# Summary of MSSM group activities

16th Workshop of the LHCHXSWG | 17 October 2019

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# Outline

- Main tasks of the group:
  - Provide recommendations & guidance for neutral Higgs boson (h/H/A) predictions in the MSSM
  - Achieved by the definition of benchmark scenarios exhibiting relevant phenomenology, with predictions for masses, cross sections and branching ratios tabulated

- In 2018 new benchmark scenarios were published

- Main improvements included:
  - Updated SM parameters
  - $N^3LO$ for the light scalar $gg \rightarrow h$ and new $bb\varphi$ predictions
  - Improved calculations of Higgs boson masses from NLL and partial NNLL resummation of large logs in latest version of FeynHiggs [Hahn et. al. '13; Bahl Hollik '16 '18; Bahl et al. '16 '17 '18] $\Rightarrow$ **lowers $m_h$ by a few GeV**
  - Account for latest sparticle exclusions from the LHC

- Not all scenarios finalised this time last year - **review the progress today**

# Overview of benchmark scenarios

- Summary of new scenarios proposed and considered $m_A$, tanβ ranges:

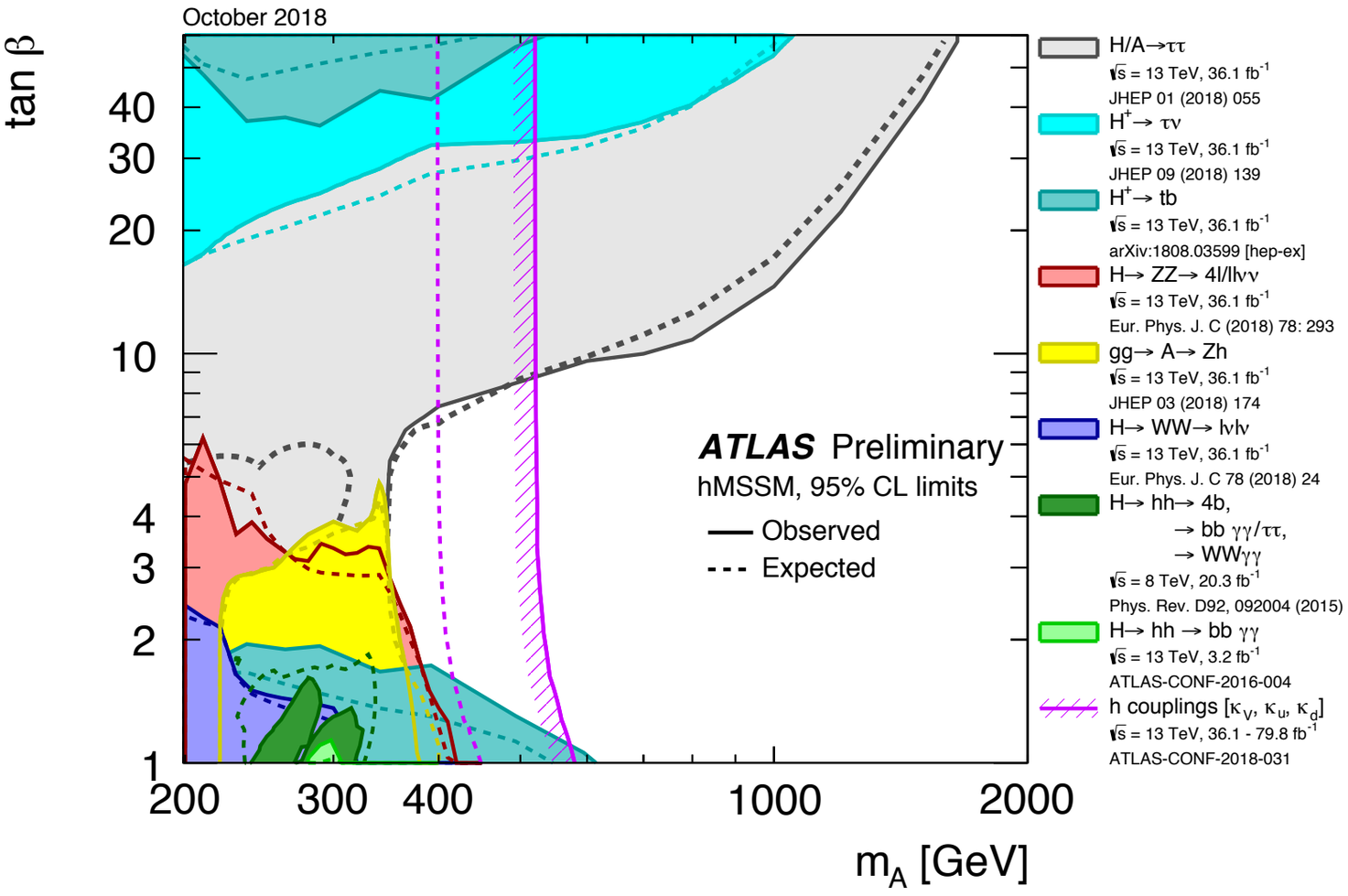
| scenario | $m_A$ [GeV] | $\tan\beta$ | $\sqrt{s}$[TeV] | ROOT files? | authors |
|---|---|---|---|---|---|
| $M_h^{125}$ | $70-2000$ | $0.5-60$ | $8, 13(, 14)$ | ✔ | [1808.07542] |
| $M_h^{125}(\tilde{\tau})$ | $70-2000$ | $0.5-60$ | $8, 13(, 14)$ | ✔ | [1808.07542] |
| $M_h^{125}(\tilde{\chi})$ | $70-2000$ | $0.5-60$ | $8, 13(, 14)$ | ✔ | [1808.07542] |
| $M_h^{125}$(alignment) | $100-1000$ | $1-20$ | $8, 13(, 14)$ | ✔ | [1808.07542] |
| $M_H^{125}$ | $m_{H^\pm} = 150-200$ | $5-6$ | $8, 13(, 14)$ | ✔ Coming soon! | [1808.07542] |
| $M_{h_1}^{125}$(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 | 70-3000 | 1-10 | $8, 13(, 14)$ | ✔ New! | [1901.05933 ] |

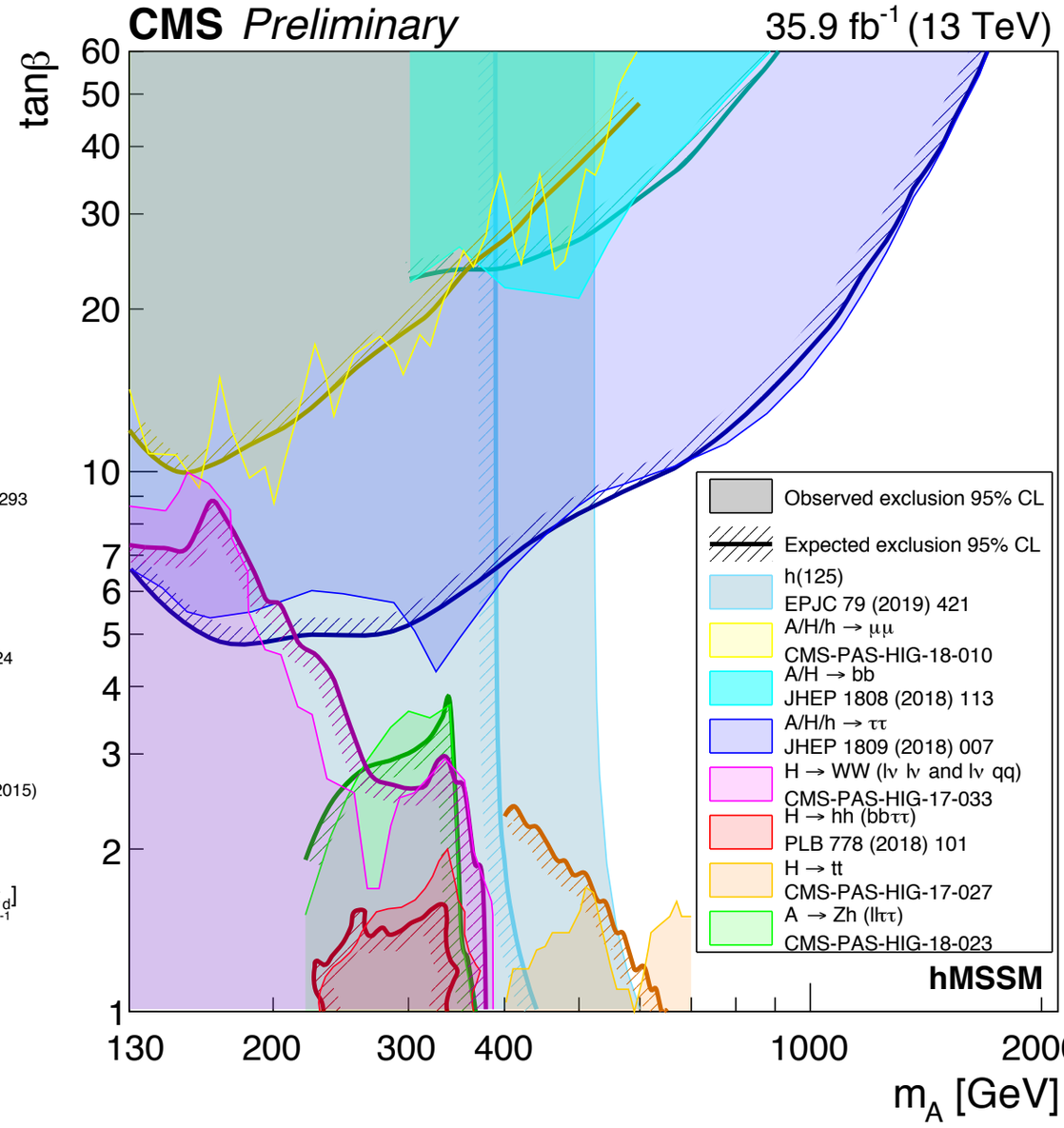
[1808.07542 by Bagnaschi, Bahl, Fuchs, Hahn, Heinemeyer, Liebler, Patel, Slavich, Stefaniak, Wagner, Weiglein]

- ROOT files on the twiki are recommended for use by the experiments
- Two new scenarios $M_{h,EFT}^{125}$ and $M_{h,EFT}^{125}(\tilde{\chi})$ proposed earlier in the year, ROOT files now available
  - Discussed today
- Remaining ROOT files will be available soon

# Experimental status

- Complementary constraints from direct search channels and indirectly via h(125) couplings
- High $m_A$ ,low tanβ region remains challenging

