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MSSM benchmark scenarios for Run 2 and beyond

(on behalf of the MSSM subgroup)
WG3 fall meeting: Recap of recent progress

Geneva – September 2018

Outline

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

✓ update of the SM input:

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

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

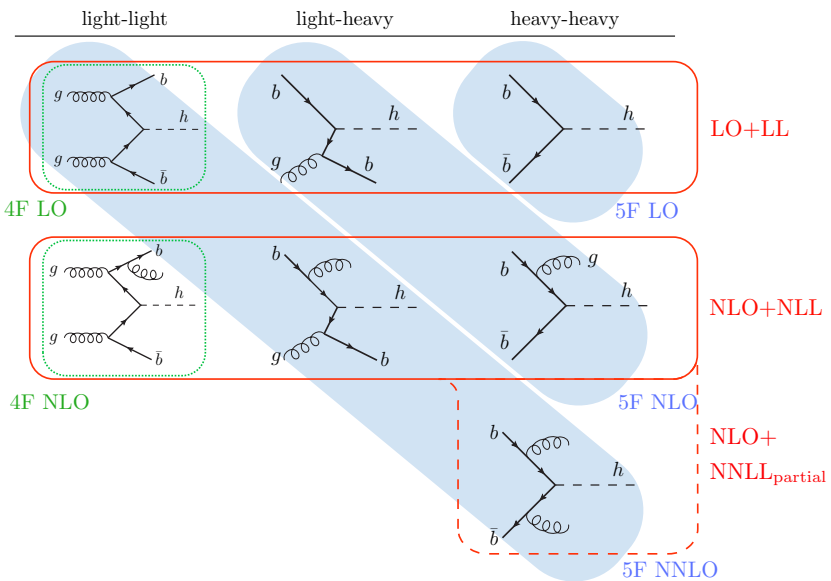
PDF sets: MSTW2008 ↔ PDF4LHC15 → special sets for $bb\phi$!

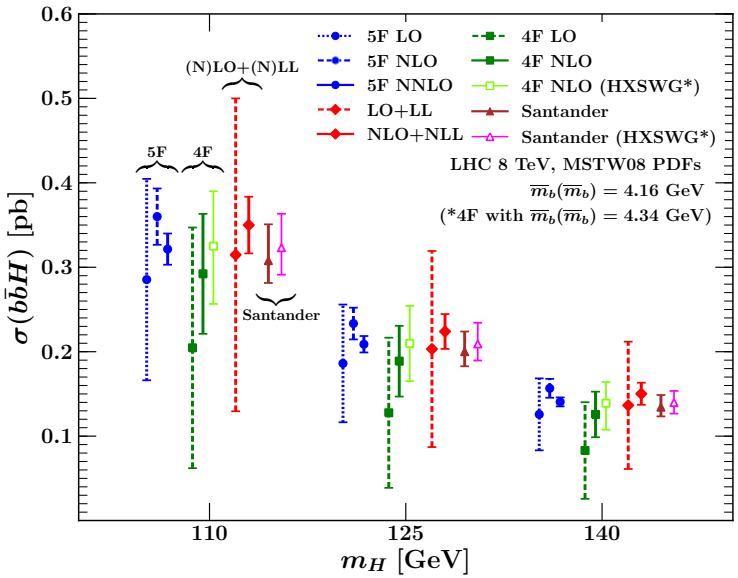
✓ N^{3}LO precision in $gg \to h$ relevant for the light Higgs boson

✓ new $bb\phi$ predictions: Progress in matching 5FS and 4FS:

FONLL scheme [Forte Napoletano Ubiali '15 '16]

SCET [Bonvini Papanastasiou Tackmann '15 '16]

