HL-LHC and ILC Sensitivities in the Hunt for Heavy Higgs Bosons

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in collaboration with

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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

QU H1+H2 interim meeting

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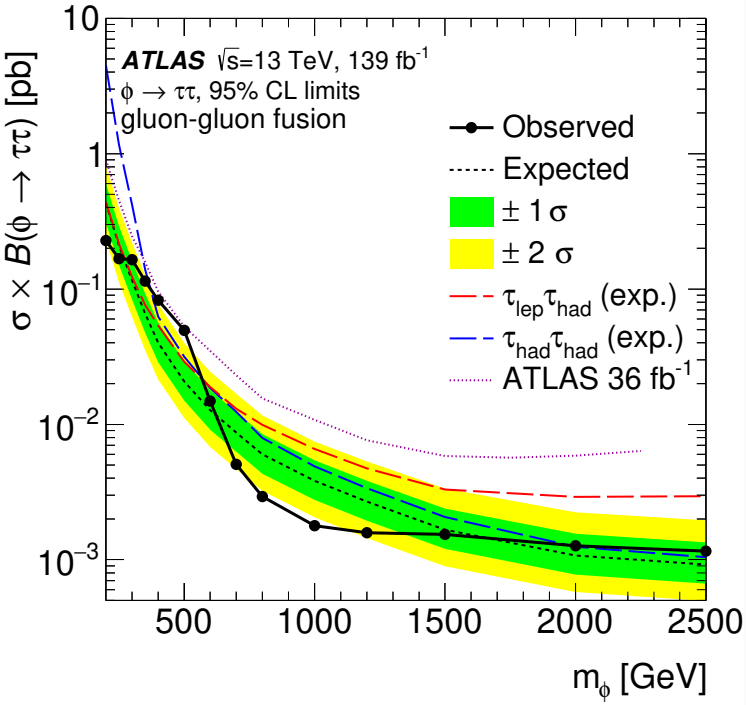
Where are *the other* Higgs bosons?

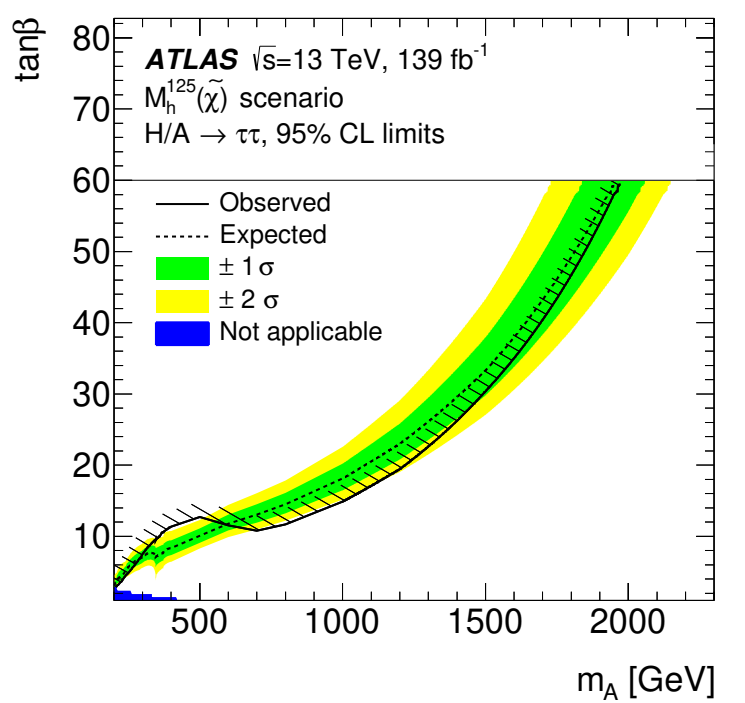
Additional Higgs bosons are predicted in many BSM models.

- Higgs properties (charges, masses, couplings, decays, etc.) are model-dependent.
- many new physics ideas ⇒ *many different* LHC signatures!

  ⇒ motivates a *broad* BSM Higgs search program!

Limits and future projections can be presented in a model-independent way, but benchmark BSM models are useful for comparison of different experimental probes.





Experimental probes of BSM Higgs bosons

direct searches at the LHC:

$gg, b\bar{b} \to \phi \to \tau^+\tau^-$	official HL-LHC projection available
$gg, b\bar{b} \to \phi \to b\bar{b}$	
$gg \to \phi \to t\bar{t}$	model-dependent (signal-BG interference)
$pp \to \phi \to hh \to \ldots$	
$pp \to \phi_2 \to \phi_1 Z$ or hZ	
$pp \to \phi \to W^+W^-, ZZ, \gamma\gamma$	
$pp \to \phi^\pm tb$, $\phi^\pm \to tb, \tau\nu, \phi W$	
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indirect (model-dependent) probes of BSM Higgs bosons:

- Higgs signal rate measurements
- Flavor physics measurements (e.g., $b \to s\gamma$).

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In this work: use MSSM benchmark scenarios for comparison of future direct and indirect probes.

The MSSM Higgs sector

- 2 Higgs doublets $\Rightarrow$ 5 Higgs bosons: $h, H, A, H^{\pm}$
- At tree-level, fully described by two parameters: M_A, $\tan\beta \equiv v_2/v_1$
- Radiative corrections very important to achieve $M_h \simeq 125\ \mathrm{GeV}$.
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Decoupling limit ($M_A \gg M_Z$): Light Higgs couplings become SM-like

Coupling		strength at M_A (for $\tan\beta = 10$) 300 GeV	500 GeV	1 TeV
hVV	$\propto \sin(\beta-\alpha)$	0.99984	0.999979	0.9999987
hbb, $h\tau\tau$	$\propto \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$	0.820	0.935	0.984
htt	$\propto \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$	1.0016	1.0006	1.00016

with $\sin^2(\beta-\alpha) \simeq 1 - \frac{1}{4}\left(\frac{M_Z}{M_A}\right)^4 \sin^2 4\beta$ in decoupling limit ($M_A \gg M_Z$).

MSSM benchmark scenarios (I/II)

The M_h^{125} and $M_{h,\text{EFT}}^{125}$ scenario: [Bagnaschi et al. '18, Bahl, Liebler, TS '19]

- "standard" scenarios with all SUSY particles heavy $\Rightarrow$ "*2HDM-like*";
- no competing non-standard heavy Higgs decays (up to $M_A \simeq 1.9\ \text{TeV}$)
  $\Rightarrow$ *maximal reach* for $H/A \to \tau^+\tau^-$ searches.
- acceptable light Higgs mass (within theory unc.):

  M_h^{125} scenario: $M_h \gtrsim 122\ \text{GeV}$ for $\tan\beta \gtrsim 6$ (fixed SUSY mass scale M_S)

  $M_{h,\text{EFT}}^{125}$ scenario: $M_h \simeq 125\ \text{GeV}$ everywhere (M_S adjusted)

The $M_h^{125}(\tilde{\chi})$ and $M_{h,\text{EFT}}^{125}(\tilde{\chi})$ scenario:

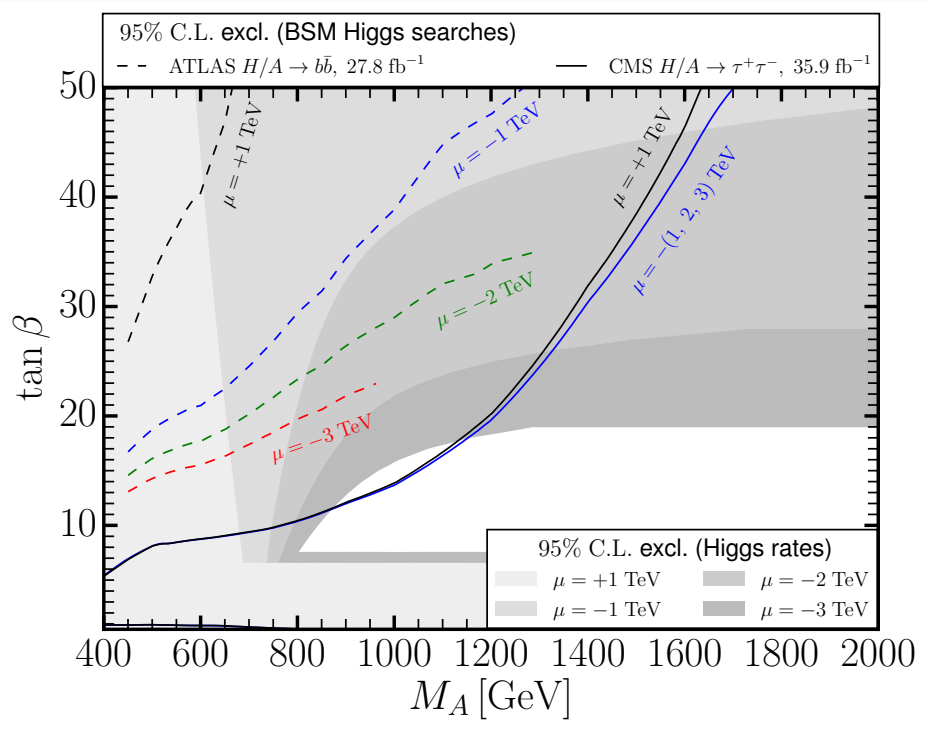
- light neutralinos and charginos ($M_1 = 160\ \text{GeV}$, $M_2 = \mu = 180\ \text{GeV}$)
- competing H/A decays to electroweakinos can become sizable
  $\Rightarrow$ *reduced reach* for "conventional" BSM Higgs searches ($\tau^+\tau^-, b\bar{b}, \ldots$).
- light chargino loop-contributions to $h \to \gamma\gamma$ decay.