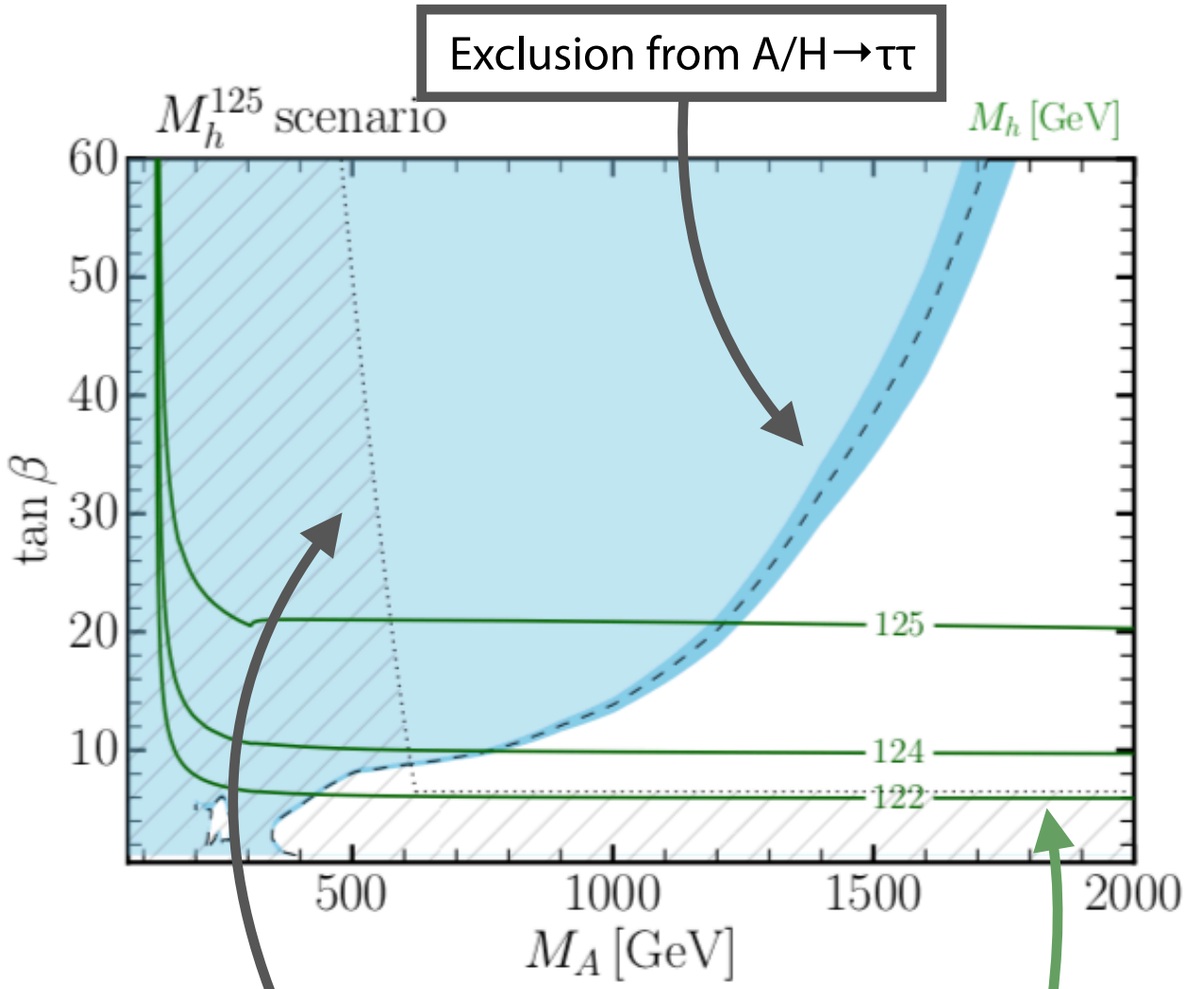


# $M_h^{125}$ scenario - Recap

- 2HDM-like Higgs sector with ≥ 1 TeV SUSY
  - Only decays to SM particles for $m_\varphi < 2$ TeV
  - Gluino and 3rd gen. squark masses above current LHC bounds
- Large value of μ ⇒ largest SUSY effect in correction of bottom quark Yukawa ($\Delta_b$) for high tanβ (~ 0.6)
- Current exclusion from direct heavy Higgs searches (HiggsBounds 5.2.0) and from light Higgs measurements (HiggsSignals 2.2.0) is shown

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

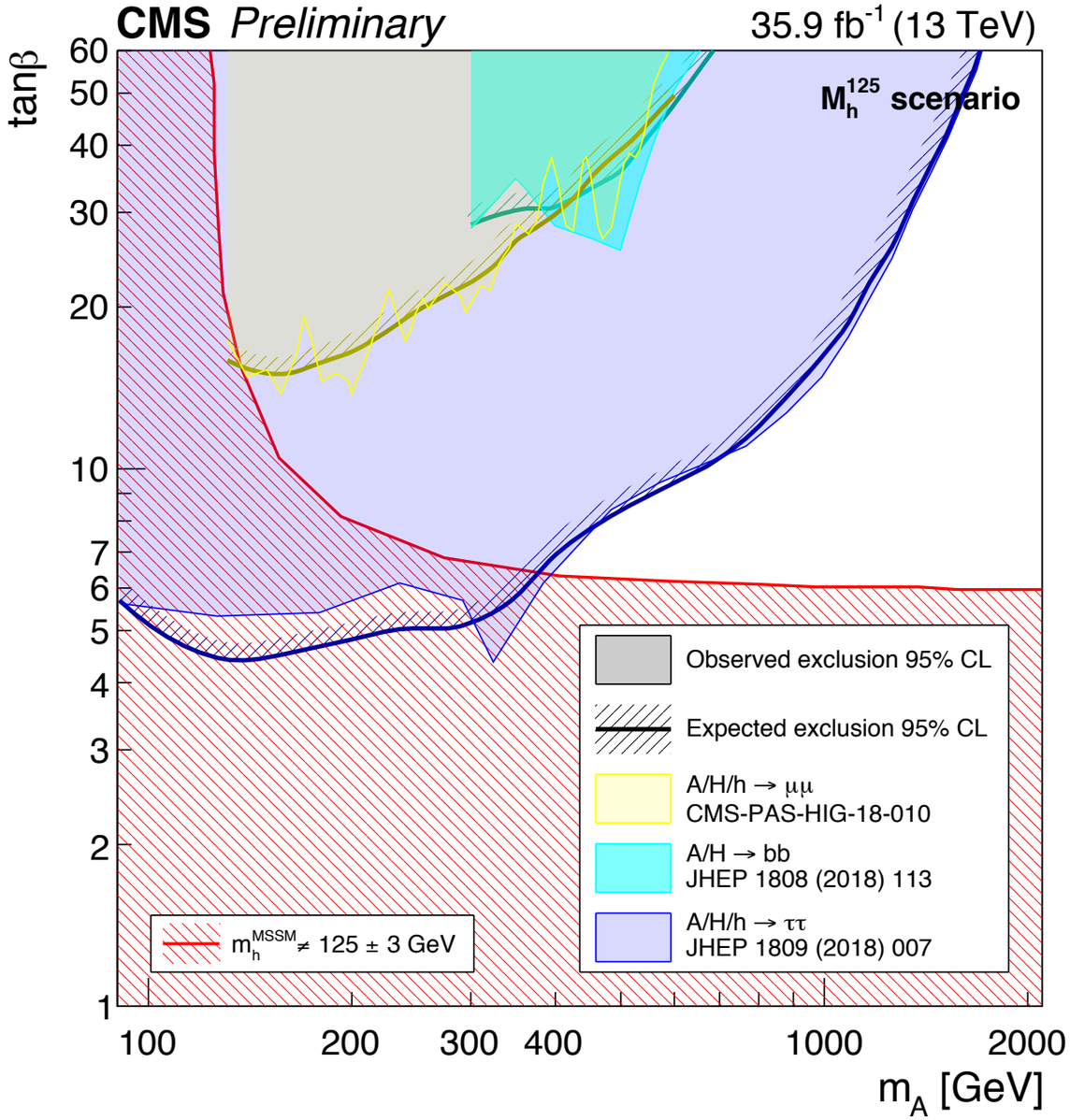


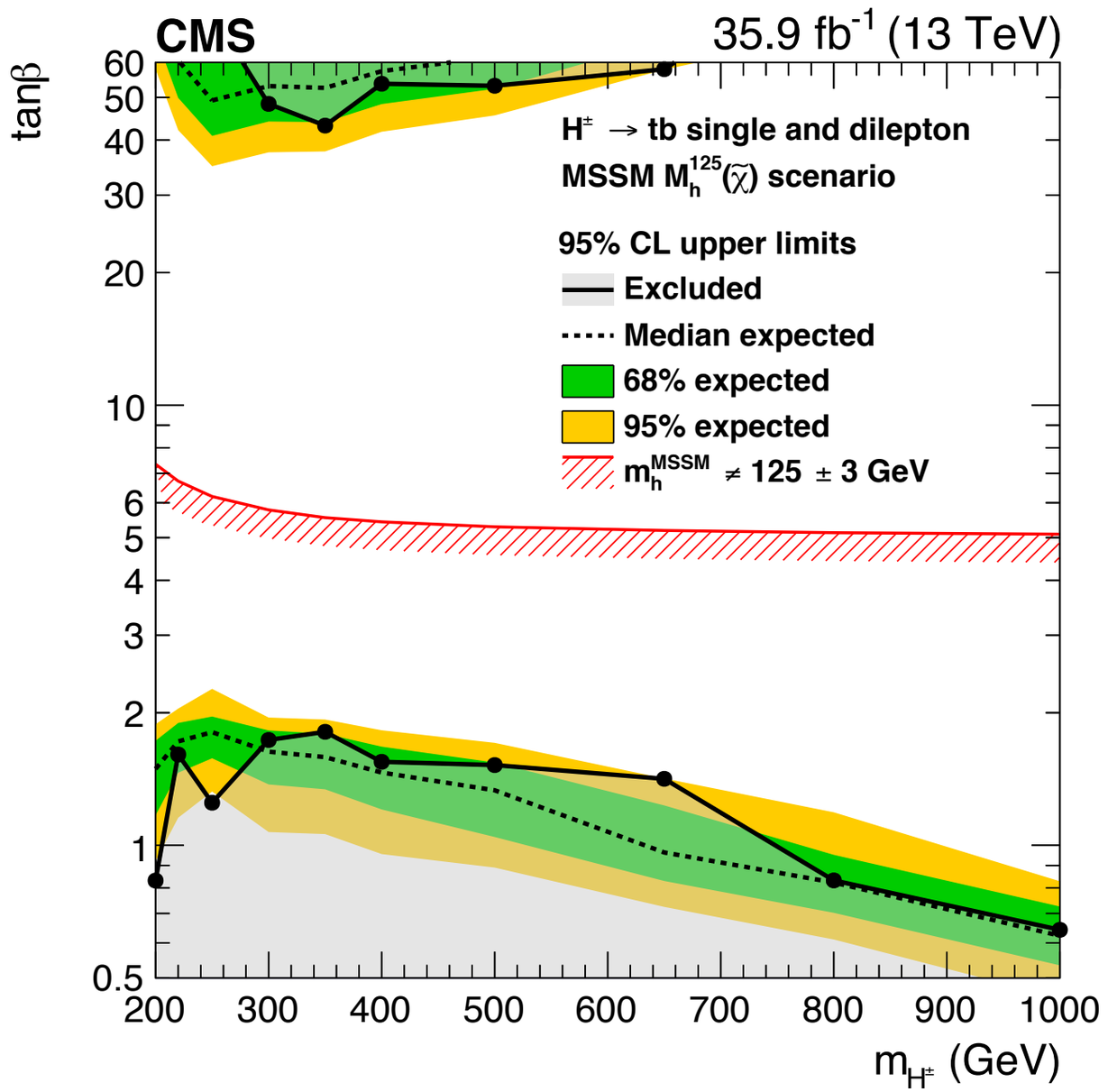

Hatched region ($m_A$ < 500-600 GeV) excluded by light Higgs coupling measurements

Compatibility with observed Higgs boson mass: require $M_h$ within 125 ± 3 GeV

# Results in new scenarios

- Plan is for full Run 2 search results to use the new scenarios almost exclusively
- Some partial dataset interpretations already available:

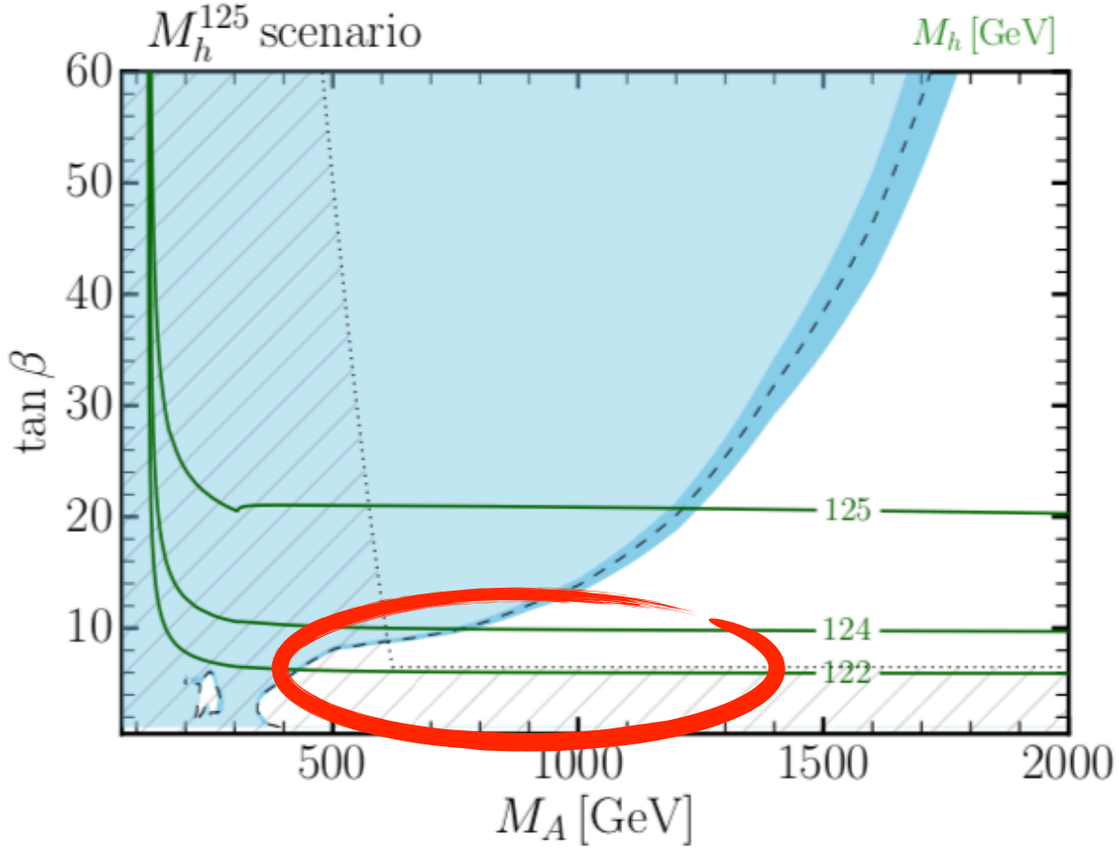


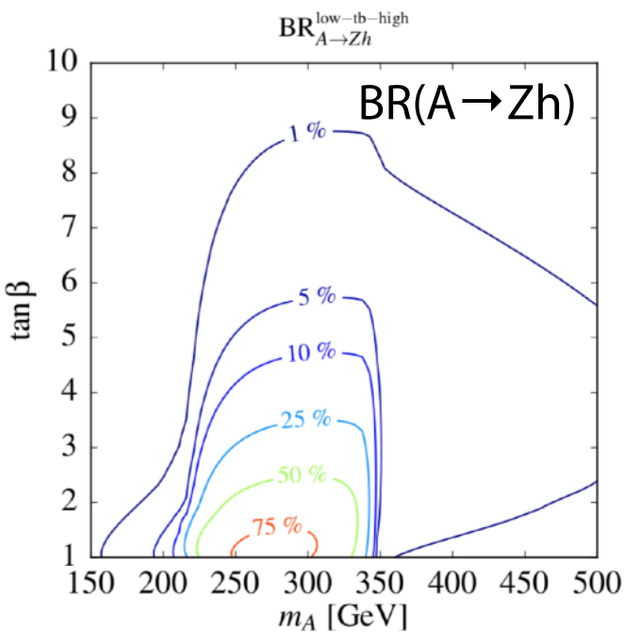



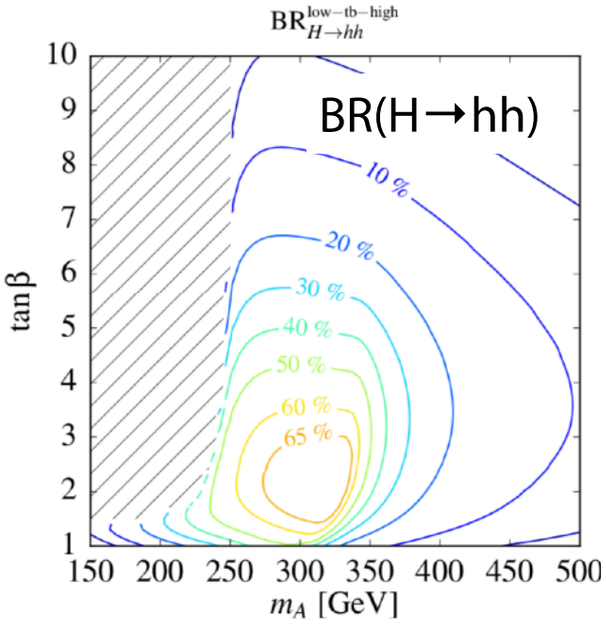
# EFT-based scenarios

- Motivation:
  - Low tanβ region interesting to probe: φ→ττ not sensitive, but other channels, e.g. H→hh, φ→tt, A→Zh open up
  - Challenge is that most scenarios do not predict $m_h \sim 125$ GeV in this region

- Two approaches have been considered so far:
  - **hMSSM** - fixes $m_h = 125$ GeV everywhere in $m_A$, tanβ - in turn fixes corrections to $m_h$ which, with assumptions, can be used to fix all mass and coupling properties
  - **low-tanβ-high** scenario [LHCHXSWG-2015-002]: increase $M_{SUSY}$ up to 100 TeV, based on SM EFT. Shown in subsequent work that $m_h$ still too low in parts of the parameter space



# $M_{h,EFT}^{125}$

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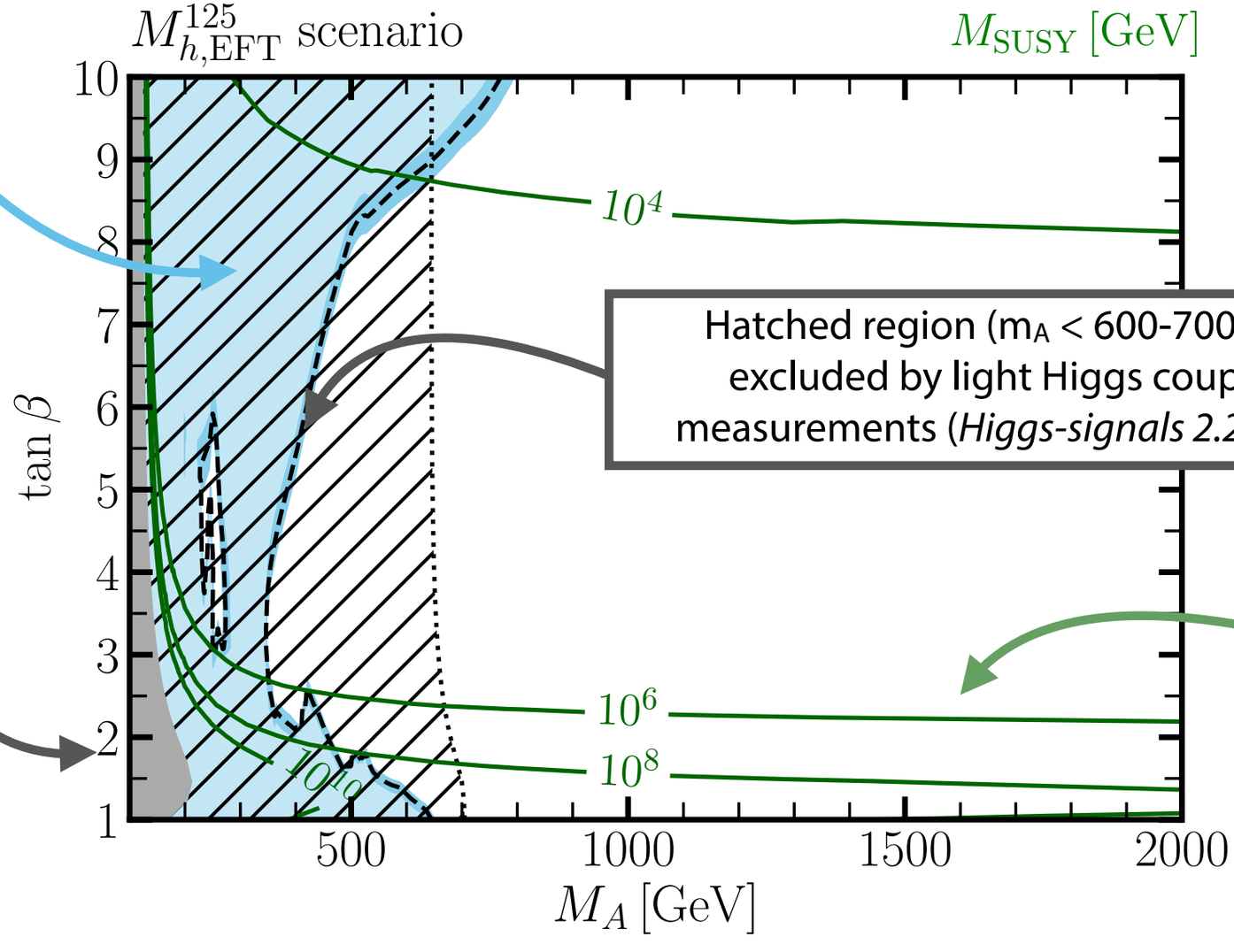
- Scenario based on 2HDM EFT with $M_{SUSY}$ up to $10^{16}$ GeV
  - All scalar fermion soft-SUSY breaking masses equal to $M_{SUSY}$

- All SUSY particles heavy ⇒ Phenomenology similar to a type-II 2HDM

$$m_t^{\text{pole}} = 172.5\ \text{GeV}, \quad \alpha_s(M_Z) = 0.118, \quad G_F = 1.16637 \cdot 10^{-5}\ \text{GeV}^{-2},$$
$$m_b(m_b) = 4.18\ \text{GeV}, \quad M_Z = 91.1876\ \text{GeV}, \quad M_W = 80.385\ \text{GeV}.$$




Exclusion from direct MSSM searches

Hatched region ($m_A$ < 600-700 GeV) excluded by light Higgs coupling measurements (*Higgs-signals 2.2.1beta*)

$m_h$ below 122 GeV

MSUSY needed for $m_h$ ~ 125 GeV

# $M_{h,EFT}^{125}(\tilde{\chi})$

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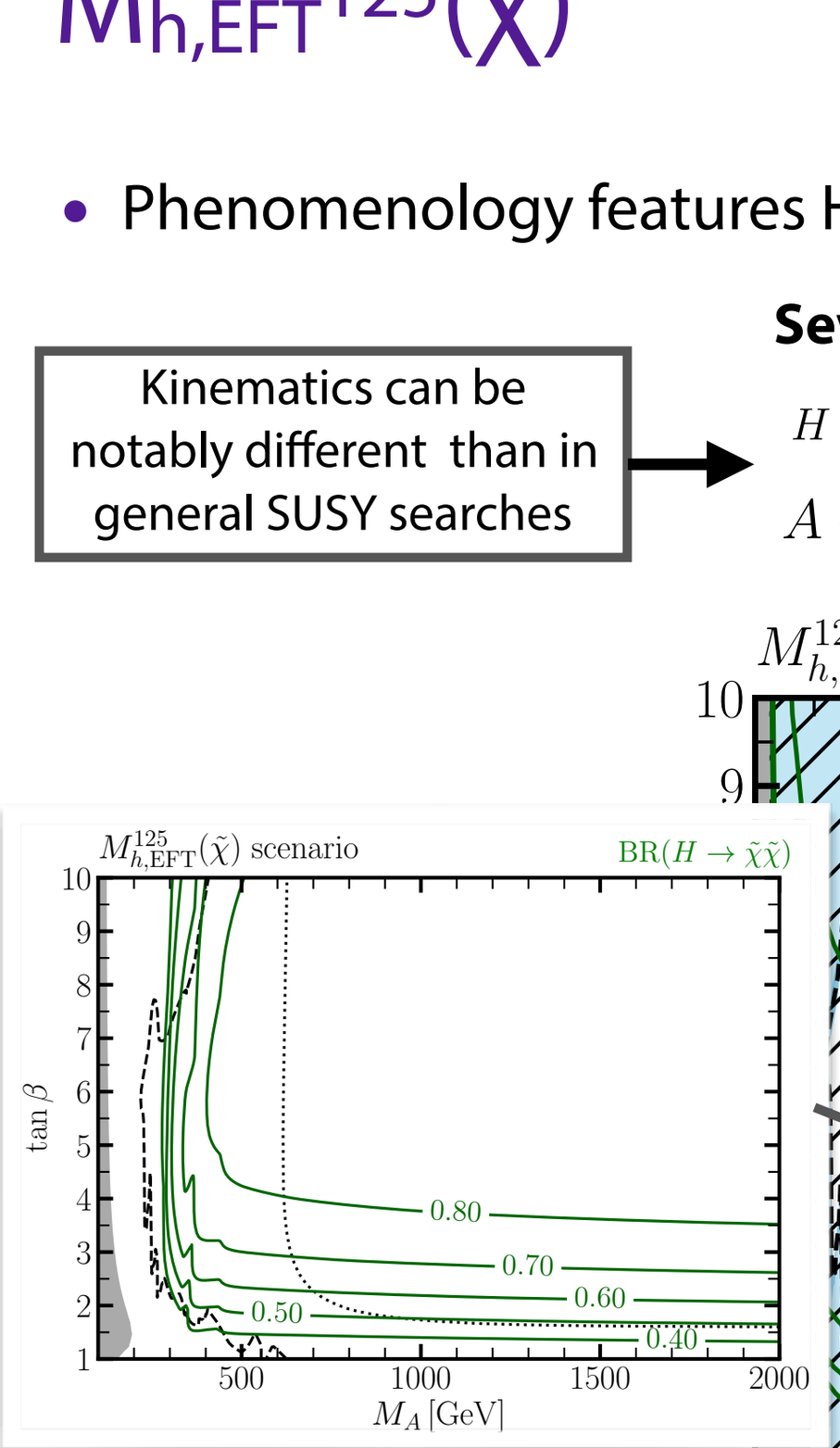
- Phenomenology features H and A decays to light neutralinos and charginos