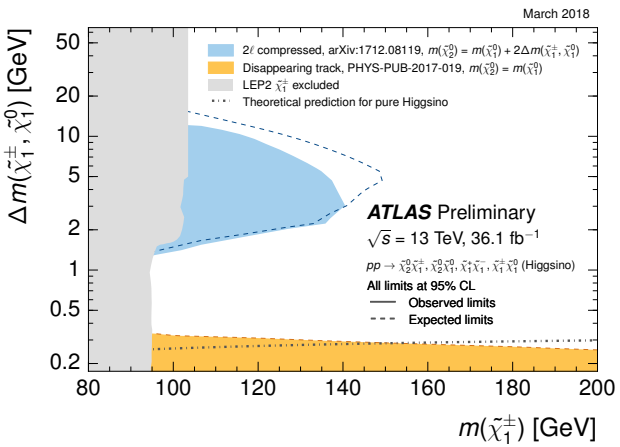


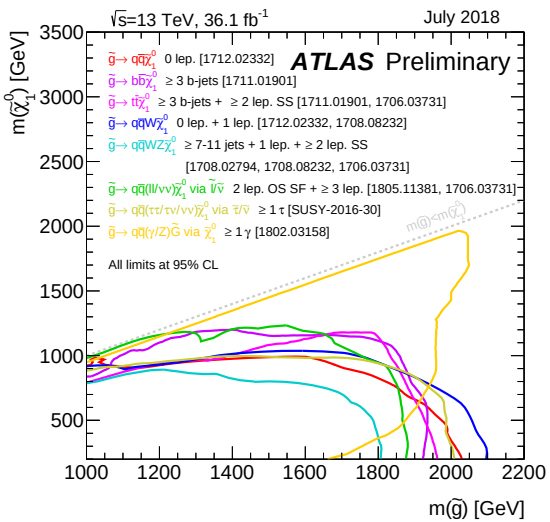


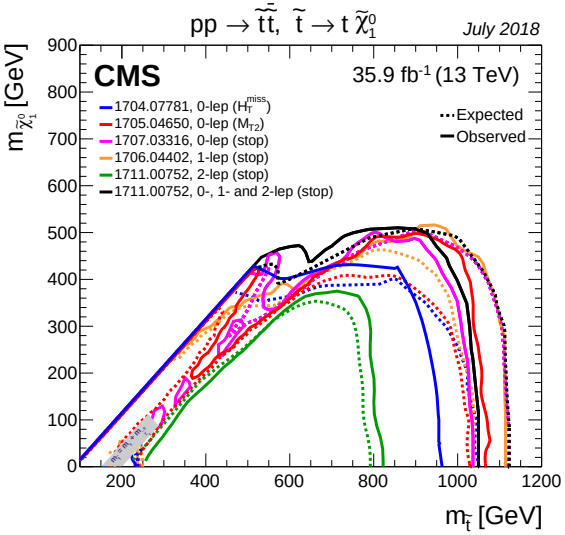
Matched predictions supersede Santander matched numbers.

FONLL-B = NLO+NNLL$_{\text{partial}}$

Why do we want to define new benchmark scenarios?
Technical and physical reason:
✓ Improvements in the calculation of the Higgs boson masses:
NLL and partial NNLL resummation of large logarithms in `FeynHiggs`
[Hahn et. al. '13; Bahl Hollik '16 '18; Bahl et al. '16 '17 '18]
$\rightarrow$ lowers m_h by a few GeV (even for TeV scale squarks)
✓ 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 $< 500\,\text{GeV}$







Suggested MSSM benchmark scenarios for the LHCHXSWG MSSM subgroup:

scenario	m_A [GeV]	$\tan\beta$	$\sqrt{s}$ [TeV]	authors
M_h^{125}	$70-2000$	$0.5-60$	$8, 13(, 14)$	[1808.07542]
$M_h^{125}(\tilde{\tau})$	$70-2000$	$0.5-60$	$8, 13(, 14)$	[1808.07542]
$M_h^{125}(\tilde{\chi})$	$70-2000$	$0.5-60$	$8, 13(, 14)$	[1808.07542]
M_h^{125}(alignment)	$100-1000$	$1-20$	$8, 13(, 14)$	[1808.07542]
M_H^{125}	$m_{H^\pm} = 150-200$	$5-6$	$8, 13(, 14)$	[1808.07542]
$M_{h_1}^{125}(\mathrm{CPV})$	$m_{H^\pm} = 120-1000$	$1-20$	$8, 13(, 14)$	[1808.07542]
hMSSM	$130-2000$	$1-60$	$8, 13(, 14)$	[Maiani et al. '13; Djouadi et al. '13 '15]
2HDM-EFT	$---$	$---$	$8, 13(, 14)$	[in progress]

[1808.07542 by Bahl, Fuchs, Hahn, Heinemeyer, Liebler, Patel, Slavich, Stefaniak, Wagner, Weiglein]

Strategy for the definition of new scenarios:

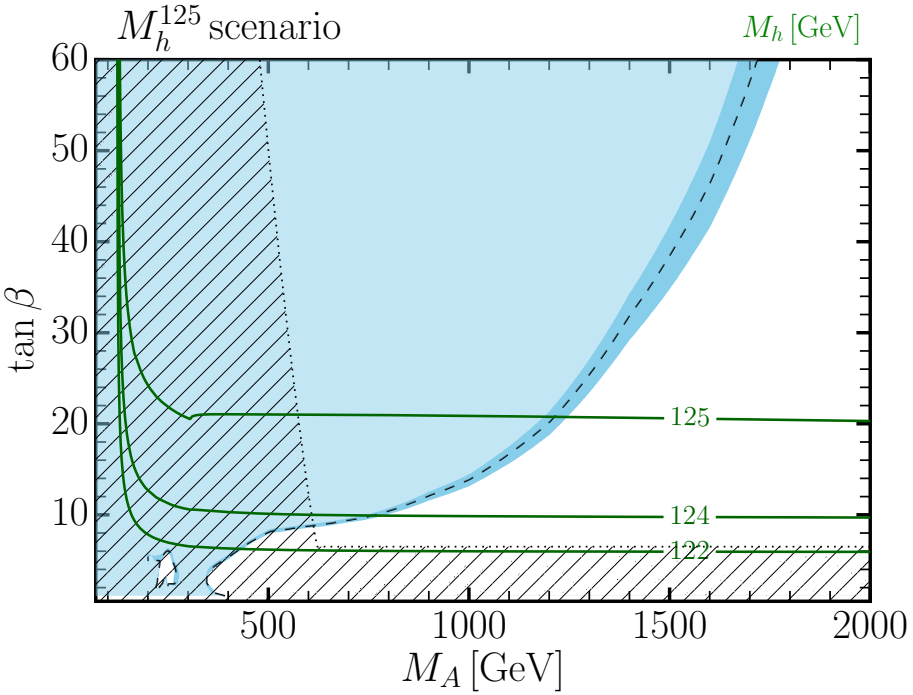
- ✓ Include SM-like Higgs with mass in the window 125 ± 3 GeV.
- ✓ Different phenomenological aspects relevant for MSSM Higgs physics:
  MSSM $\leftrightarrow$ 2HDM type II with (potentially) additional light particles.
  Light particles alter couplings of the SM-like Higgs.
  Light particles induce differences in the search for heavy Higgs bosons.
  CP violation in the Higgs sector through complex A_t.
- ✓ Provide a 2HDM-EFT scenario to be compared against the hMSSM.