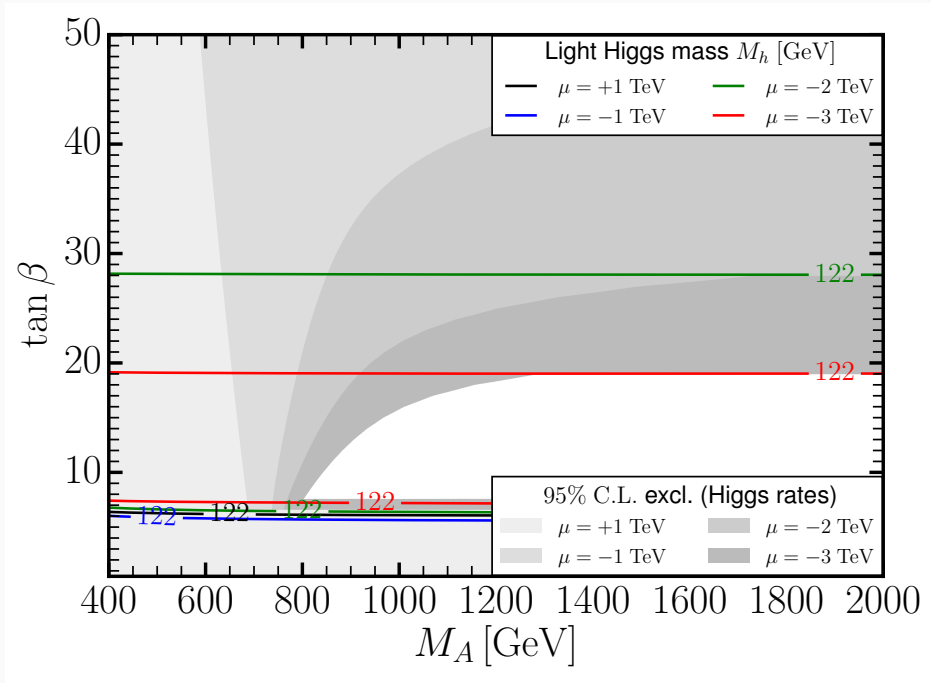
MSSM benchmark scenarios (II/II)

A scenario with maximal reach for $gg, b\bar{b} \to H/A \to b\bar{b}$ searches?

Bottom-quark Yukawa coupling: $h_b \sim \frac{m_b}{1+\Delta_b}$ with $\Delta_b \propto \mu \tan\beta$.

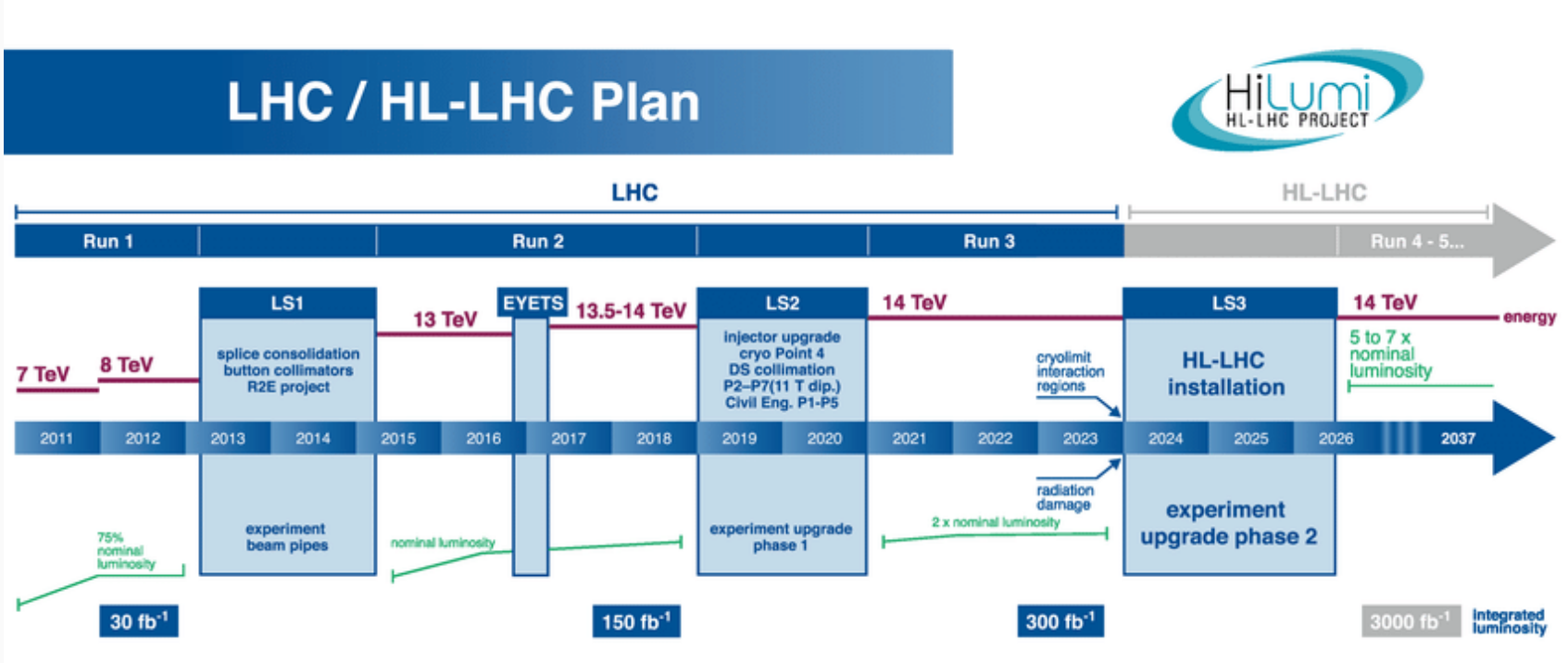
$\Rightarrow$ large negative $\mu \to$ enhanced h_b!





Modified M_h^{125} scenario with $\mu = -2$ TeV $\Rightarrow$ $M_h^{125,\mu-}$ scenario NEW

The High-Luminosity (HL)-LHC



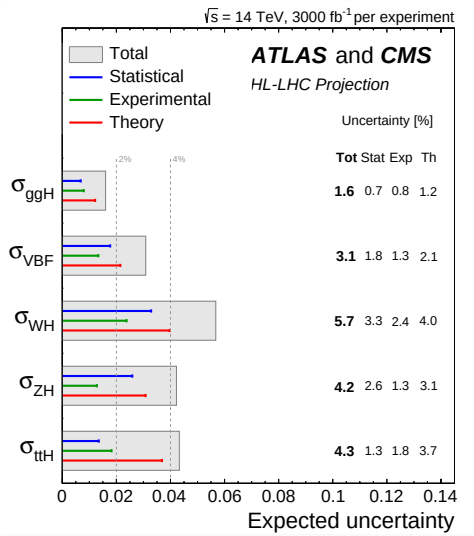
Physics potential reassessed in 2018/19 in

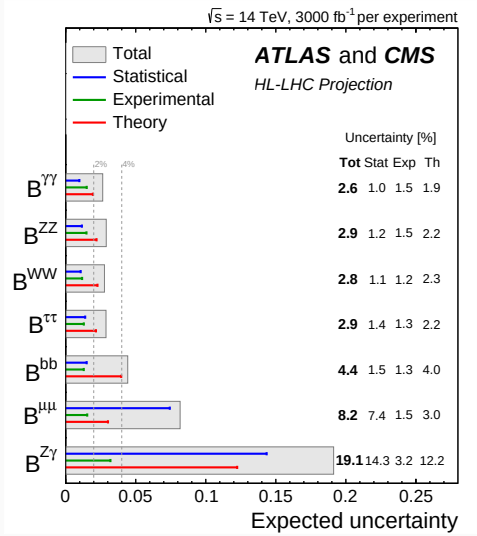
Workshop *"The physics of HL-LHC, and perspectives on HE-LHC"*.