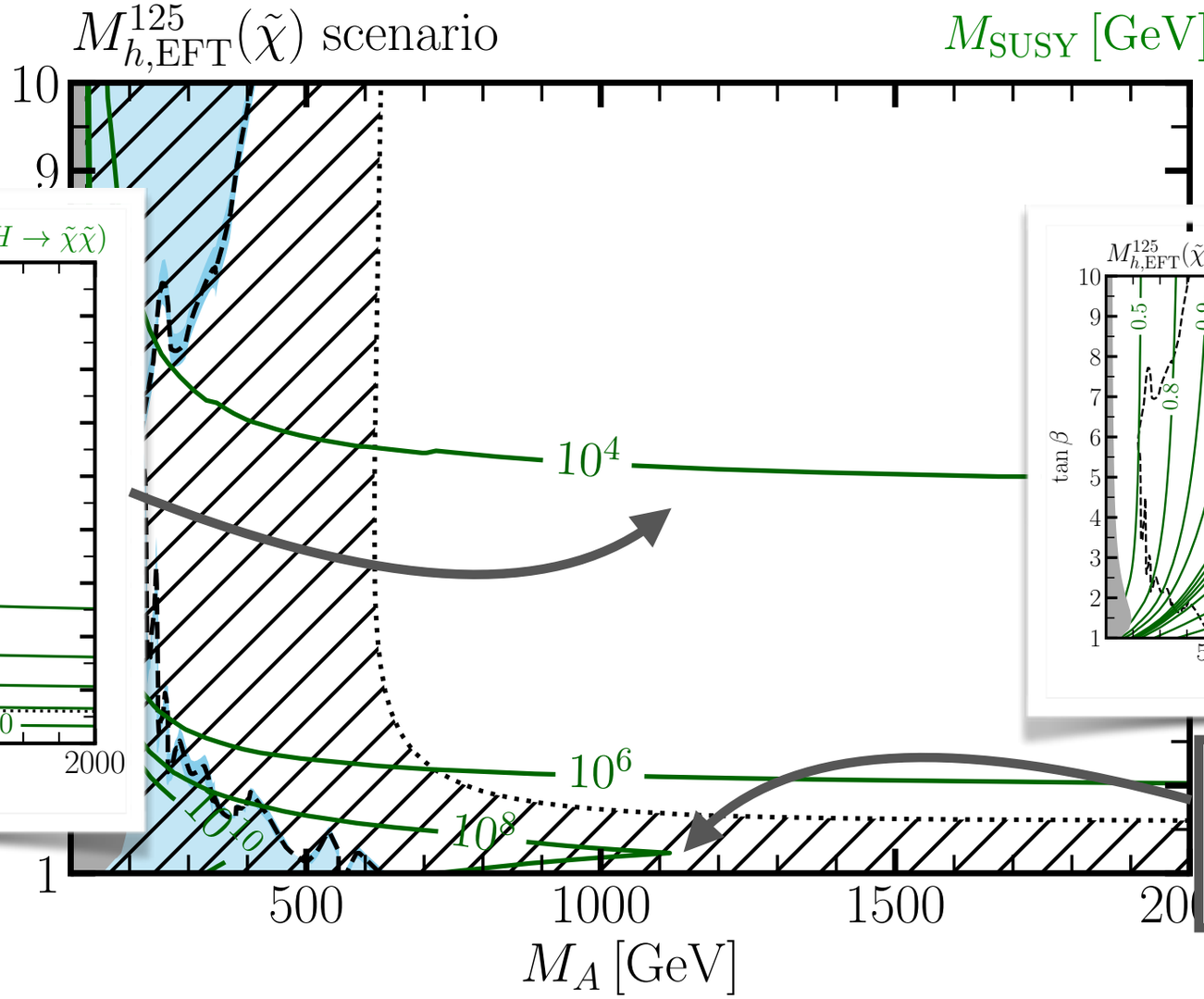
Kinematics can be notably different than in general SUSY searches

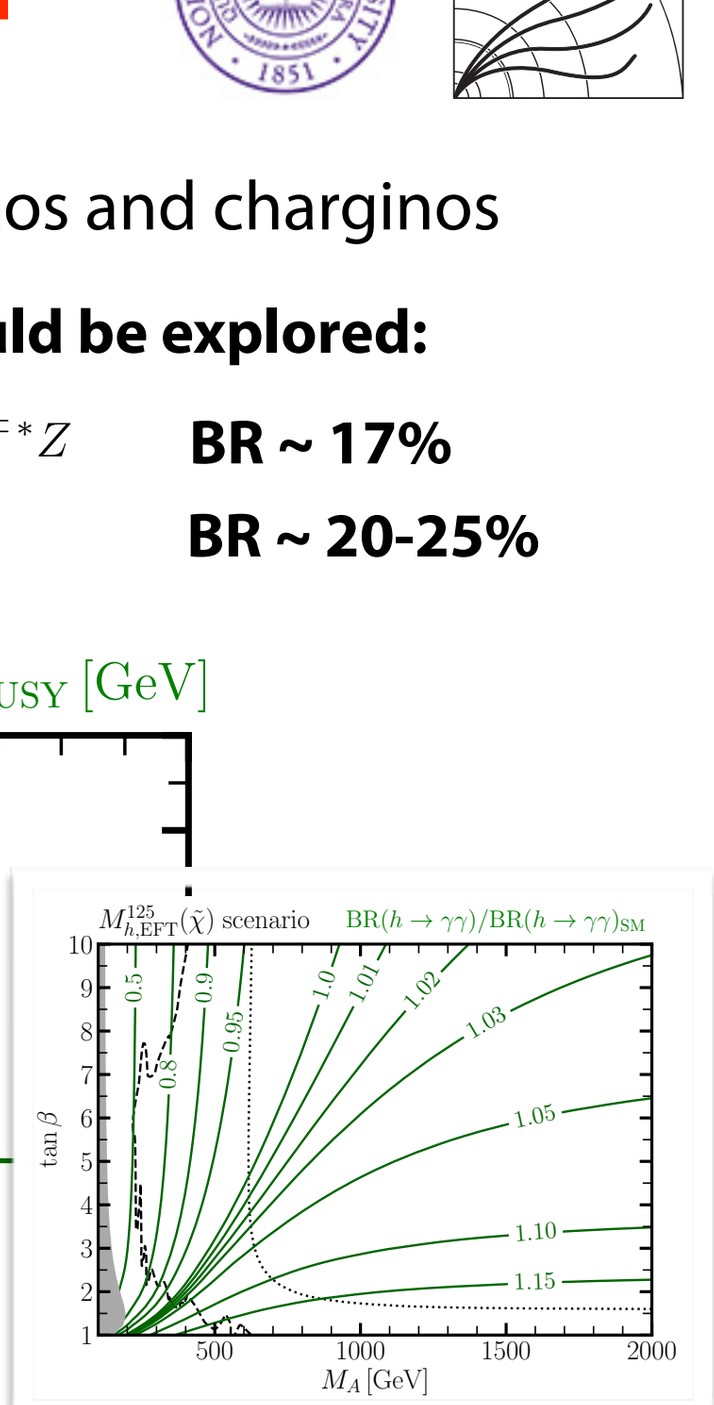
**Several promising channels that could be explored:**

$H \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp} \to (\tilde{\chi}_1 W^{\pm *})(\tilde{\chi}_1^{\mp} Z) \to \tilde{\chi}_1\tilde{\chi}_1 W^{\pm *} W^{\mp *} Z$ **BR ~ 17%**

$A \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} \to \tilde{\chi}_1\tilde{\chi}_1 W^{\pm *} W^{\mp *}$ **BR ~ 20-25%**



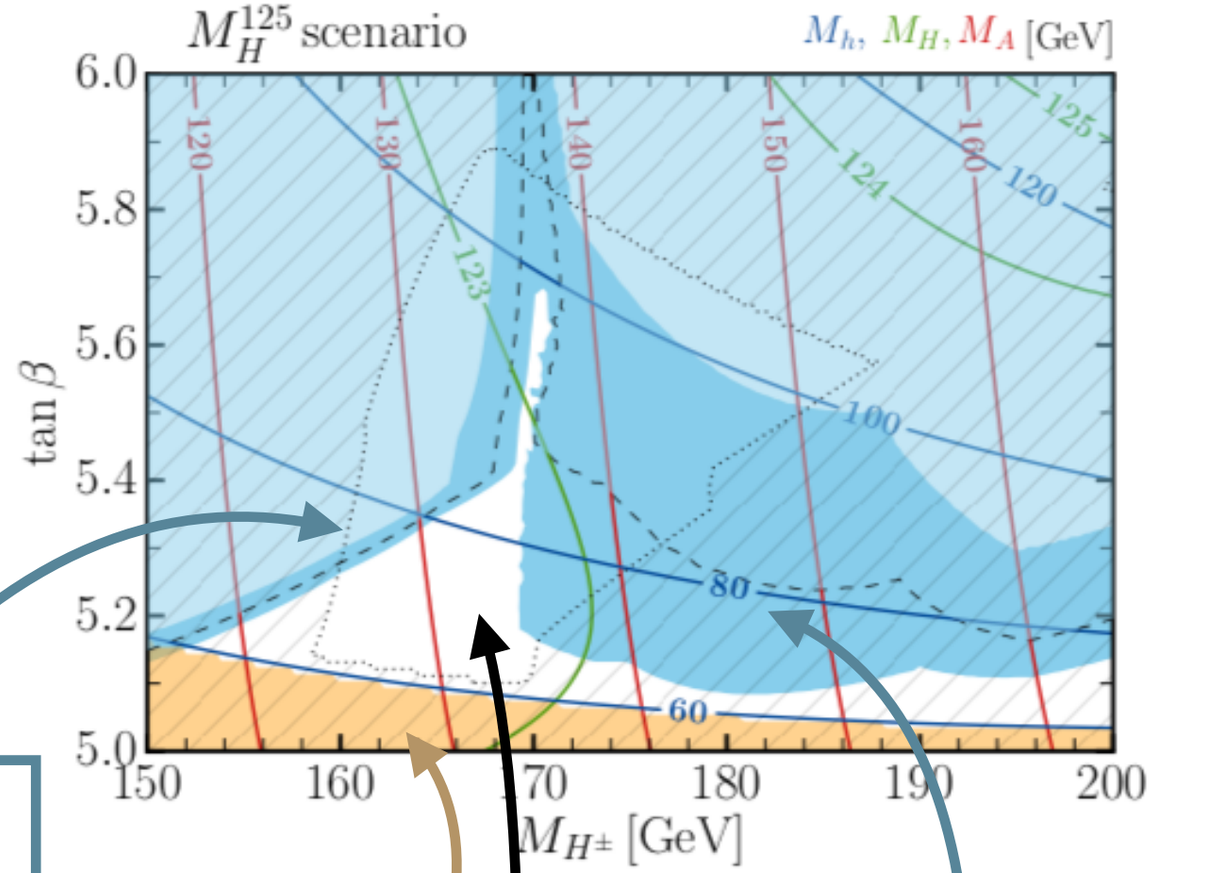




h→γγ enhanced by loop corrections from charginos at low tanβ

# $M_H^{125}$ scenario

- Scenario in which the heavier CP-even Higgs is SM-like
- Allowed region constrained by light $H^{+/-}$ searches, SM Higgs couplings and heavy neutral $A \to \tau\tau$ searches
  - Hatched regions accounts for contributions of h and A to SM rates when masses are within experimental resolution