What classic 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 ≥ 1 TeV $\Rightarrow$ No influence on BRs of Higgs bosons $m_\phi < 2$ TeV.

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

New setup used:
m_ϕ and BR: `FH 2.14.3` (tbr)
$gg\phi$: `SusHi 1.7.0` (tbr)
new $bb\phi$ XS (only Y_b^2)

Checked existing bounds with:
`HiggsBounds 5.2.0 beta`
(blue area, dashed contour)
`HiggsSignals 2.2.0 beta`
(shaded area, dotted contour)
(up to 13 TeV 36fb^{-1})



We suggest the subsequent scenarios:
Definition of classic scenarios (with SUSY < 2.5 TeV):
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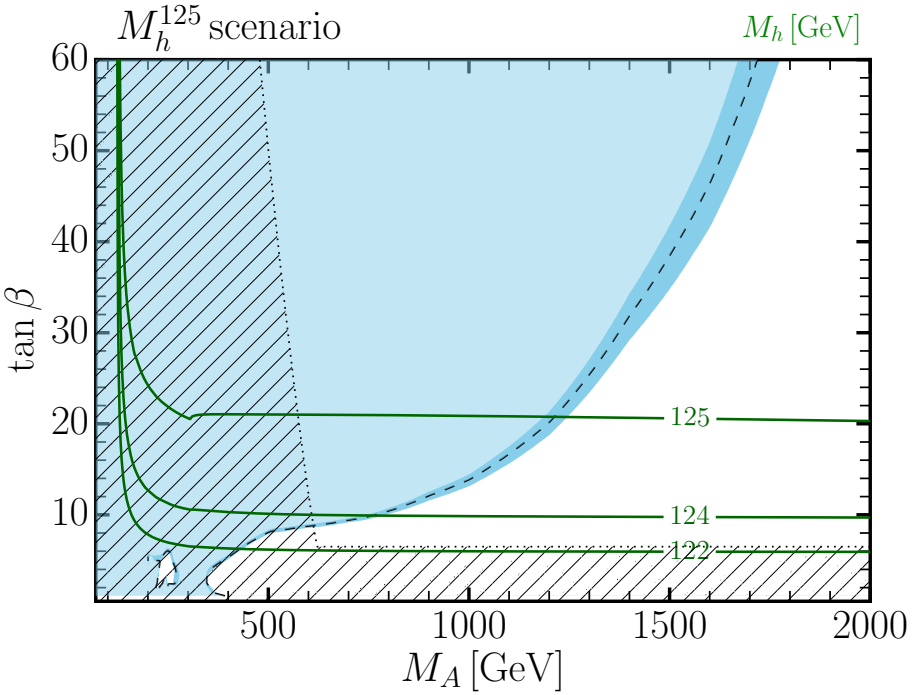
$$M_1 = 1\,\text{TeV}, \quad M_2 = 1\,\text{TeV}, \quad M_3 = 2.5\,\text{TeV}$$
$$X_t = 2.8\,\text{TeV}, \quad A_\tau = A_b = A_t\,.$$

Features:
Large value of μ:
Largest SUSY effect through
$\Delta_b \to 0.6$ for high $\tan\beta$
Δ_b decouples in light Higgs boson couplings.
Direct influence on heavy Higgs boson searches.



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 $\tan\beta$.

$$M_{\text{SUSY}} = 2\,\text{TeV}, \quad M_{Q_3} = M_{U_3} = M_{D_3} = 1.5\,\text{TeV}, \quad \mu = 1\,\text{TeV}$$
$$M_1 = 180\,\text{GeV}, \quad M_2 = 300\,\text{GeV}, \quad M_3 = 2.5\,\text{TeV}$$
$$M_{L_3} = 350\,\text{GeV}, \quad M_{E_3} = 350\,\text{GeV}$$
$$X_t = 2.8\,\text{TeV}, \quad A_b = A_t, \quad A_\tau = 800\,\text{GeV}\,.$$

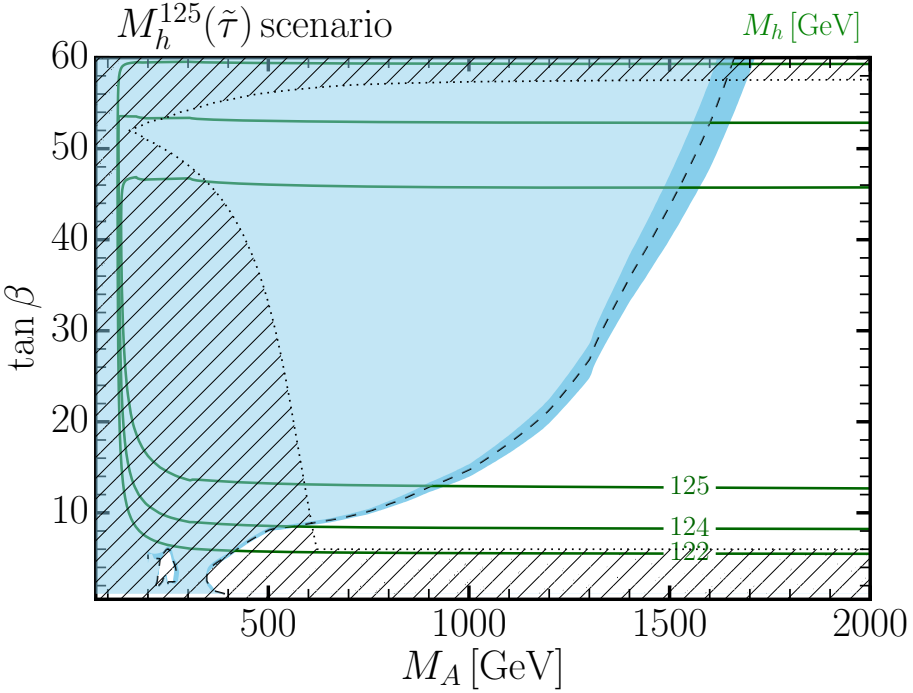
Main concern:
Light staus influence vacuum stability, fullfills naive bound:

[Nilles et al. '83, Alvarez-Gaume et al. '83, Claudson et al. '83, Derendinger et al. '84]

$$A_\tau^2 < 3(M_{H_d}^2 + \mu^2 + M_{L_3}^2 + M_{E_3}^2)$$

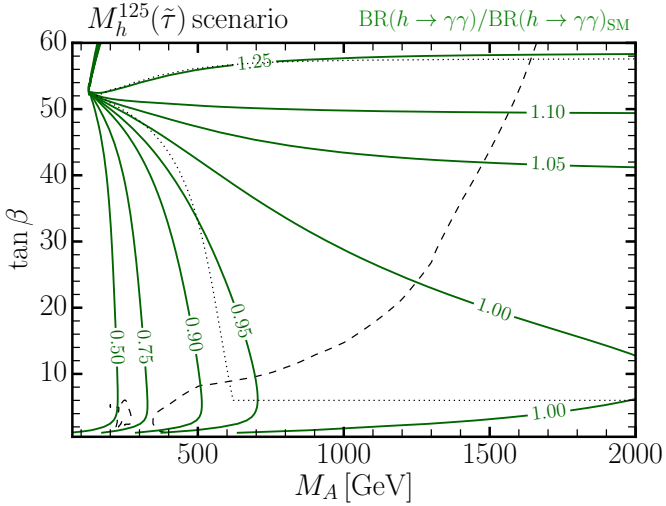
Checked with Vevacious:

[Camargo-Molina et al. '13 '14]

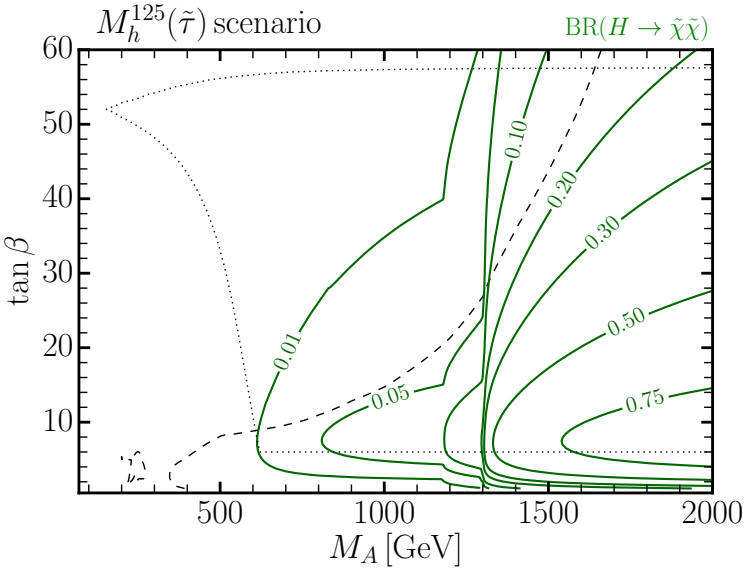


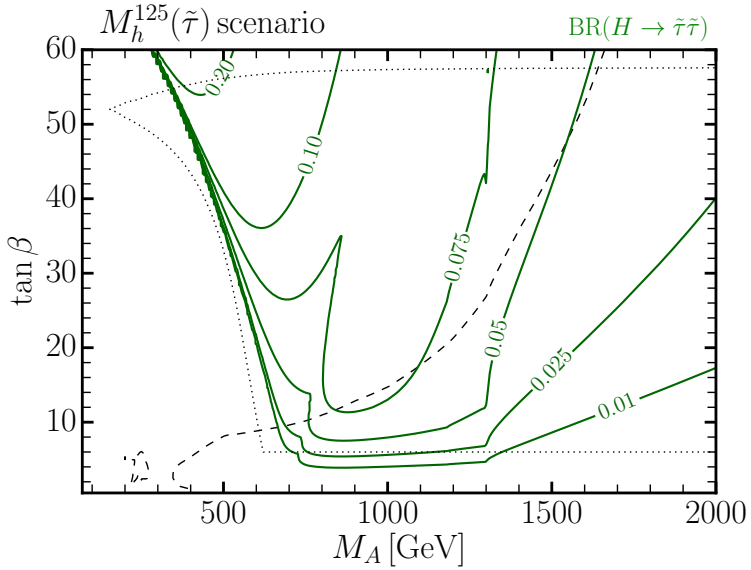
Definition of classic scenarios (with $\mathrm{SUSY} < 2.5\,\mathrm{TeV}$):