Prospects on SM and BSM Higgs physics: [Cepeda et al. '19]

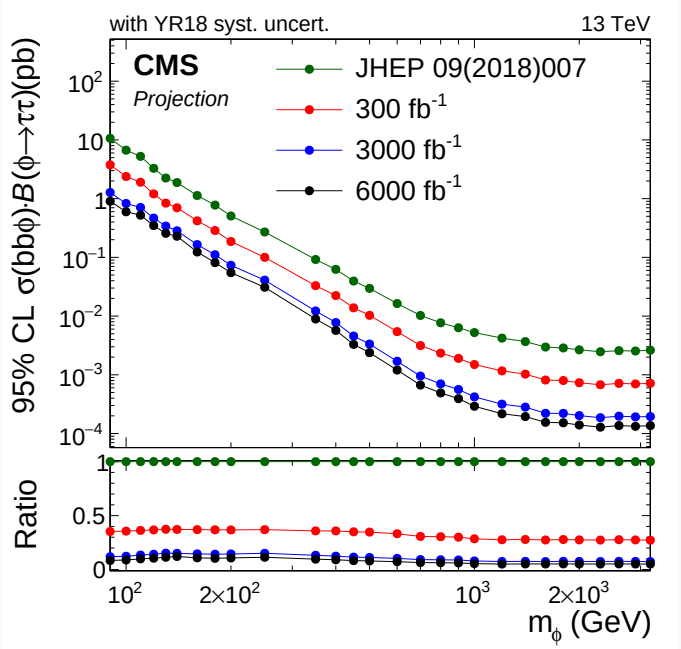
HL-LHC prospects on BSM Higgs physics

Higgs signal rate measurements:





$pp \to \phi \to \tau^+\tau^-$ searches:



"YR18 syst. uncert.": theory uncertainties halved, careful estimates with reasonable assumptions of experimental systematic uncertainties.

- Implemented ATLAS and CMS projections for Higgs rates (per production × decay mode, including correlations) in `HiggsSignals`;
- Use CMS 6 ab^{-1} projection for $gg/b\bar{b} \to \phi \to \tau^+\tau^-$ limit.
- Other direct searches ($b\bar{b}$, hh) naively projected from current limits.

HL-LHC sensitivity to heavy MSSM Higgs bosons

M_h^{125} scenario:

$pp \to H/A \to \tau^+\tau^-$

probes up to

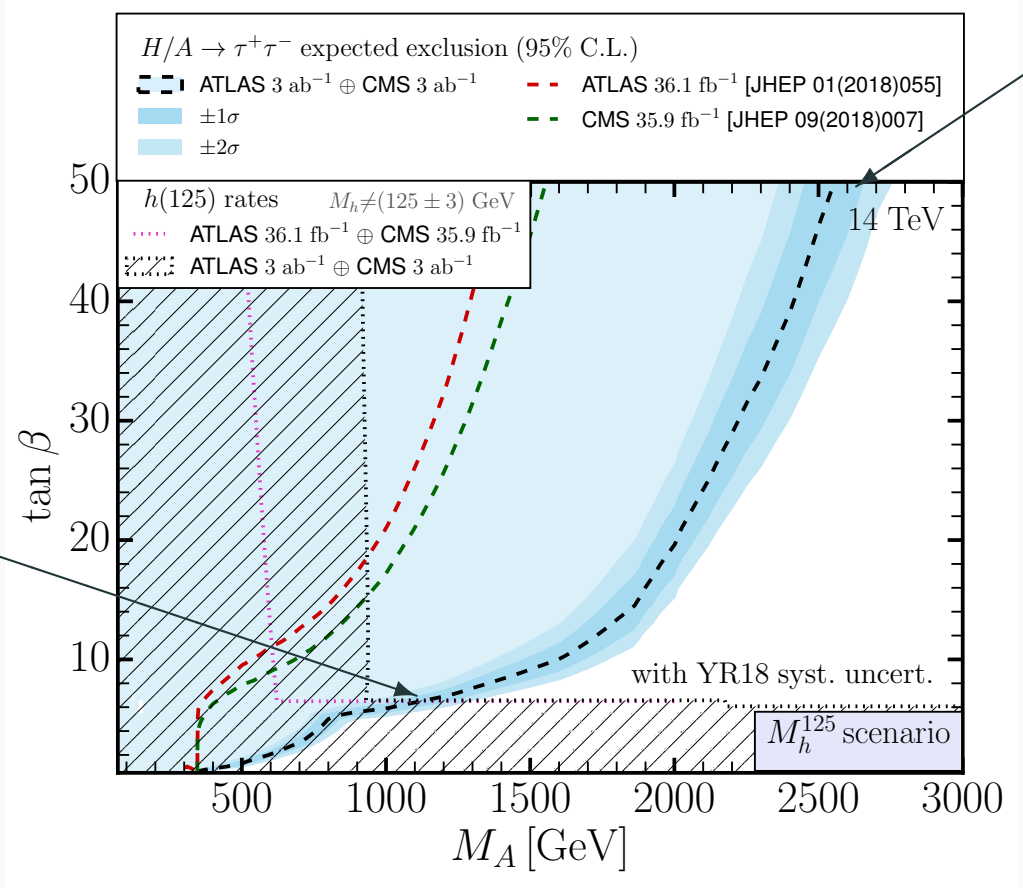
$M_A \sim 2.5$ TeV

Higgs mass $M_h \oplus$

$pp \to H/A \to \tau^+\tau^-$

$\Rightarrow M_A \gtrsim 1.2$ TeV

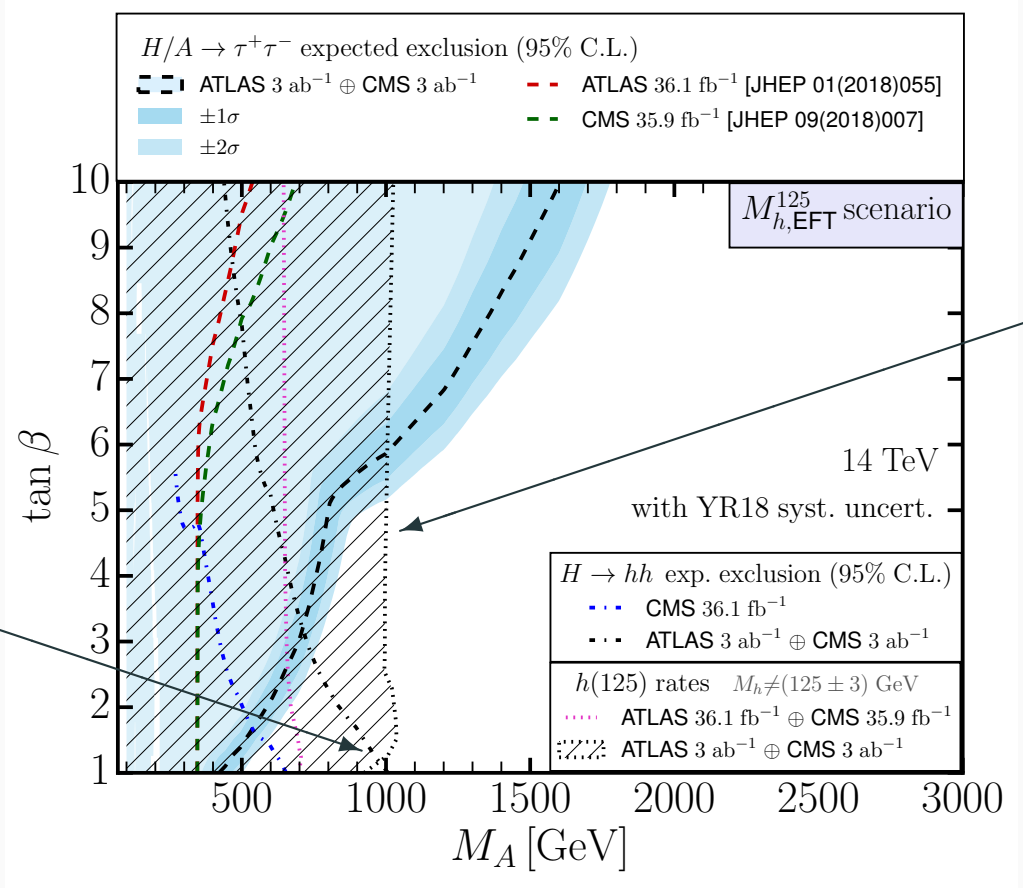
(exp. lower bound)