Exclusion from H+→τν searches

Orange region excluded by H→hh

Exclusion from A→ττ searches

Decay $H^+ \to hW^+$ dominates in this region

$$M_{Q_3} = M_{U_3} = 750\,\text{GeV} - 2\,(M_{H^\pm} - 150\,\text{GeV})\,,$$

$$\mu = [5800\,\text{GeV} + 20\,(M_{H^\pm} - 150\,\text{GeV})]\;M_{Q_3}/(750\,\text{GeV})\,,$$

$$A_t = A_b = A_\tau = 0.65\,M_{Q_3}, \quad M_{D_3} = M_{L_3} = M_{E_3} = 2\ \text{TeV}\,,$$

$$M_1 = M_{Q_3} - 75\,\text{GeV}, \quad M_2 = 1\ \text{TeV}, \quad M_3 = 2.5\,\text{TeV}\,.$$

# Status of the ROOT files

- Models are linked from the twiki page:
  - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGMSSMNeutral
  - Citation guide for analysts is also provided - please check this carefully if you make use of the scenarios!

- $M_h^{125}$
  - mh125_8.root: 8 TeV, tanβ= 0.5-60, mA = 70-2600 GeV
  - mh125_13.root: 13 TeV, tanβ= 0.5-60, mA = 70-2600 GeV
  - mh125_14.root: 14 TeV, tanβ= 0.5-60, mA = 70-2600 GeV
- $M_h^{125}(\tilde \chi)$
  - mh125_lc_8.root: 8 TeV, tanβ= 0.5-60, mA = 70-2600 GeV
  - mh125_lc_13.root: 13 TeV, tanβ= 0.5-60, mA = 70-2600 GeV
  - mh125_lc_14.root: 14 TeV, tanβ= 0.5-60, mA = 70-2600 GeV
- $M_h^{125}(\tilde\tau)$
  - mh125_ls_8.root: 8 TeV, tanβ= 0.5-60, mA = 70-2600 GeV
  - mh125_ls_13.root: 13 TeV, tanβ= 0.5-60, mA = 70-2600 GeV
  - mh125_ls_14.root: 14 TeV, tanβ= 0.5-60, mA = 70-2600 GeV
- $M_h^{125}$(alignment)
  - This scenario yields a SM-like Higgs boson h also for low values of mA at about tanβ=7 due to alignment. In contrast to the definition in arXiv:1808.07542 the ROOT files start only at mA > 120 GeV due to a theoretically inaccessible region at low mA < 120 GeV and tanβ>10.
  - mh125_align_8.root: 8 TeV, tanβ= 1-20, mA = 120-1000 GeV
  - mh125_align_13.root: 13 TeV, tanβ= 1-20, mA = 120-1000 GeV
  - mh125_align_14.root: 14 TeV, tanβ= 1-20, mA = 120-1000 GeV

- $M_{h,\text{EFT}}^{125}$
  - mh125EFT_8.root: 8 TeV, tanβ= 1-10, mA = 70-3000 GeV
  - mh125EFT_13.root: 13 TeV, tanβ= 1-10, mA = 70-3000 GeV
  - mh125EFT_14.root: 14 TeV, tanβ= 1-10, mA = 70-3000 GeV
- $M_{h,\text{EFT}}^{125}(\tilde \chi)$
  - mh125EFT_lc_8.root: 8 TeV, tanβ= 1-10, mA = 70-3000 GeV
  - mh125EFT_lc_13.root: 13 TeV, tanβ= 1-10, mA = 70-3000 GeV
  - mh125EFT_lc_14.root: 14 TeV, tanβ= 1-10, mA = 70-3000 GeV

- Access tools (C++/python) are provided to make extracting numerical values straightforward

# Planned developments

- Remaining ROOT files will be added to the twiki soon
  - All to be updated to include specific sparticle decay branching ratios - currently only the sum available
- A revised hMSSM scenario is well motivated
  - Update with the most recent SM input parameters
  - Proposal to include one-loop top-quark corrections to the trillinear Higgs self-coupling [1810.10979]
  - Motivates a detailed comparison of H→hh BR between EFT and this improved hMSSM approach
- A variant of the $M_h^{125}$ scenario with opposite sign μ is of interest for the A/H→bb channel
  - Δb correction then enhances the Hbb and Abb coupling instead of suppressing them
  - Further studies are ongoing to find a combination of MSSM parameters that maximizes the ratio of the Hbb coupling to the Htautau coupling
- A XSWG note will be prepared to detail the scenarios and how the predictions have been determined
- **Timeline**: end of 2019 - start of 2020

# Summary

- Significant progress on finalising the new scenarios proposed in arXiv:1808.07542 and arXiv:1901.05933

- In particular the EFT-based scenario ROOT files are now available
  - $M_H^{125}$ expected very soon
  - Phenomenology of decays to charginos and neutralinos explored in detail

- A long-standing goal is also to provide ROOT files which give the gluon fusion A/H pT spectrum as a function of $m_A$, tanβ (see backup)
  - We hope to attract new interest in completing this from within CMS and ATLAS

# Backup

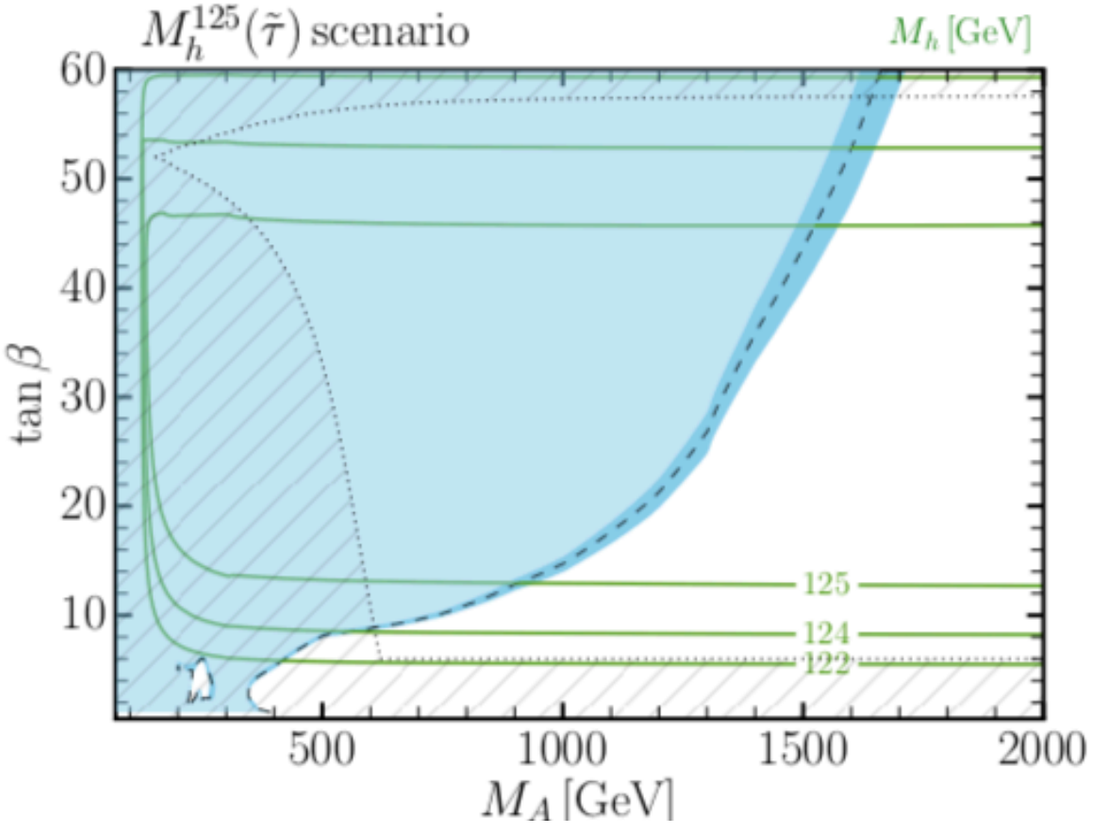
# $M_h^{125}$ ($\tilde{\tau}$) scenario

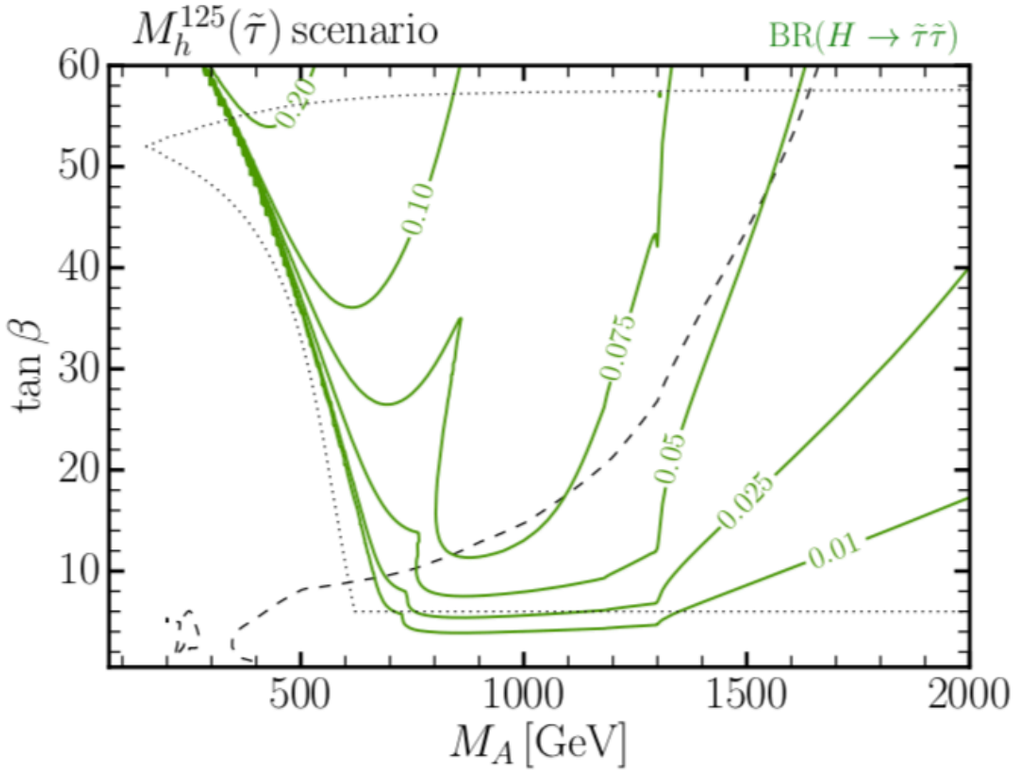
- Scenario with light staus
  - Allows for BR(H/A→$\tilde{\tau}\tilde{\tau}$) ~ 10-20% for high tanβ, decays to SM particles reduced
  - Modifies h→γγ branching ratio, enhanced at high tanβ

