$

$A_{h_i}$ is the amplitude for I$\to h_i \to$F.

CPint scenario (preliminary):

$$M_{\text{SUSY}} = 1.5\,\text{TeV}, \quad M_{L_{1,2}} = M_{E_{1,2}} = 0.5\,\text{TeV}$$
$$\mu = 1.5\,\text{TeV}, \quad M_1 = 0.5\,\text{TeV}, \quad M_2 = 1.0\,\text{TeV}$$
$$M_3 = 2.5e^{i\pi/3}\,\text{TeV}, \quad X_t = 2.5\,\text{TeV}$$
$$\phi(A_t) = \pi/4, \quad A_b = A_t, \quad A_\tau = |A_t|\,.$$

Idea: Provide `ROOT` files with $\eta_{\text{IF}}$ factors.
Then $\sigma = \sigma(\text{I} \to h_i)\eta_{\text{IF}}\text{BR}(h_i \to \text{F})$.



[Disclaimer: Slide from Pietro's talk at HDays 2016/my last LHCHXSWG talk!]

Dominant corrections to Higgs masses through top quarks and squarks:

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

(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 stop masses
→ resummation of large logarithms

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

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

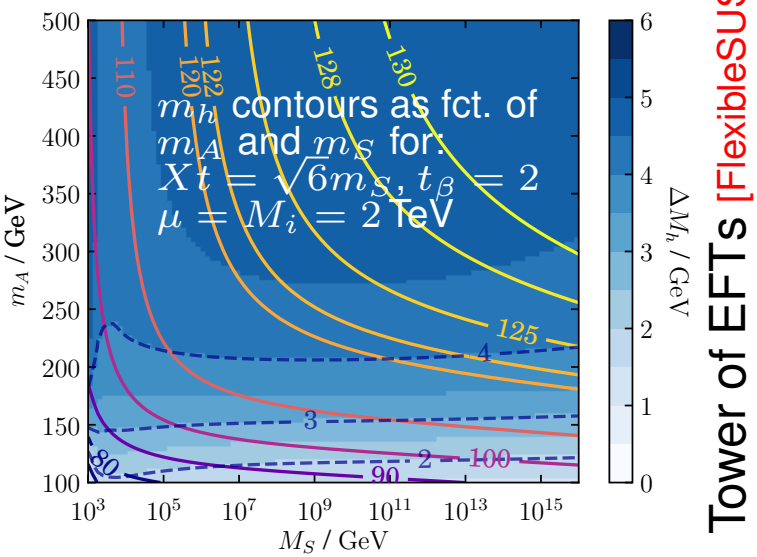
"EFT" codes
(`SusyHD`, `MhEFT`, `HSSUSY`)
new in 2016!

hMSSM reopened the low $(m_A, t_\beta)$ region in combination with heavy SUSY.
Looking for: Effective 2HDM scenario with heavy SUSY to check the validity of hMSSM approach (hMSSM scenario remains unchanged!). Available codes:

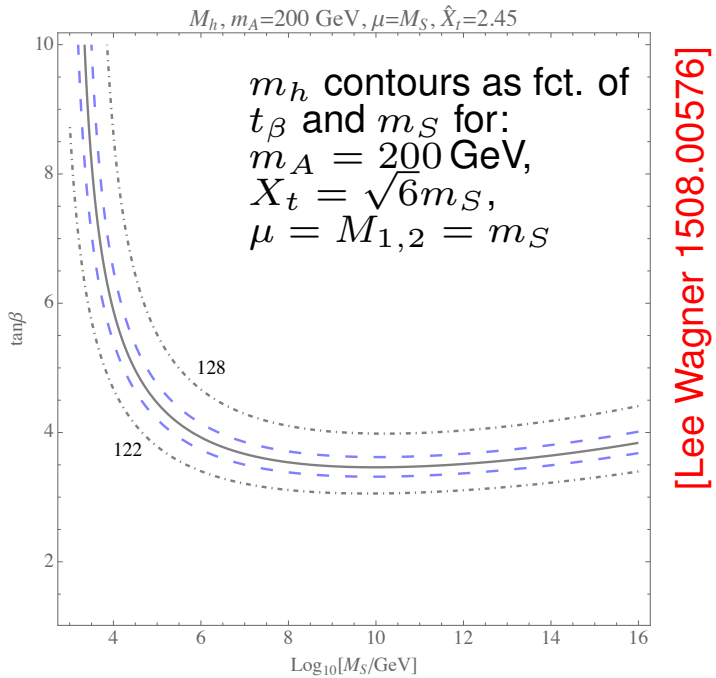
- ▷`MhEFT`: [Lee Wagner 1508.00576]
- ▷`FlexibleSUSY` framework: [Athron Park Steudtner Stöckinger Voigt 1609.00371] [Bagnaschi Brümmer Buchmüller Voigt Weiglein 1512.07761]

✓ Various towers of EFTs to study six different mass hierarchies of the MSSM.
✓ Includes fair uncertainty estimate.