HL-LHC sensitivity to heavy MSSM Higgs bosons

$M_{h,\text{EFT}}^{125}$ scenario (low $\tan\beta$ region):

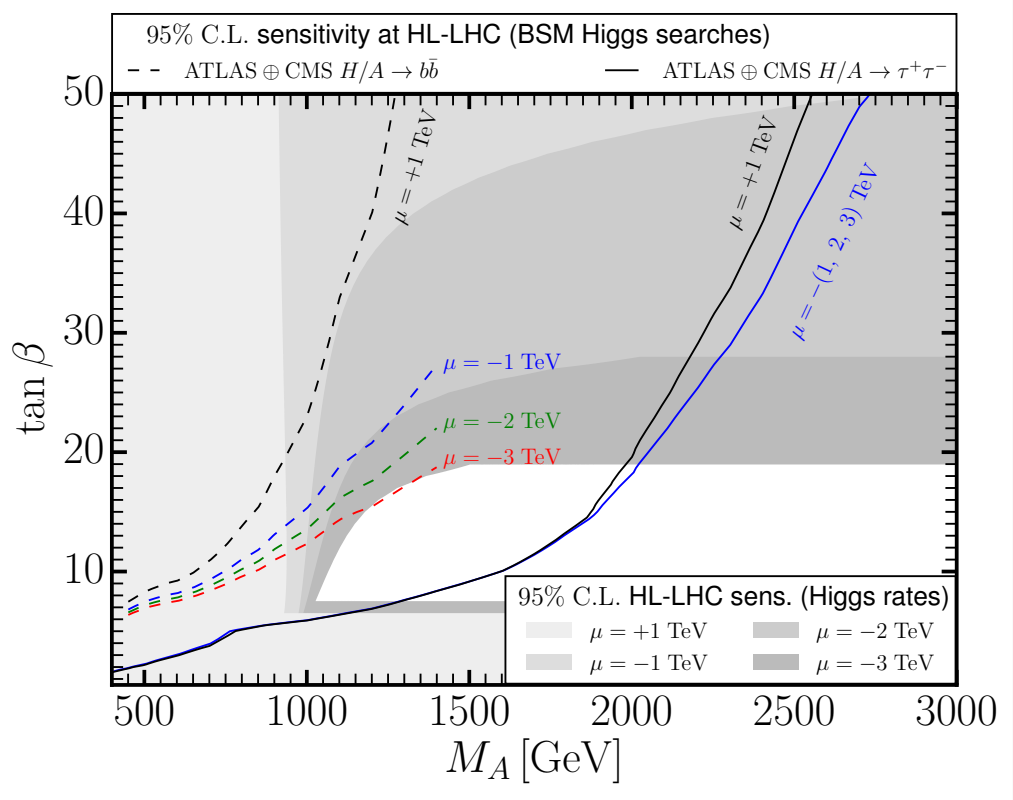
$pp \to H \to hh$ probes up to $M_A \sim 1\,\text{TeV}$



Higgs rates most sensitive, probing $M_A \sim 1\,\text{TeV}$

HL-LHC sensitivity to heavy MSSM Higgs bosons

Modified M_h^{125} scenario (varying μ):

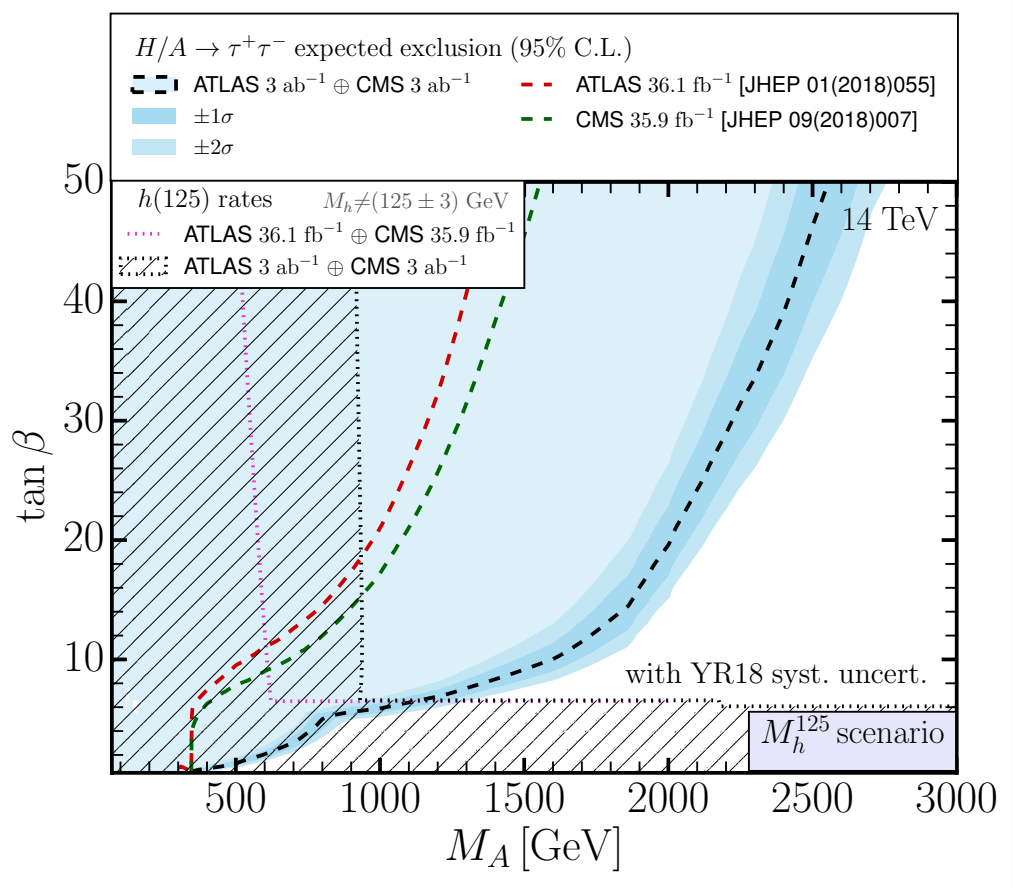


$\Rightarrow H/A \to \tau^+\tau^-$ searches always more sensitive than $H/A \to b\bar{b}$ searches.

Higgs mass & rates impose an (M_A-dependent) upper limit on **tan** β.

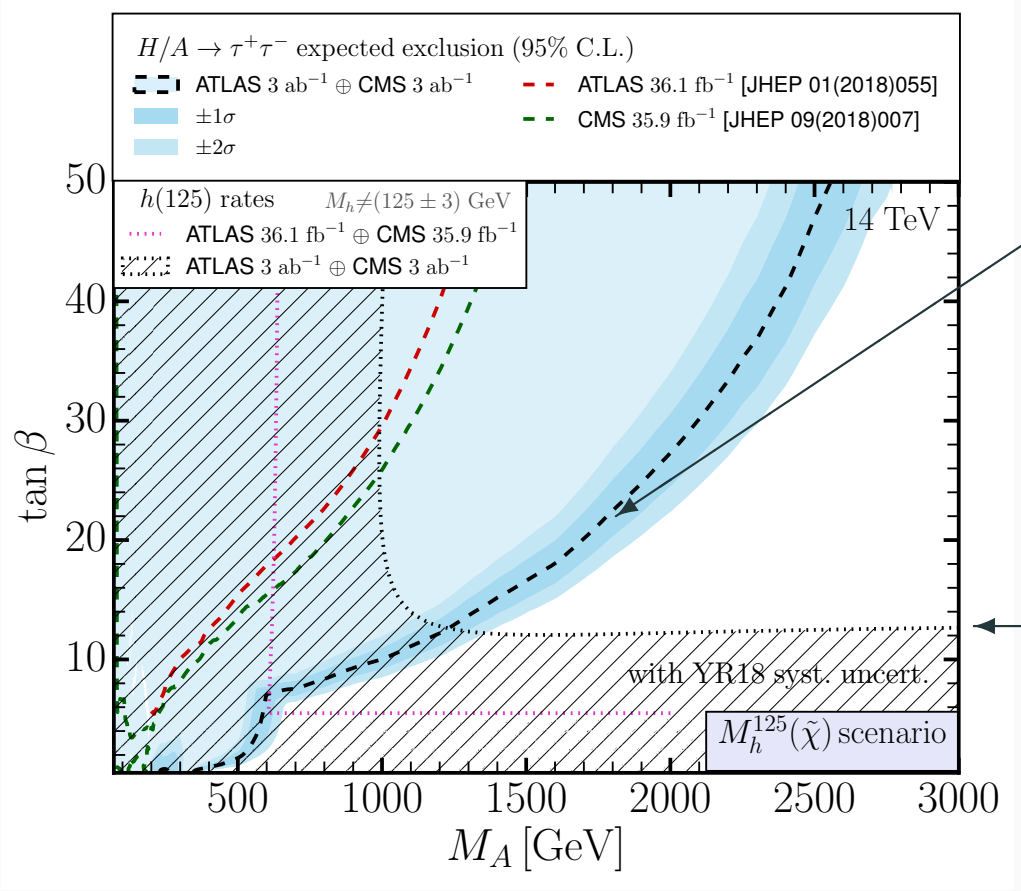
HL-LHC sensitivity to heavy MSSM Higgs bosons