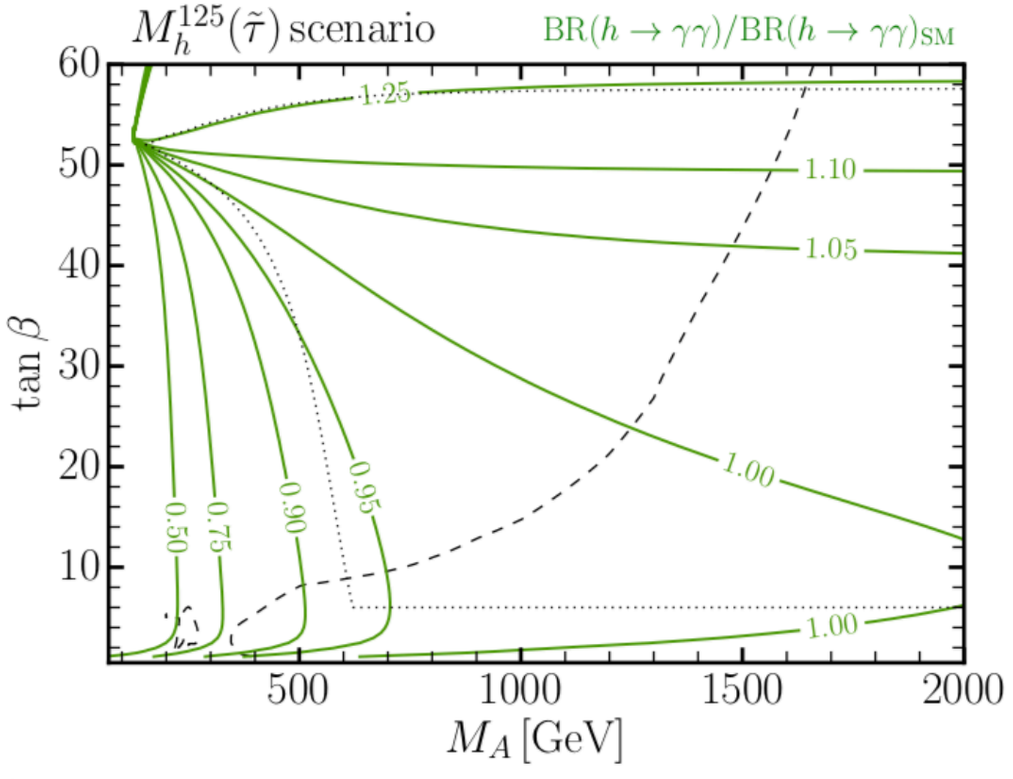
$$M_{Q_3} = M_{U_3} = M_{D_3} = 1.5 \text{ TeV}, \quad M_{L_3} = M_{E_3} = 350 \text{ GeV},$$

$$\mu = 1 \text{ TeV}, \quad M_1 = 180 \text{ GeV}, \quad M_2 = 300 \text{ GeV}, \quad M_3 = 2.5 \text{ TeV},$$

$$X_t = 2.8 \text{ TeV}, \quad A_b = A_t, \quad A_\tau = 800 \text{ GeV}.$$



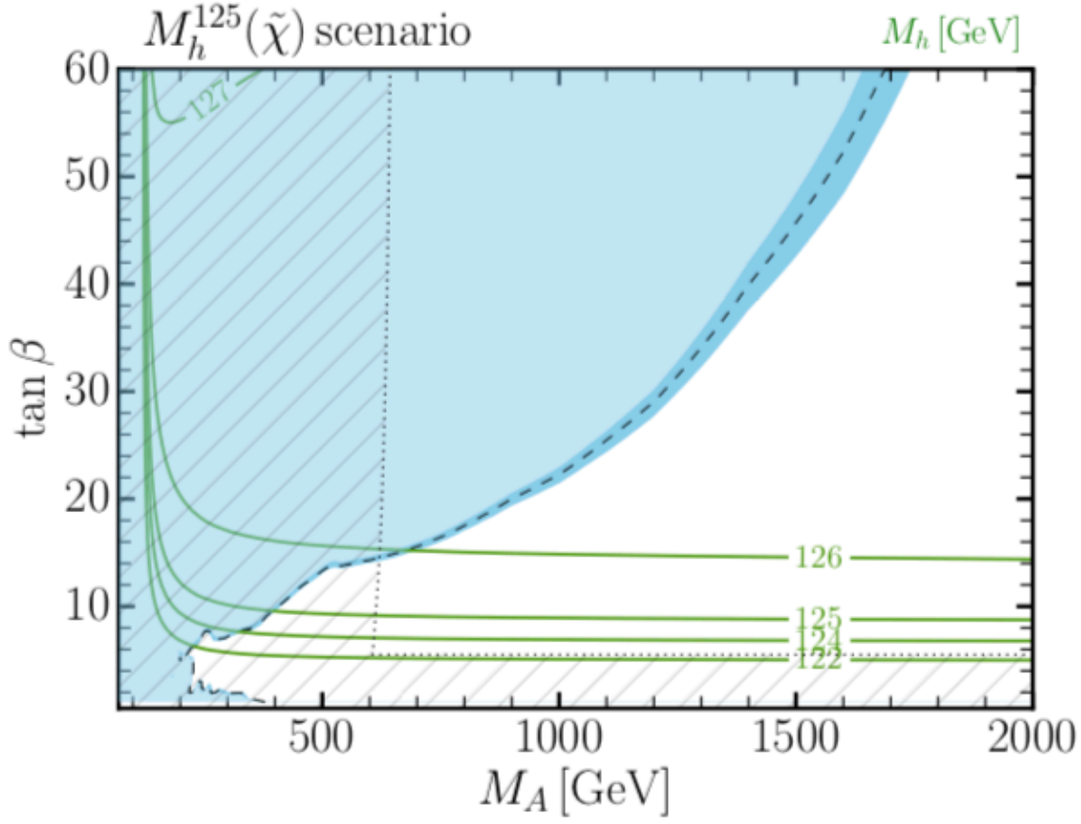



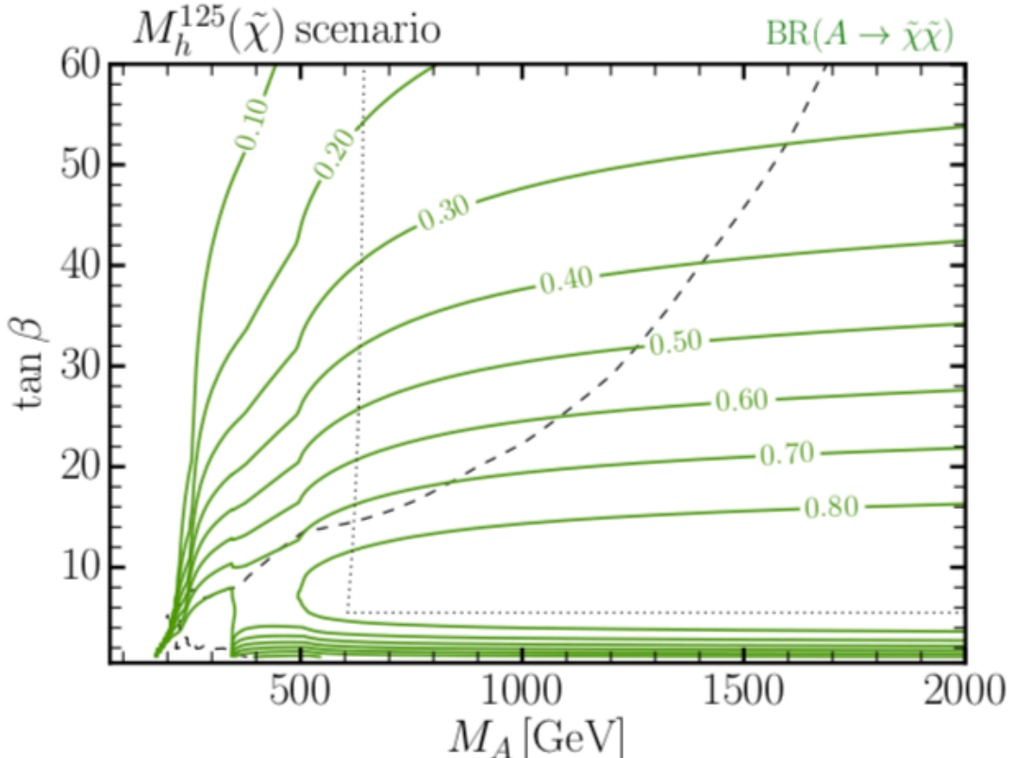



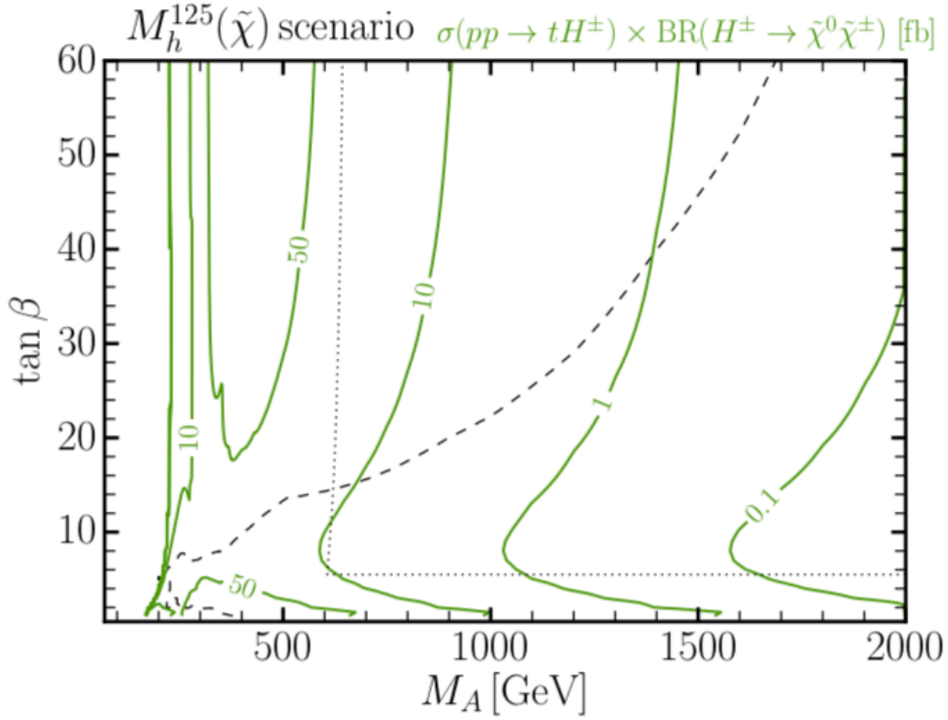
# $M_h^{125}$ ($\tilde{\chi}$) scenario

- Scenario with light electroweakinos
  - Opens significant BR(H/A→$\tilde{\chi}_i\tilde{\chi}_j$), up to 80% for $m_A$ > 500 GeV and 5 < tanβ < 10
  - $H^+ \to \tilde{\chi}^0\tilde{\chi}^+$ can be a dominant channel for $M_{H^+}$ > 600 GeV, but experimentally challenging

$$M_{Q_3} = M_{U_3} = M_{D_3} = 1.5 \text{ TeV}, \quad M_{L_3} = M_{E_3} = 2 \text{ TeV},$$
$$\mu = 180 \text{ GeV}, \quad M_1 = 160 \text{ GeV}, \quad M_2 = 180 \text{ GeV}, \quad M_3 = 2.5 \text{ TeV},$$
$$X_t = 2.5 \text{ TeV}, \quad A_b = A_\tau = A_t .$$