✓ $M_h^{125}(\tilde{\tau})$ scenario: Features of the scenario



Alignment without decoupling around
$\tan\beta = 52 \leftrightarrow \cos(\beta - \alpha) = 0$
Enhanced $\mathrm{BR}(h \to \gamma\gamma)$ at large $\tan\beta$
$\leftrightarrow$ testable through h couplings
$\mathrm{BR}(H \to \tilde{\tau}_i^+ \tilde{\tau}_j^-) < 0.2$ at large $\tan\beta$



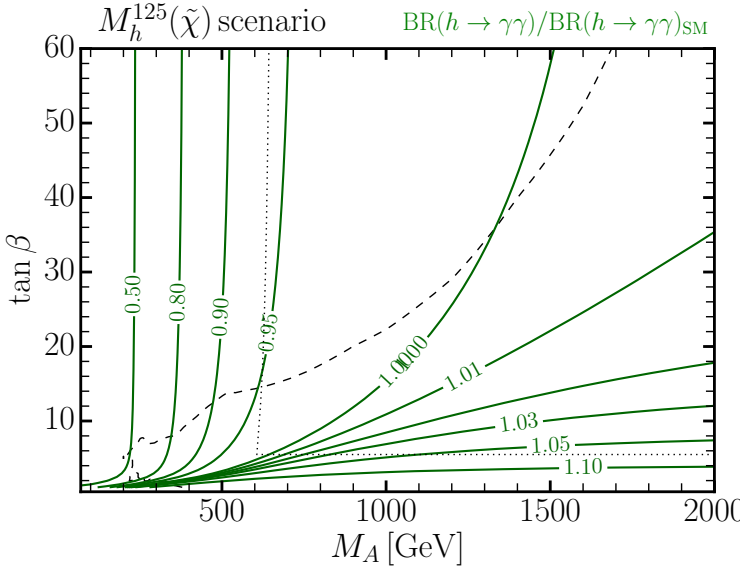


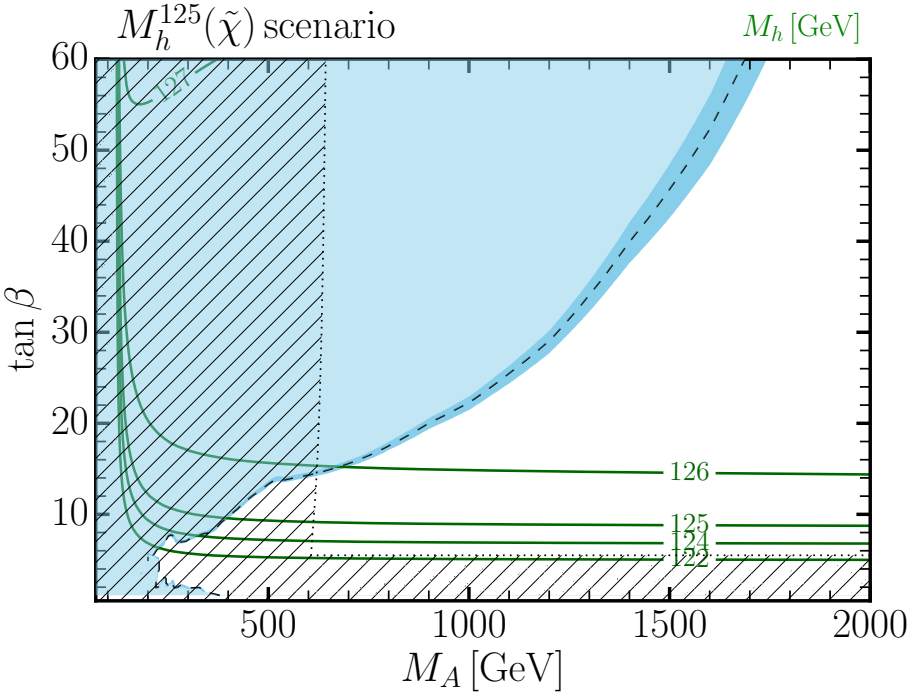
Definition of classic scenarios (with SUSY < 2.5 TeV):

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

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

Features: Enhanced BR$(h \to \gamma\gamma)$ at low $\tan\beta$.