M_h^{125} scenario (as shown before):



HL-LHC sensitivity to heavy MSSM Higgs bosons

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

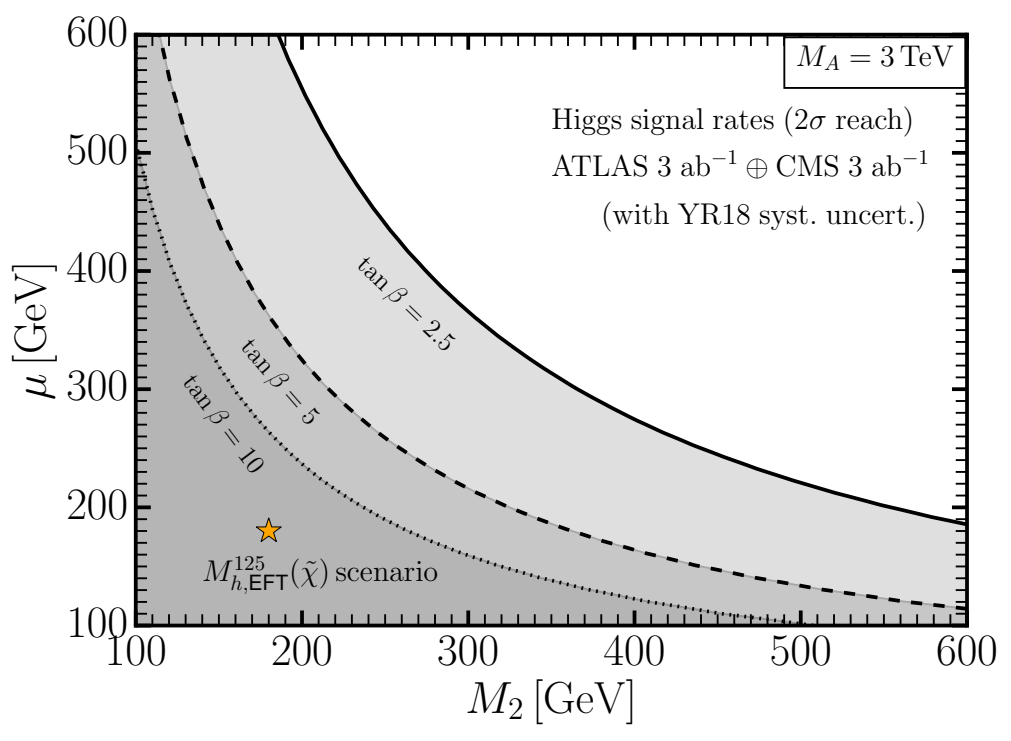


reduced sensitivity of $H/A \to \tau^+\tau^-$ searches, due to $H/A \to \tilde{\chi}\tilde{\chi}$

$h \to \gamma\gamma$ enhancement by light charginos

$\Rightarrow$ **tan** $\beta \gtrsim 12.5$ (exp. lower bound)

Indirect sensitivity to electroweakino mass spectrum



- HL-LHC sensitivity (at 2σ): $\delta\text{BR}(h \to \gamma\gamma) \lesssim 2.6\%$. [Cepeda et al. '19]
- Maximal sensitivity for $M_2 \approx \mu$ and low $\tan\beta$.

$\Rightarrow$ Complementarity to direct LHC searches for neutralinos/charginos!

Future HL-LHC $\oplus$ ILC scenarios

We consider two future HL-LHC $\oplus$ ILC scenarios:

"ILC250": HL-LHC $\oplus$ ILC at 250 GeV with 2 ab^{-1}

"ILC500": "ILC250" $\oplus$ ILC at 350/500 GeV with 0.2/4.0 ab^{-1}

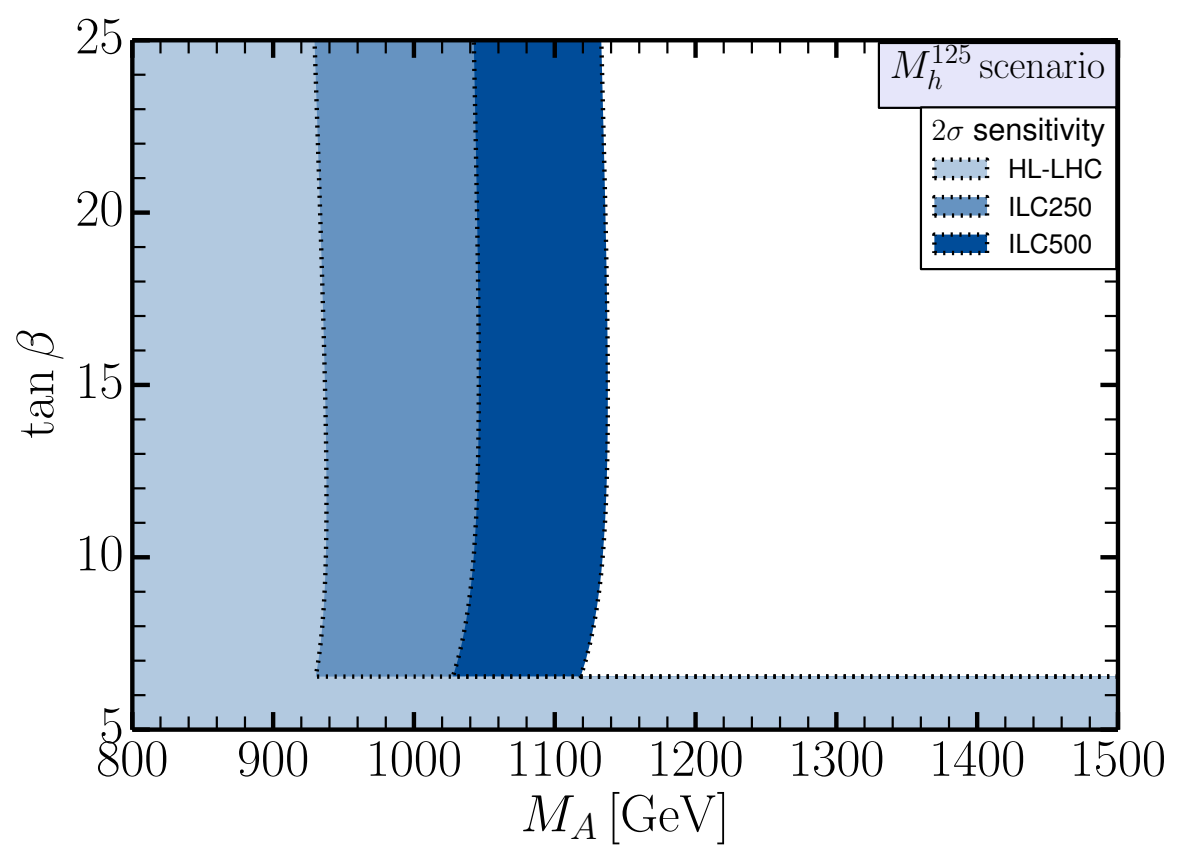
All ILC runs assume e^- (e^+) polarization of -80% ($+30\%$).

- Higgs signal strength projections taken from [de Blas et al. '19] and implemented in `HiggsSignals`.
- Assume theory uncertainty on $e^+e^- \to Zh$ ($\nu\bar{\nu}h$) cross section of 0.5% (1.0%).
- Other theory uncertainties same as in HL-LHC projection.

Rate measurements: sensitivity improvement at the ILC

Assume measurements consistent with SM.

M_h^{125} scenario:



$\Rightarrow$ Each ILC scenario improves sensitivity by $\sim 100\ \mathrm{GeV}$ in M_A.