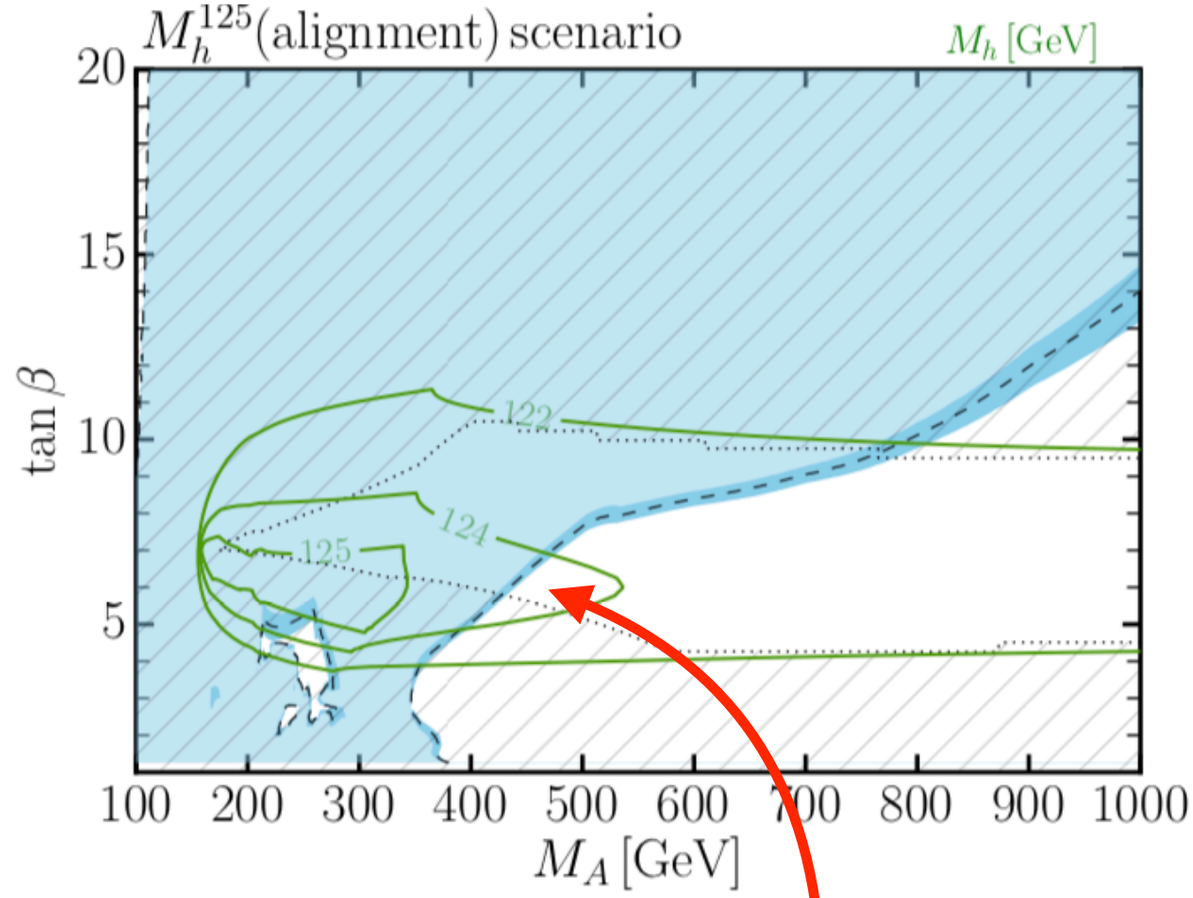


# $M_h^{125}$ (alignment) scenario

- In a general 2HDM the alignment limit, where one Higgs has SM-like couplings, usually features decoupling:
  - Lightest CP-even h associated with SM Higgs
  - Other Higgs bosons significantly heavier
- Scenarios proposed that feature alignment ***without*** decoupling
- This version keeps the SM-like Higgs as h
- Under tension from vacuum stability




Wedge-like region around tanβ ≈ 7 where alignment occurs
⇒ $m_A$ down to ~ 430 GeV still viable

$$M_{Q_3} = M_{U_3} = M_{D_3} = 2.5 \text{ TeV}, \quad M_{L_3} = M_{E_3} = 2 \text{ TeV},$$
$$\mu = 7.5 \text{ TeV}, \quad M_1 = 500 \text{ GeV}, \quad M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV},$$
$$A_t = A_b = A_\tau = 6.25 \text{ TeV}.$$

# CP-violating scenario

*Fuchs, Weiglein '16 '17*

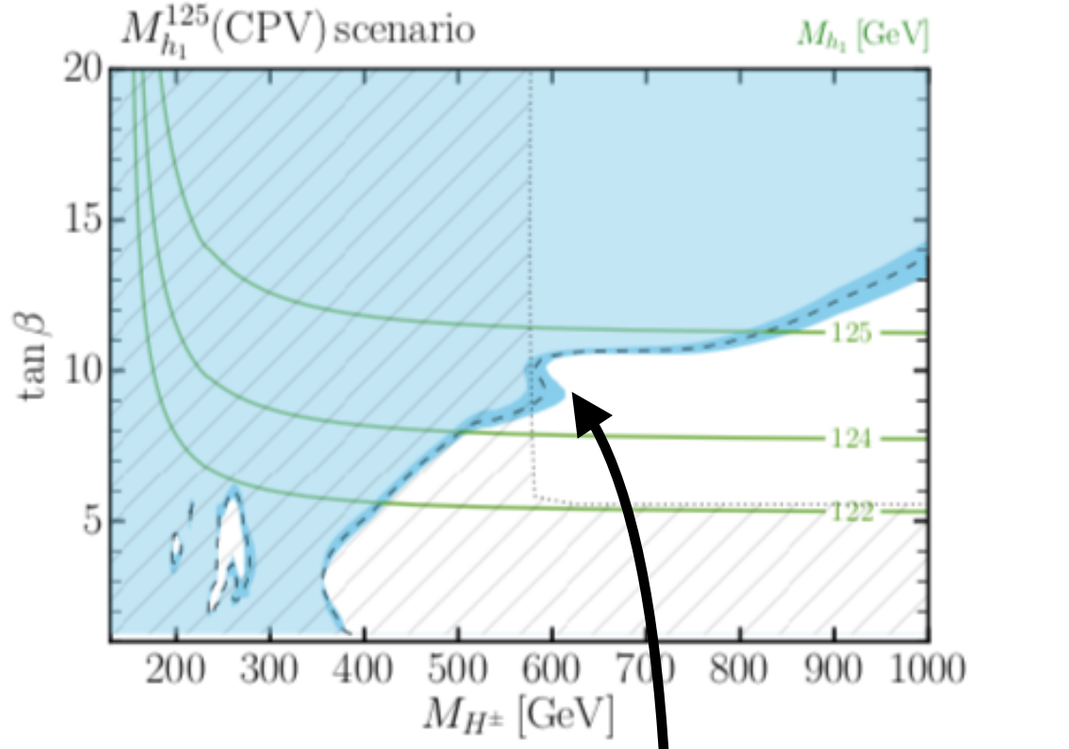
- h, H, A mix to three mass eigenstates $h_{1,2,3}$ through phase in trilinear coupling $A_t$
- Parameters chosen to have strongest interference in region close to the current exclusion in other benchmarks
- Model is now under tension from latest EDM measurements [Nature 562, 355-360 '18]
- Interference factors for $I \to h_i \to f$ process calculated:

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

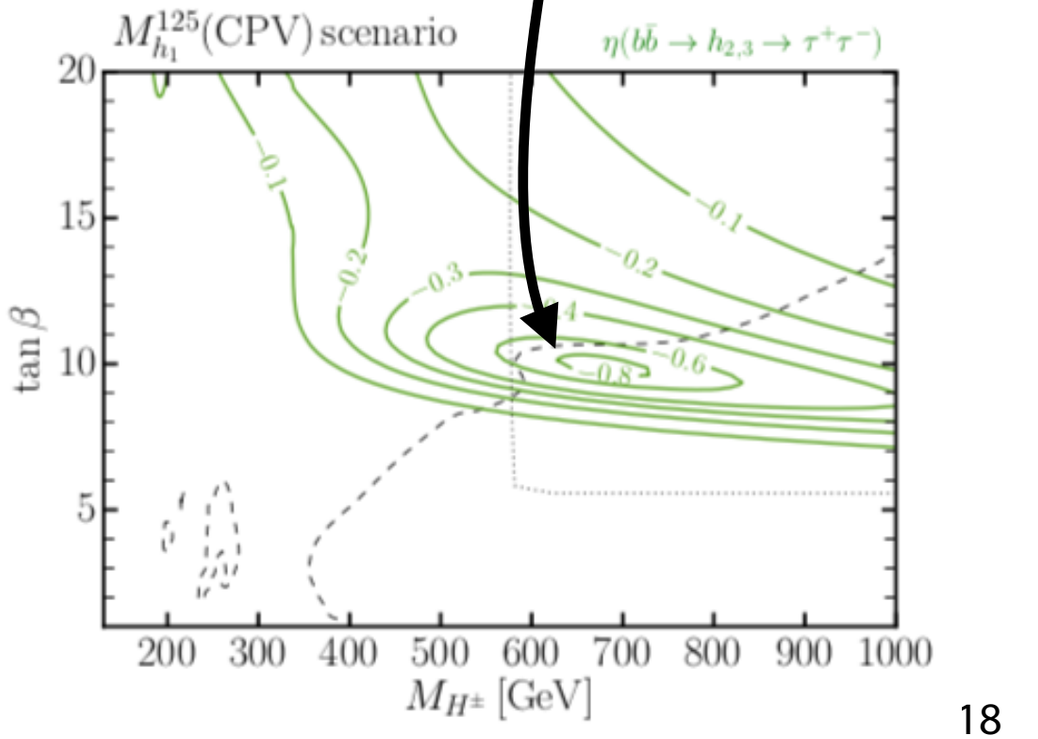
$$M_{Q_3} = M_{U_3} = M_{D_3} = M_{L_3} = M_{E_3} = 2 \text{ TeV},$$

$$\mu = 1.65 \text{ TeV}, \quad M_1 = M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV},$$

$$|A_t| = \mu \cot\beta + 2.8 \text{ TeV}, \quad \phi_{A_t} = \tfrac{2\pi}{15}, \quad A_b = A_\tau = |A_t| \,.$$