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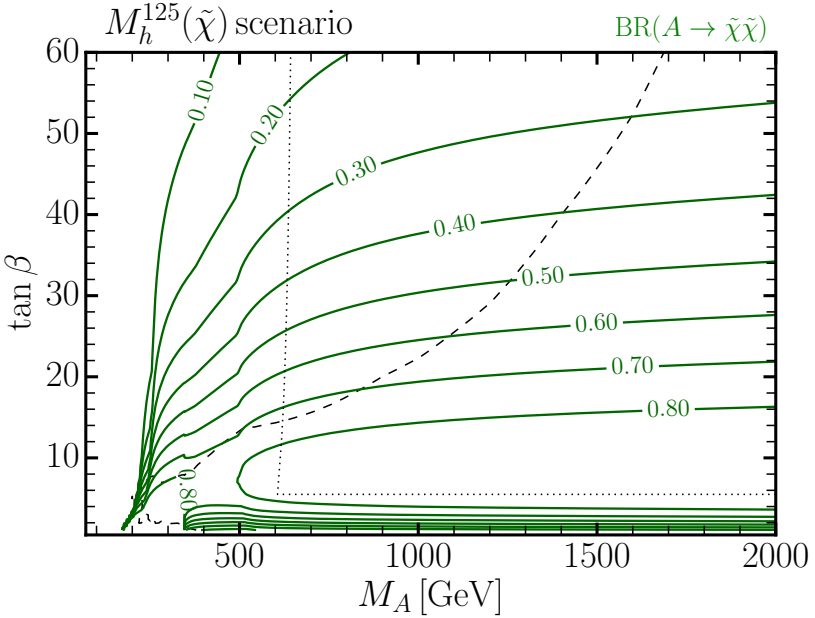
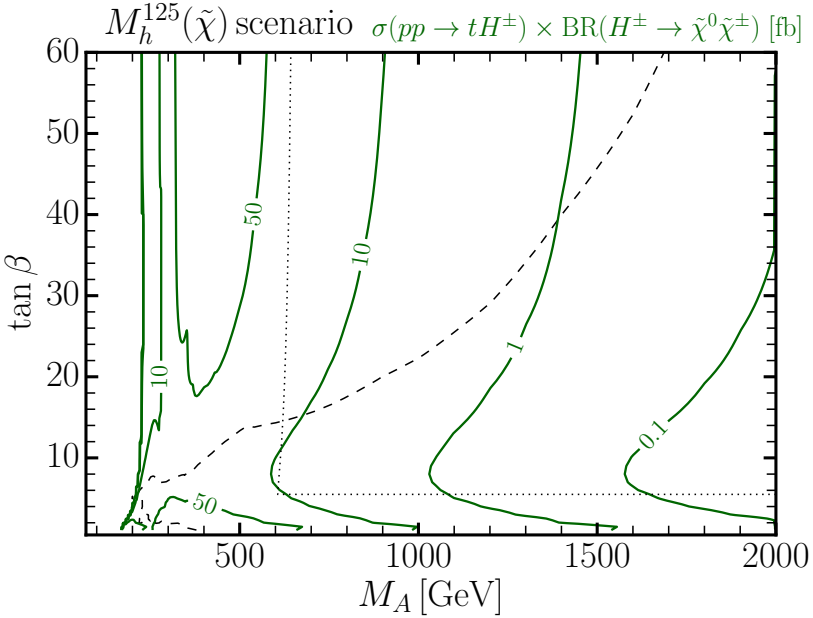
$$M_1 = 160\,\text{GeV}, \quad M_2 = 180\,\text{GeV}, \quad M_3 = 2.5\,\text{TeV}$$
$$X_t = 2.5\,\text{TeV}, \quad A_\tau = A_b = A_t\,.$$

Features: Enhanced BR$(h \to \gamma\gamma)$ at low $\tan\beta$.

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

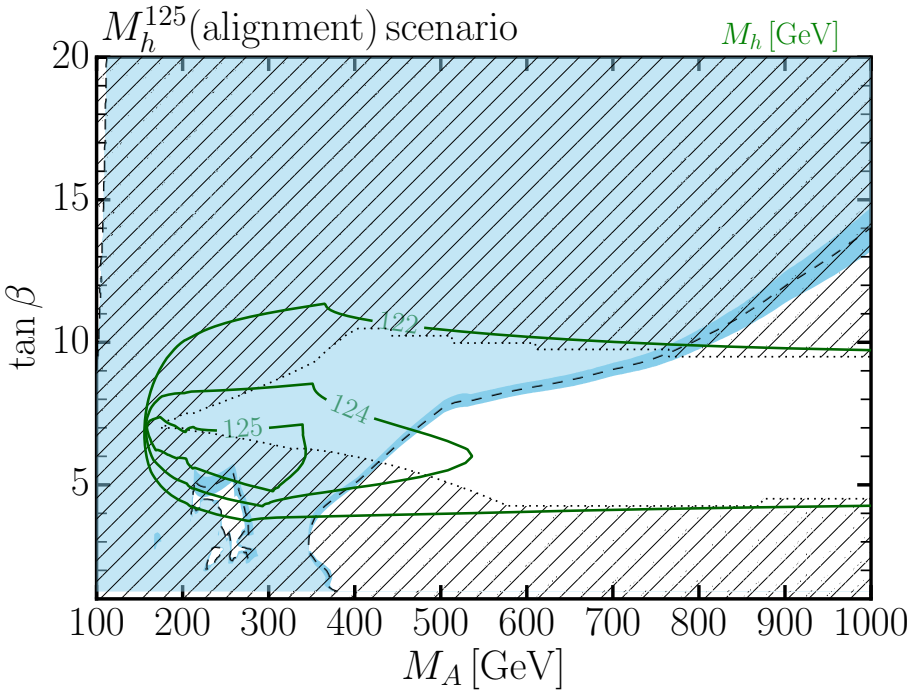




Two exotic scenarios: Alignment instead of decoupling.