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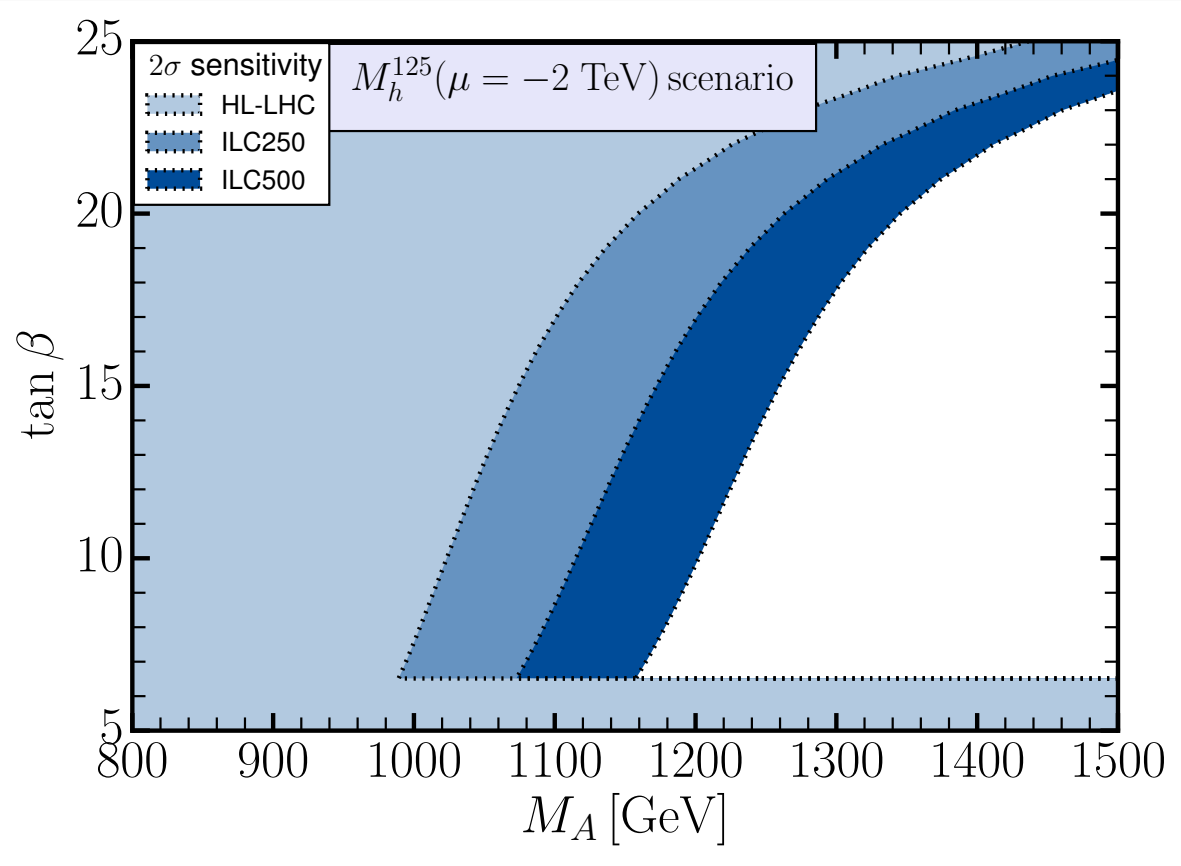
$M_h^{125,\mu-}$ scenario:



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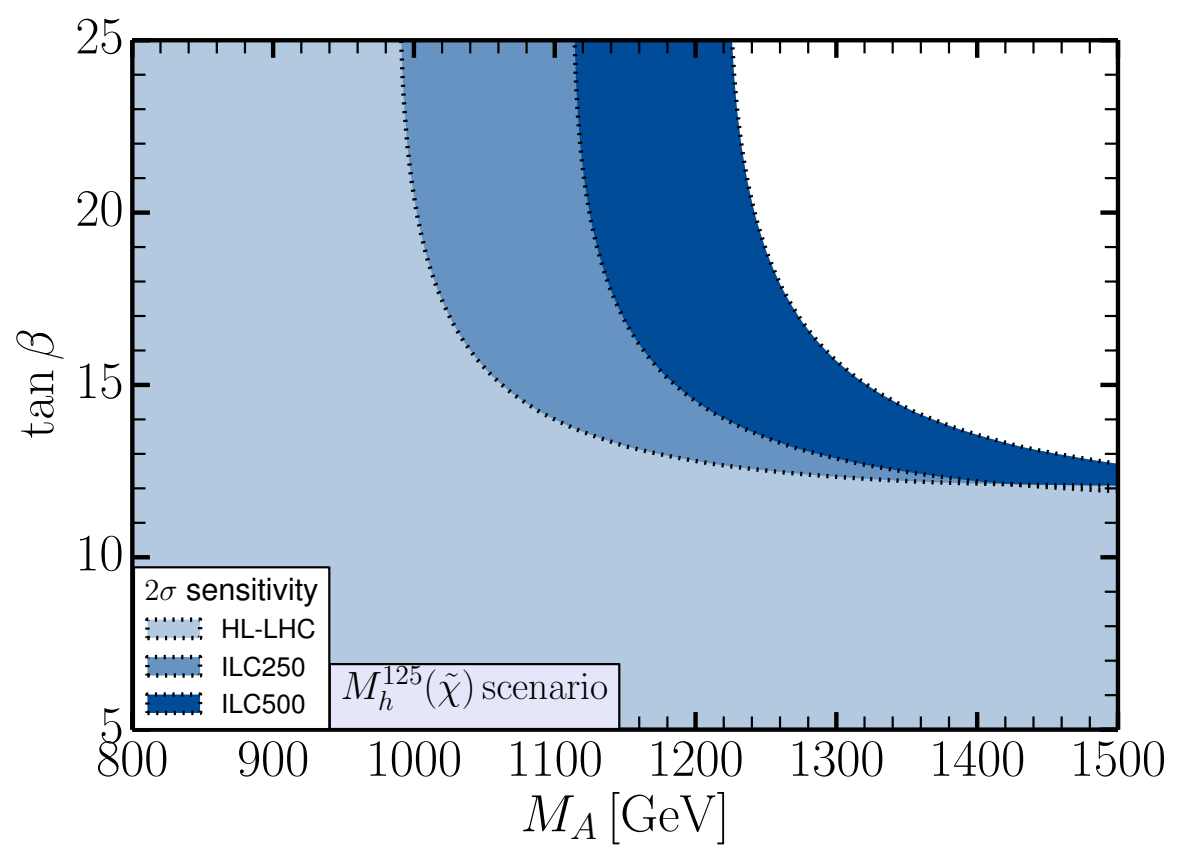

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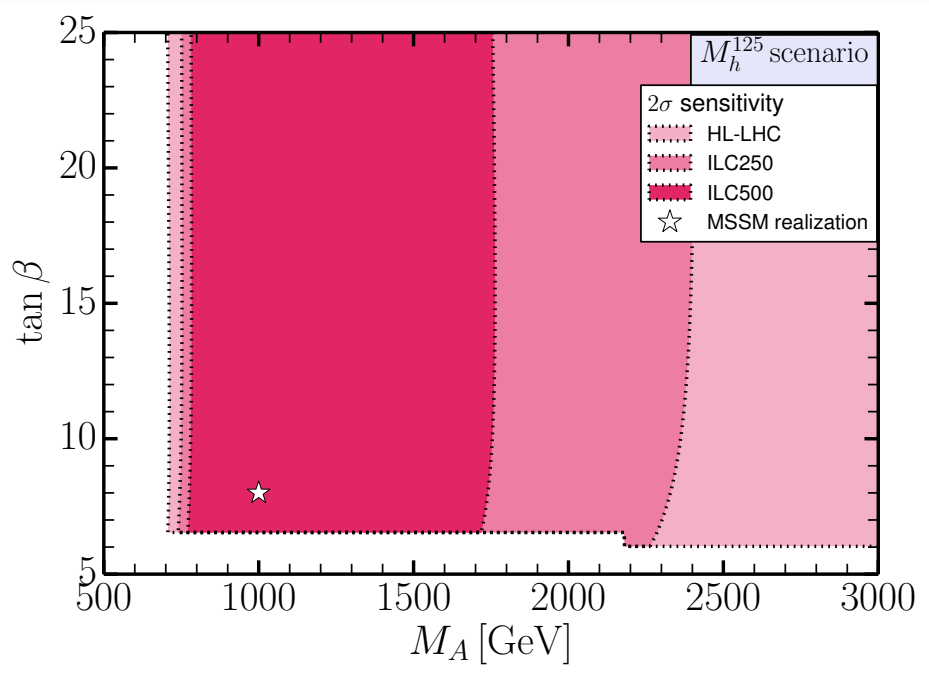
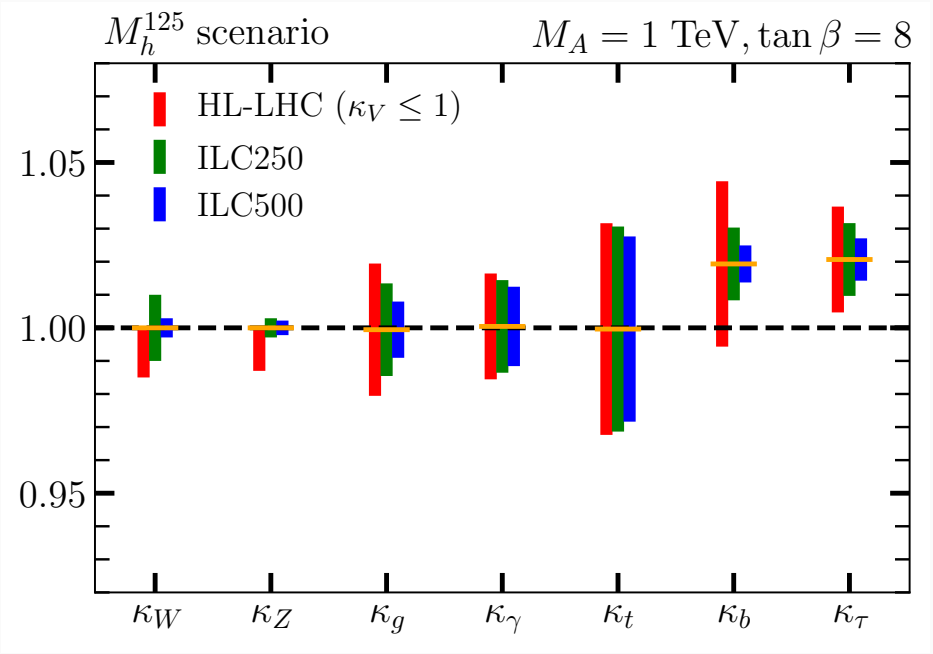
Parameter determination at HL-LHC and ILC