- ▷`FeynHiggs`: in progress




Tower of EFTs [FlexibleSUSY]




[Lee Wagner 1508.00576]

Difficult to reach the low $(m_A, t_\beta)$ region advocated by the hMSSM approach.
Note: We also need predictions for BRs!

# Outline

Higgs $p_T$ distributions need to be resummed, since $p_T \to 0$ diverges at FO.
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]

Recent work by Andrew Gilbert (started by Rene Caspart, Yuta Takahashi):
Higgs $p_T$ spectra produced using POWHEG gg_H_2HDM.
Distributions for $H$ and $A$ bosons and $t$-only, $b$-only and interference terms for reference $\tan\beta$ value and mass values ranging from $90$ GeV to $3.2$ TeV.
Reweighting from 2HDM to MSSM:

Cross sections in 2HDM at reference $\tan\beta$ value

Yukawa couplings for 2HDM at ref. $\tan\beta$ value, for MSSM stored in ROOT file

$$\left(\frac{Y_{t,\text{MSSM}}}{Y_{t,\text{2HDM}}}\right)^2 \sigma^t_{\text{2HDM}}(Q_t) + \left(\frac{Y_{b,\text{MSSM}}}{Y_{b,\text{2HDM}}}\right)^2 \sigma^b_{\text{2HDM}}(Q_b) + \left(\frac{Y_{t,\text{MSSM}}}{Y_{t,\text{2HDM}}}\frac{Y_{b,\text{MSSM}}}{Y_{b,\text{2HDM}}}\right) \sigma^{\text{int}}_{\text{2HDM}}(Q_{tb})$$

$p_T$ distributions to reweight reference Monte Carlo:

Weights and scale factors will be distributed within a `RooFit` workspace inside a single `ROOT` file.

✓ Advantages: no additional code or interface needed, format widely used within ATLAS/CMS

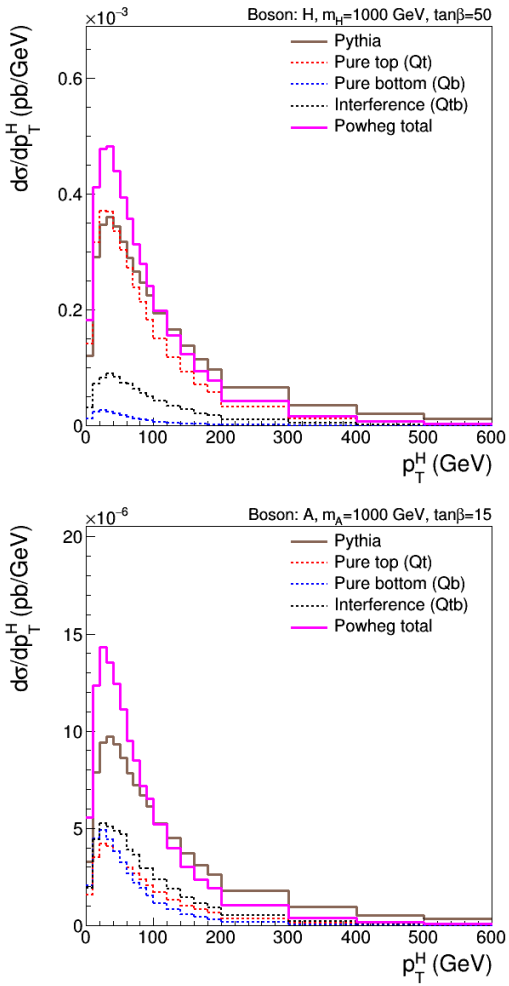
✓ Simple handling:

```
auto w = (RooWorkspace*)file->Get(workspace");
w->var("mA")->setVal(1000.);
w->var("tanb")->setVal(30.);
double xs=w->function("ggA_t_MSSM_xsec")->getVal();
```

✓ Method to obtain uncertainties to be added

[see my talk at the 12th meeting of the LHCHXSWG!]

✓ Available for testing soon (↔ Andrew Gilbert)




[Andrew Gilbert]

# Outline

**Status of the subgroup:**
We restarted work in the MSSM subgroup after YR4 about 3 months ago.
**Ongoing:** (summer/fall 2017)
Definition of new benchmark scenarios for new ROOT files:
✓ Update of classic scenarios (due to new Higgs mass calculations).
✓ New low-$m_H$ scenario.
✓ Extension to CP-violating scenario(s) (FeynHiggs and SusHiMi).
✗ Proper EFT scenario with effective 2HDM.

The new ROOT files will include new SM input, N$^3$LO 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).

**Possible future directions (identical to my talk at 12th meeting):**
✗ 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.