✓ M_h^{125}(alignment) scenario:

$$M_{Q_3} = M_{U_3} = M_{D_3} = 2.5\,\text{TeV}$$
$$M_1 = 500\,\text{TeV},\ M_2 = 1\,\text{TeV},\ M_3 = 2.5\,\text{TeV}$$
$$\mu = 7.5\,\text{TeV}, \quad A_b = A_\tau = A_t = 6.25\,\text{TeV}.$$

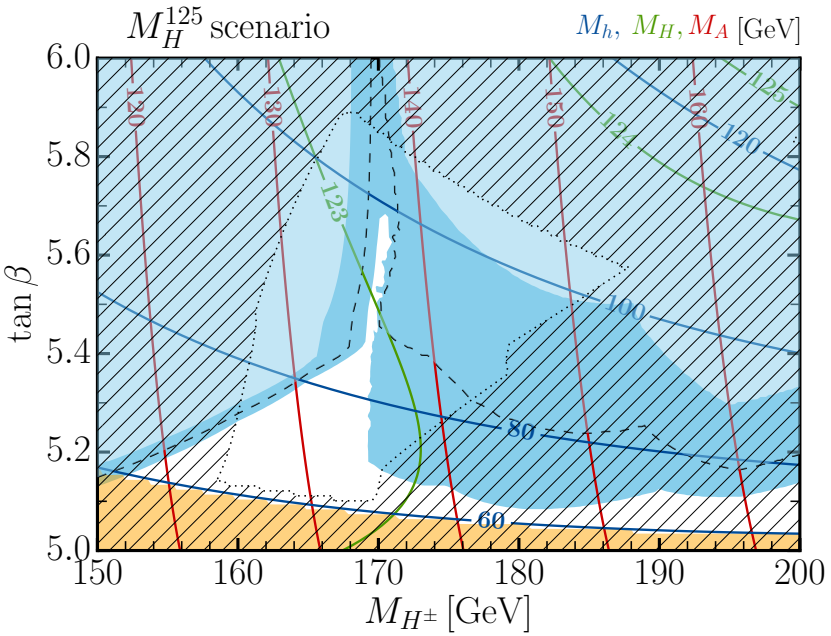


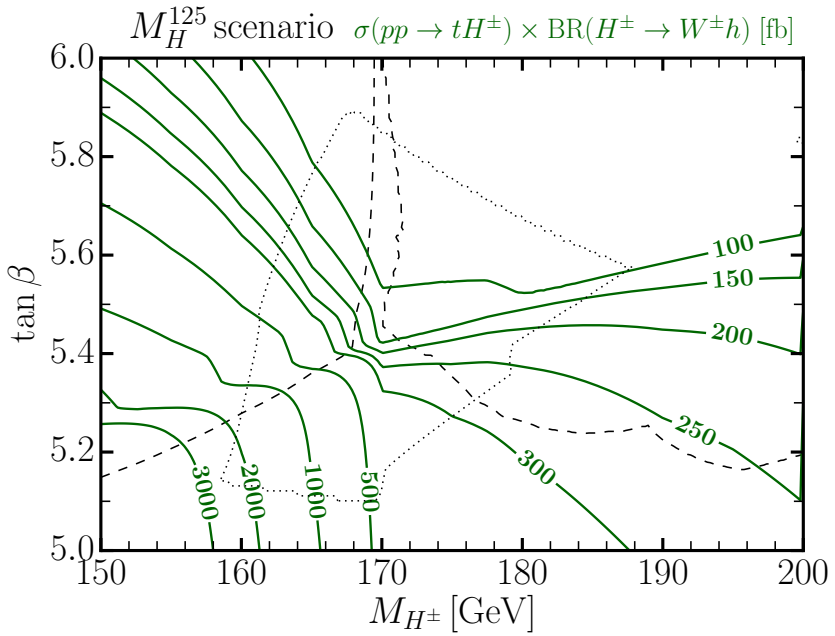
Both this and the following scenario are under tension from vacuum stability.

Two exotic scenarios: Alignment instead of decoupling.

✓ M_H^{125} scenario:

$$M_{Q_3} = M_{U_3} = M_{D_3} = 750\,\text{GeV} - 2\,(M_{H^\pm} - 150\,\text{GeV})$$
$$\mu = [5800\,\text{GeV} + 20\,(M_{H^\pm} - 150\,\text{GeV})]\; M_{Q_3}/(750\,\text{GeV})$$
$$M_1 = M_{Q_3} - 75\,\text{GeV}, \quad M_2 = 1\,\text{TeV}$$
$$M_3 = 2.5\,\text{TeV}, \quad A_t = A_b = A_\tau = 0.65 M_{Q_3}.$$





CP-violating scenario: ✓ M_h^{125}(CPV) scenario:
$\{h, H, A\}$ mix to three mass eigenstates h_i through phase in trilinear couplings A_f.

$$M_{\text{SUSY}} = 2\,\text{TeV}, \quad \mu = 1.65\,\text{TeV}, \quad M_1 = M_2 = 1\,\text{TeV}$$
$$M_3 = 2.5\,\text{TeV}, \quad |A_t| = \mu/\tan\beta + 2.8\,\text{TeV}$$
$$\phi_{A_t} = \tfrac{2\pi}{15}, \quad A_b = A_\tau = |A_t|$$

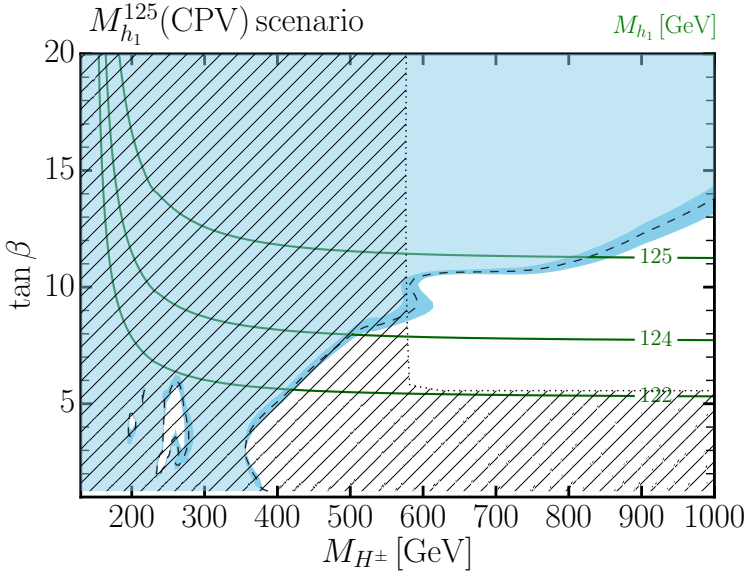
Checked compatibility with EDM bounds.
Stick to narrow-width approximation, but add interference factor (computed by `SusHi`):