Assume measurements consistent with MSSM ($M_A = 1\,\text{TeV}, \tan\beta = 8$).

M_h^{125} scenario:



"Wäscheleinen-Plot"



κ_i projection taken from [de Blas et al. '19]

$\Rightarrow$ ILC measurements provide upper limit on M_A (i.e., discrimination from SM).

ILC precision determination of various Higgs couplings (κ_b, κ_τ, ...) is essential for establishing evidence for a BSM signal.

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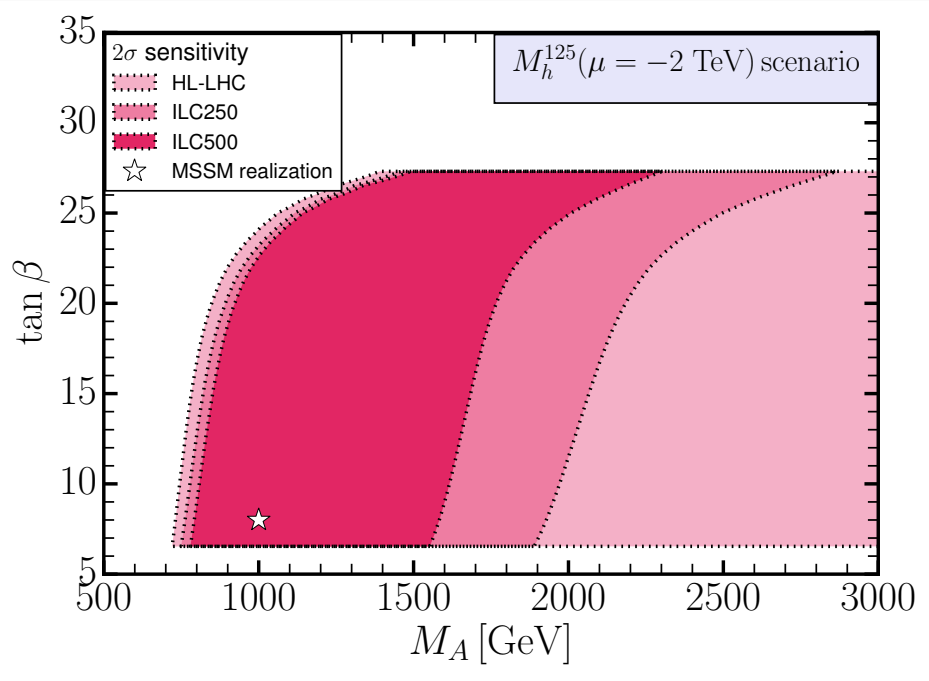

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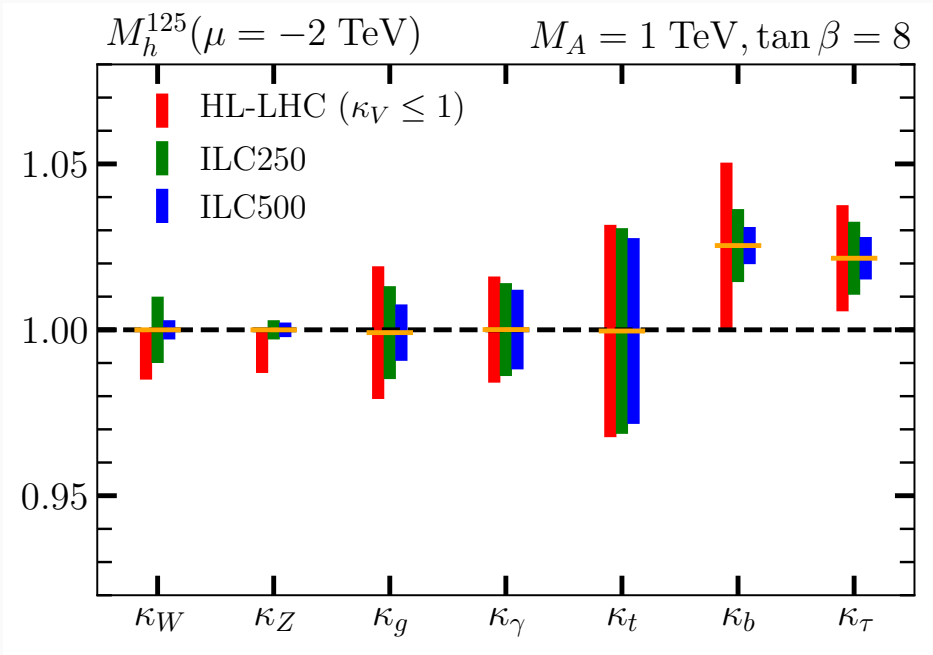

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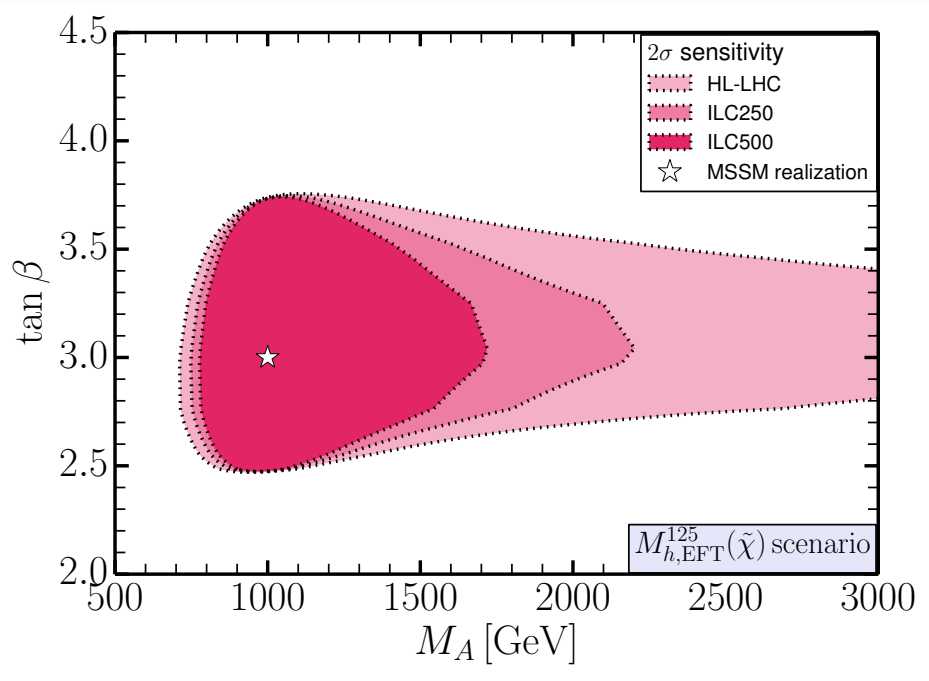
Parameter determination at HL-LHC and ILC

Assume measurements consistent with MSSM ($M_A = 1\ \mathrm{TeV}, \tan\beta = 3$).