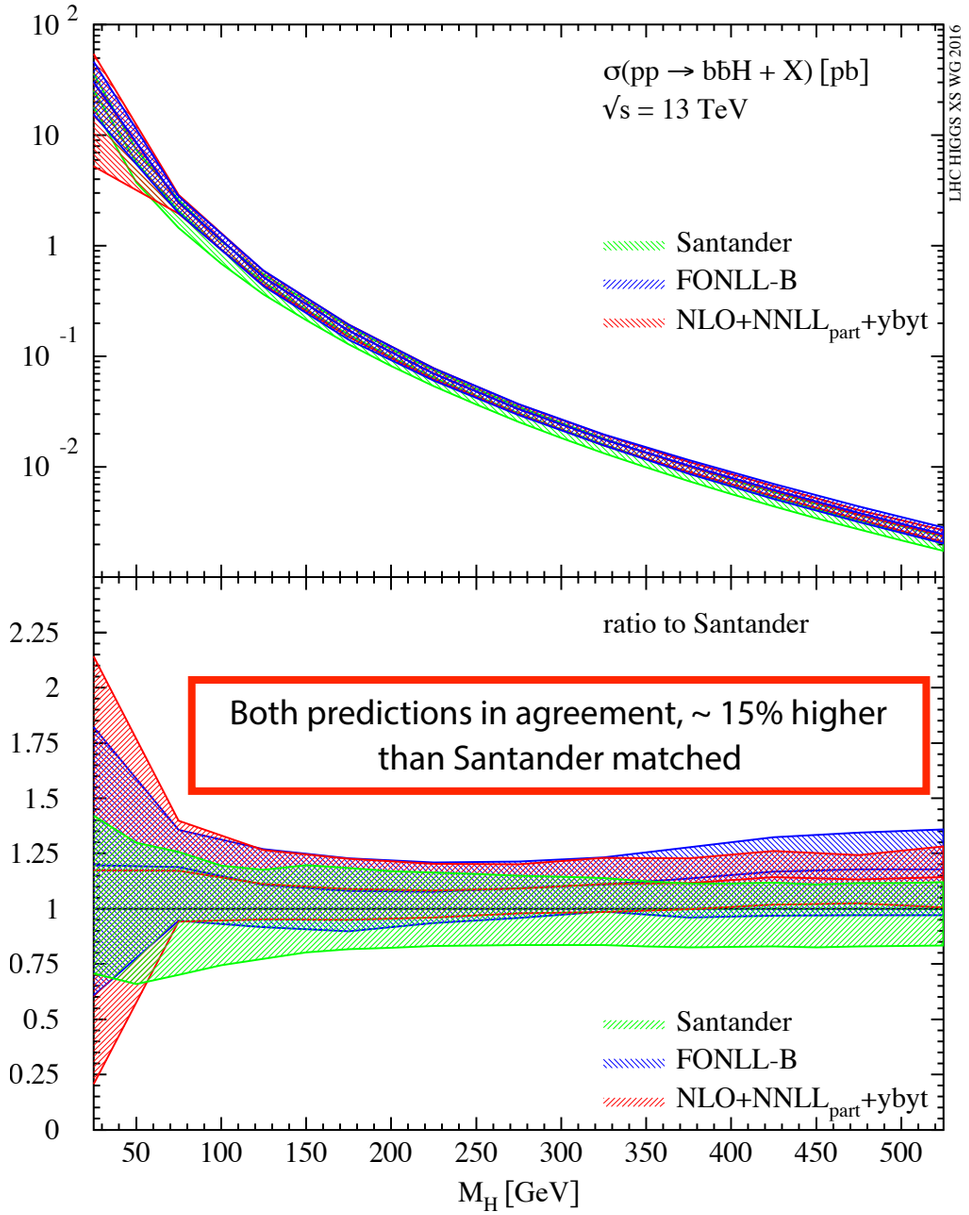



Region where interference reduces σxB for $h_{2,3} \to \tau\tau$

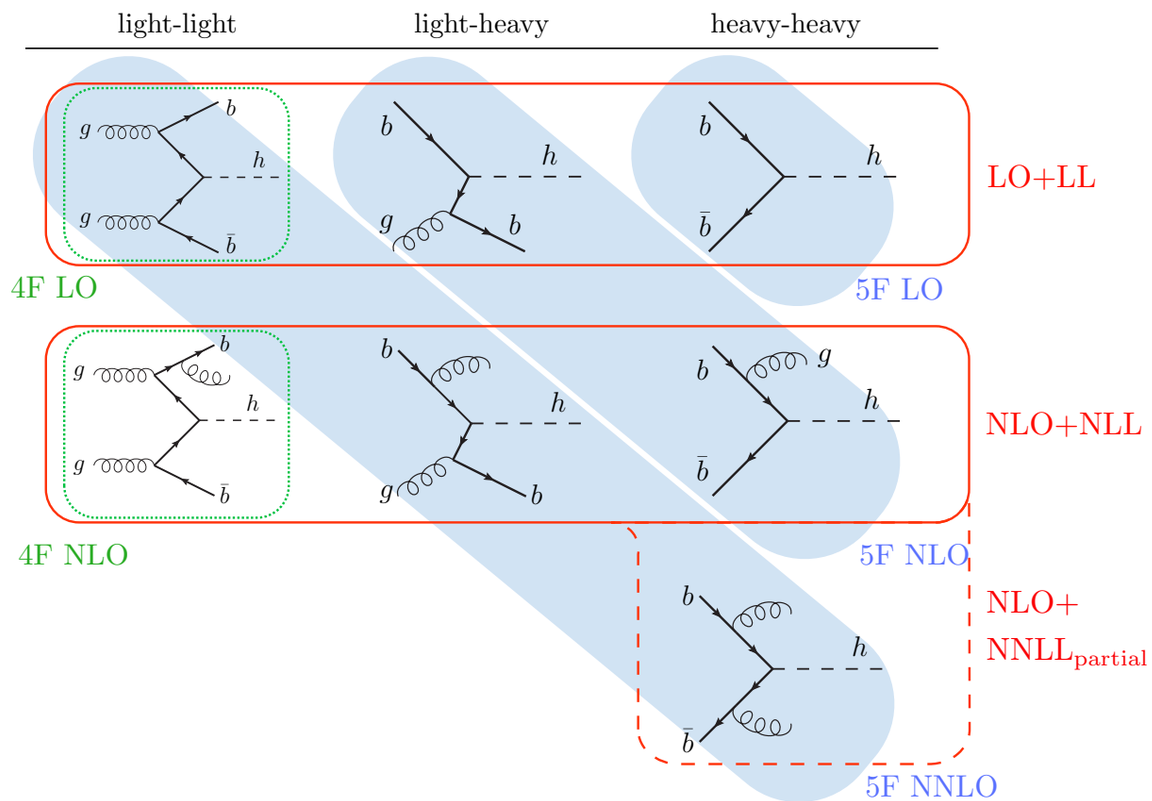


# bbH production

- Progress has been made in matching 4FS and 5FS calculations
  - Up to now we have relied on the "Santander" empirical matching scheme




- Two new consistently matched schemes:
  - FONLL-B (Forte, Napoletano, Ubiali)
    - arXiv:1508.01529, arXiv:1607.00389
  - NLO+NNLLpart+ybyt (Bonvini, Papanastasiou, Tackmann)
    - arXiv:1508.03288, arXiv:1605.01733

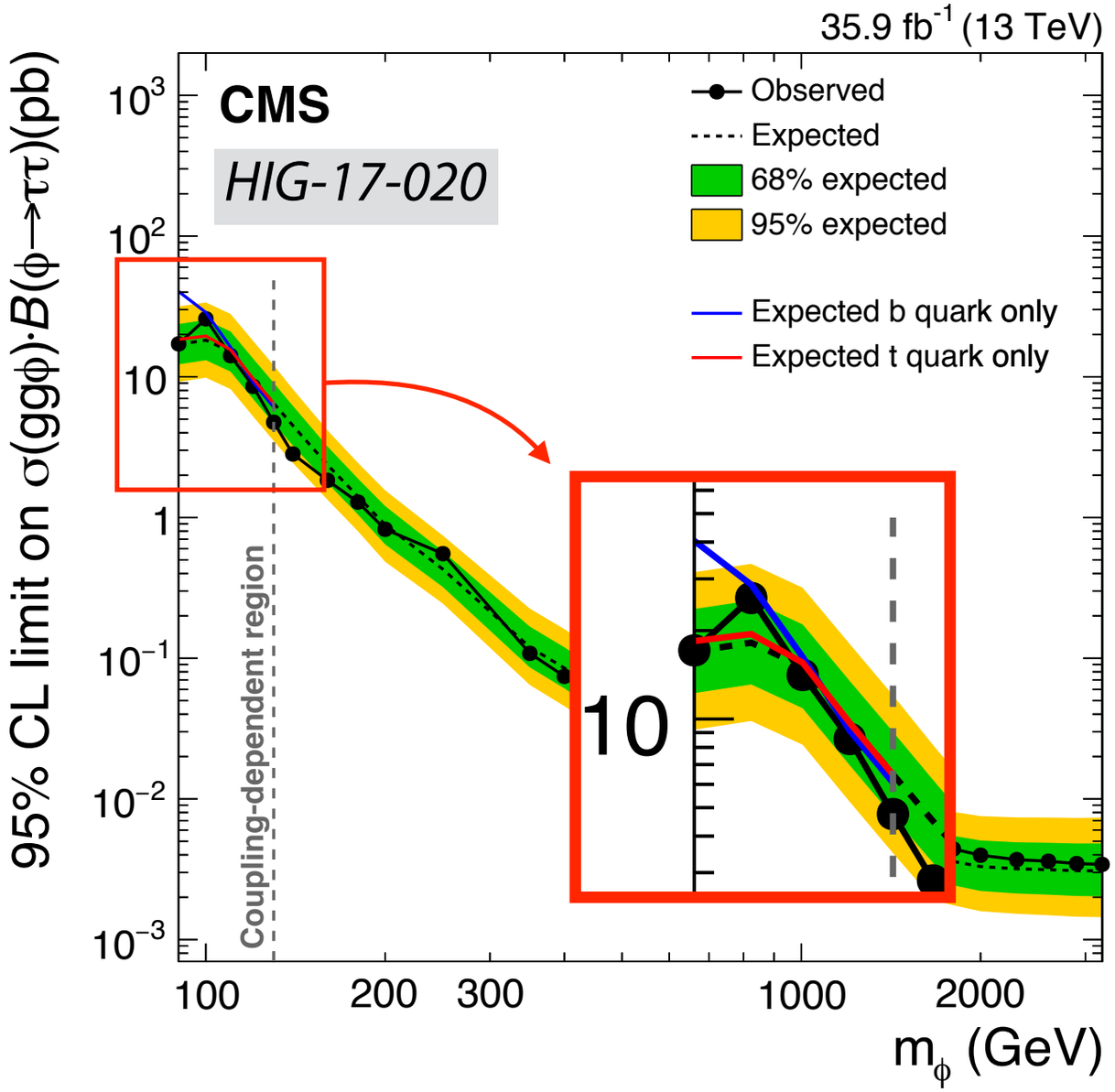


# Higgs $p_T$ reweighting

- Higgs pT distribution requires resummation - currently define separate scales μ for different contributions:
  - Implemented in POWHEG [JHEP 1202:088,2012, JHEP 01 (2016) 056], aMCSusHi [JHEP07(2014)079, arXiv: 1504.06625], MoRe-Sushi [JHEP11(2014)116]

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

- In the MSSM the relative strength of the top and bottom Yukawa couplings affects the $p_T^H$ distribution
- CMS has published results showing the "model independent" gluon-fusion limits are sensitive to the relative top-bottom contributions
  - Changes the acceptance for $m_\varphi < 130$ GeV



# Higgs $p_T$ reweighting

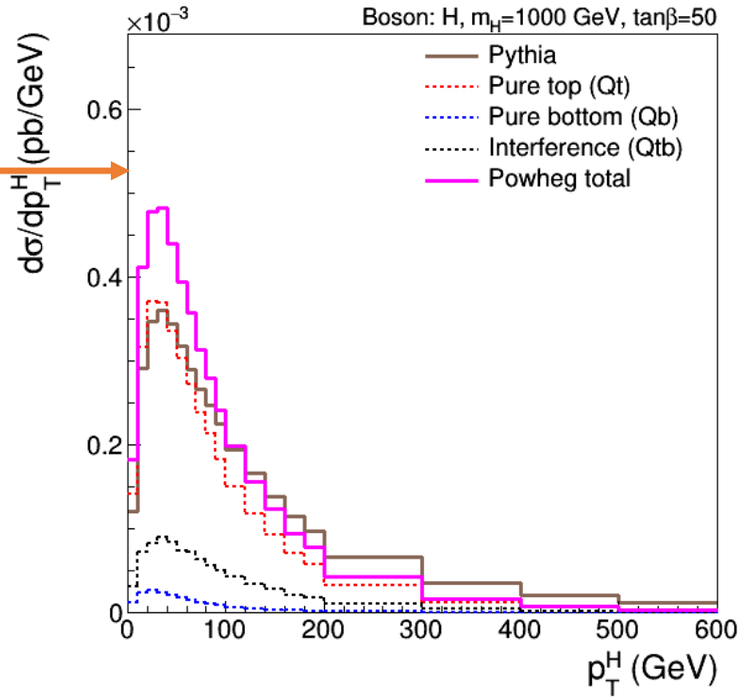
- Effort to provide tool for determining distribution for arbitrary mA, tanβ: several ingredients needed to construct the total spectrum:

$p_T$ distributions to reweight MC (given some reference, e.g PY8

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

Cross sections in 2HDM at reference tanβ values

Yukawa couplings for: 2HDM at reference values + MSSM vs $m_A$,tanβ




- All Higgs $p_T$ distributions will be packaged within a RooFit workspace inside a ROOT file
  - Advantages: no additional code or interface needed, format widely used within CMS and ATLAS
  - Simply set parameters and look-up desired values:

```
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();
```