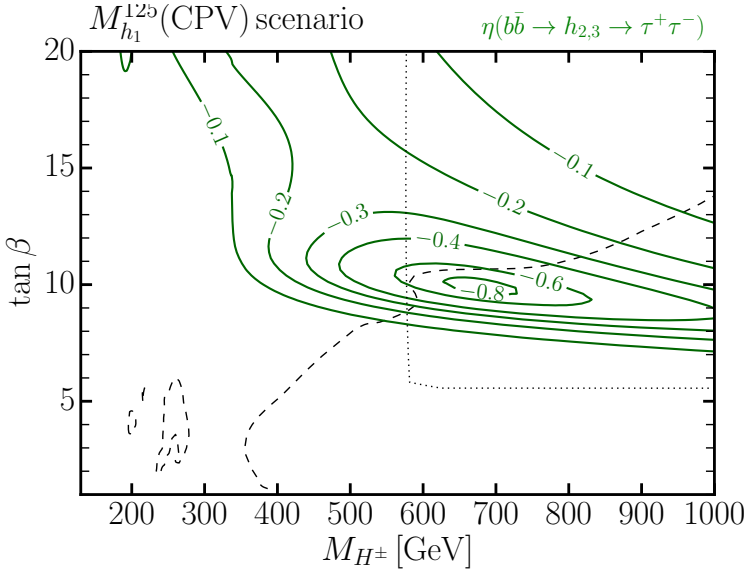
$$\eta_{\text{IF}} = \frac{2\text{Re}[A_{h_2} A_{h_3}^*]}{|A_{h_2}|^2 + |A_{h_3}|^2}$$

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

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

Based on studies by [Fuchs Weiglein '16 '17].





Outline

With this talk we suggest that the MSSM benchmark scenarios presented in [1808.07542] update the scenarios used in the MSSM subgroup.
We are open to receive further ideas/suggestions/recommendations!

Next steps:
ROOT files for the new benchmark scenarios should be delivered together with a common "LHCHXSWG official report" written by the MSSM subgroup and interested enthusiasts, which explains the content of the ROOT files and puts them into perspective.
When we are about to finalize the report we should have another public MSSM subgroup meeting.

Updates of the ROOT files will:
✗ use the matched $bb\phi$ predictions and include $\mathrm{N^3LO}$ precision for $gg \to \phi$.
✗ contain updated SM input.
✗ contain fragments to get p_T distributions.

Subsequently I list suggestions and wishes for what concerns the ROOT files that were expressed in the last 2 years.

Suggestions and wishes within the last two years (only if time permits):

✗ Martin Flechl: Provide numbers up to $m_A = 3$ TeV (for future projections).

✗ Jérémie Quevillon:
1. Provide cross sections at LO in order to get the k-factor.
2. Provide files for $\sqrt{s} = 27$ and 100 TeV (for future projections).

✗ David Englert: Abandon ROOT files and provide ASCII files instead.
↔ We have the tendency to stay with the ROOT files.

✗ CMS (Karlsruhe): Provide all cross sections for the Higgs bosons in order to make exclusions from the compatibility of the SM-like Higgs boson with the properties of the state at 125 GeV. We would need to add:
1. Cross sections for all production modes: VBF, VH, ttH.
2. Provide the corresponding cross sections for a SM Higgs of equal mass calculated at exactly the same(!) order to allow for proper normalizations.

Outline

Conclusions:

New MSSM benchmark scenarios are suggested:

✓ updated Higgs mass calculations to fit 125 ± 3 GeV.

✓ cover different interesting phenomenological aspcets of the MSSM.

Classic scenarios:

✓ M_h^{125}: MSSM/2HDM with moderately heavy SUSY (Δ_b)

✓ $M_h^{125}(\tilde{\tau})$: MSSM with light $\tilde{\tau}$ (BR$(h \to \gamma\gamma)$, $H/A \to \tilde{\tau}\tilde{\tau}$)

✓ $M_h^{125}(\tilde{\chi})$: MSSM with light $\tilde{\chi}$ ($H/A/H^{\pm} \to \tilde{\chi}_i\tilde{\chi}_j$)

✓ hMSSM: as before

New aspects:

✓ M_h^{125} (alignment): MSSM with lower values of m_A not excluded by 125 GeV

✓ M_H^{125}: MSSM with the heavy Higgs being the state at 125 GeV ($H^{\pm} \to W^{\pm}h$)

✓ $M_{h_1}^{125}$ (CPV): MSSM with CP violation and interference effects

All scenarios should be delivered in terms of new ROOT files together with a "LHCHXSWG official report"! We wait for a suggestion of a new 2HDM-EFT scenario to be compared against the hMSSM.

Waiting for your feedback! Thanks for your attention!