$M_{h,\mathrm{EFT}}^{125}(\tilde{\chi})$ scenario:



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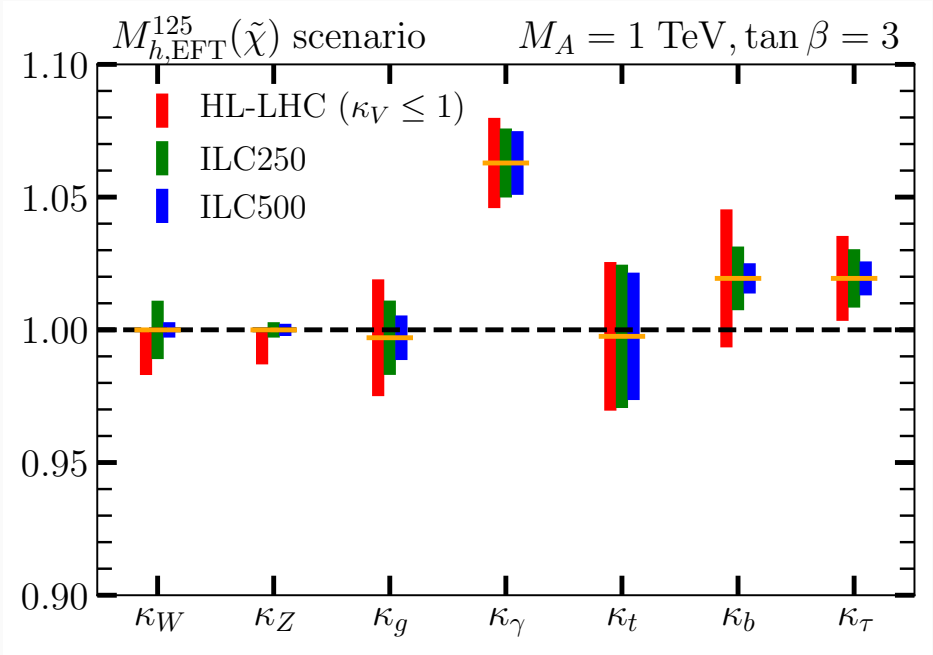

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Conclusions

We studied the future sensitivity to heavy neutral MSSM Higgs bosons of future HL-LHC and ILC scenarios.

We defined new $M_h^{125,\mu-}$ scenario: maximal reach of $H/A \to b\bar{b}$ searches.

The HL-LHC will probe entire parameter space below $M_A \lesssim 1\,\mathrm{TeV}$ (and more).

Assuming SM-consistent measurements, the ILC improvement of the exclusion reach in the MSSM parameter space is rather weak (due to the decoupling limit). Yet, it still provides an important check of possible (statistically-caused) LHC excesses.

If BSM signal is realized, the ILC precision determination of various couplings (κ_b, κ_τ etc.) is needed to establish convincing evidence, and provides a crucial consistency test of any possible BSM model interpretation.

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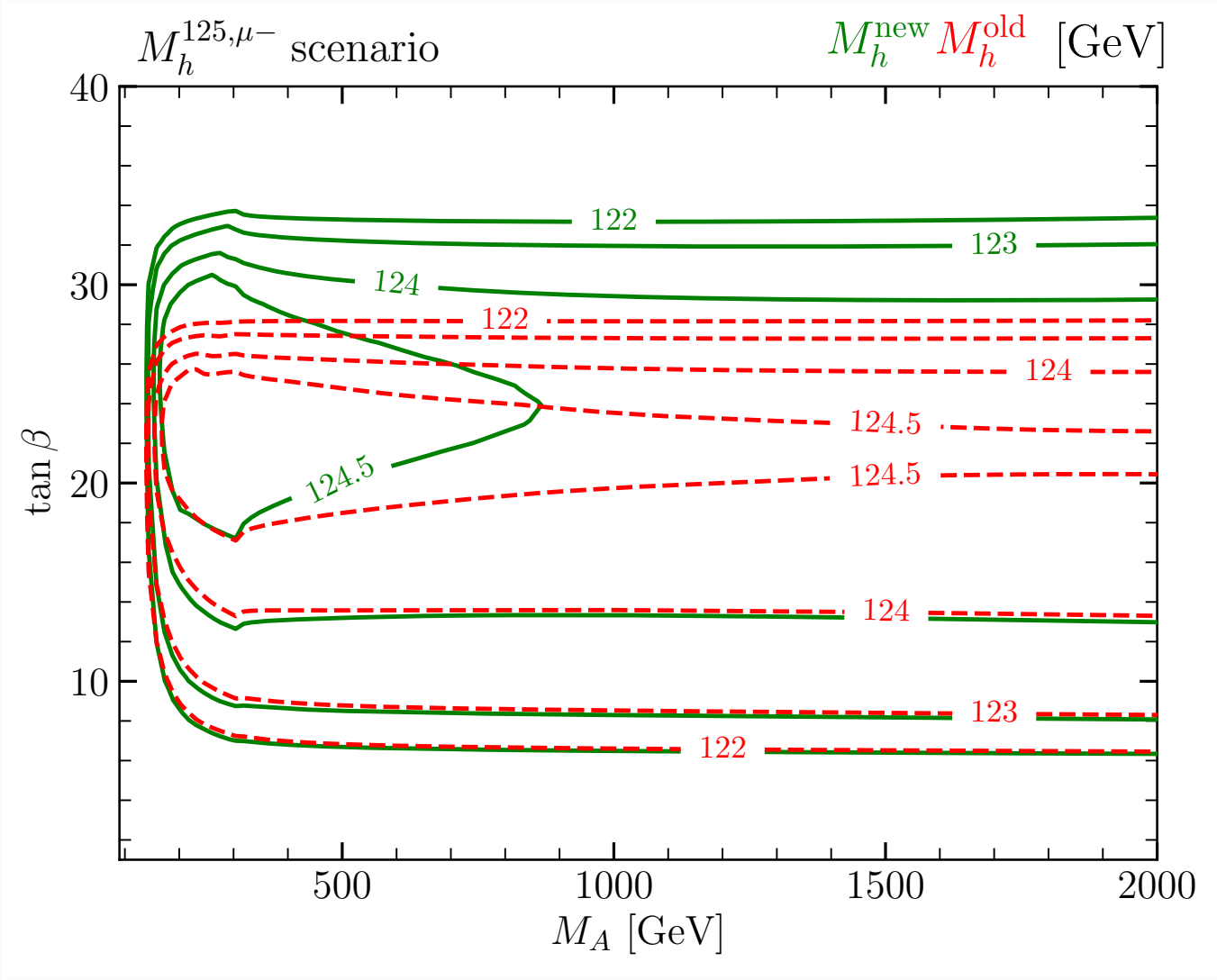
Thank you very much for your attention!

Backup Slides

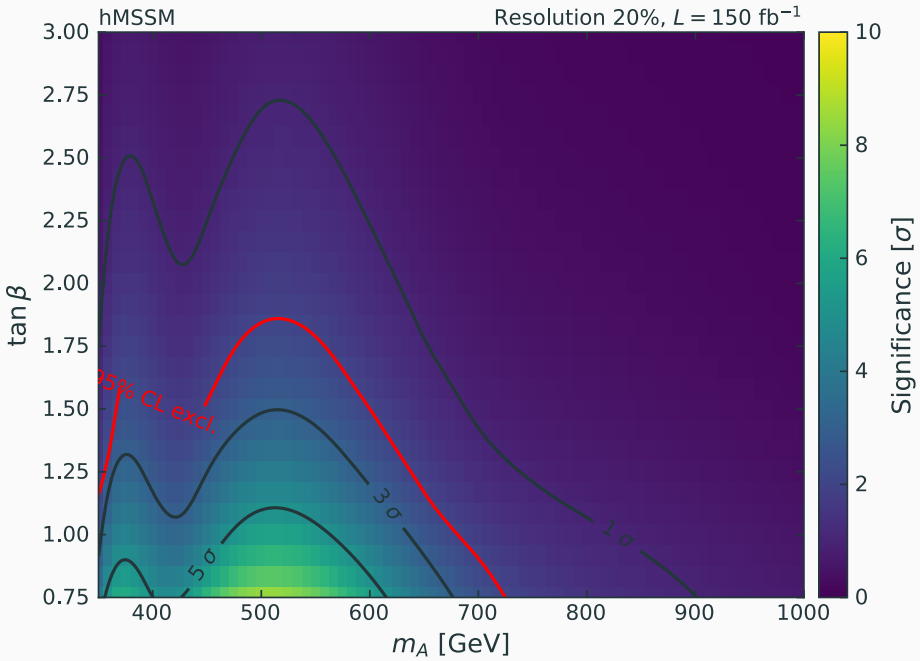
Improved mass calculation in $M_h^{125,\mu-}$ scenario



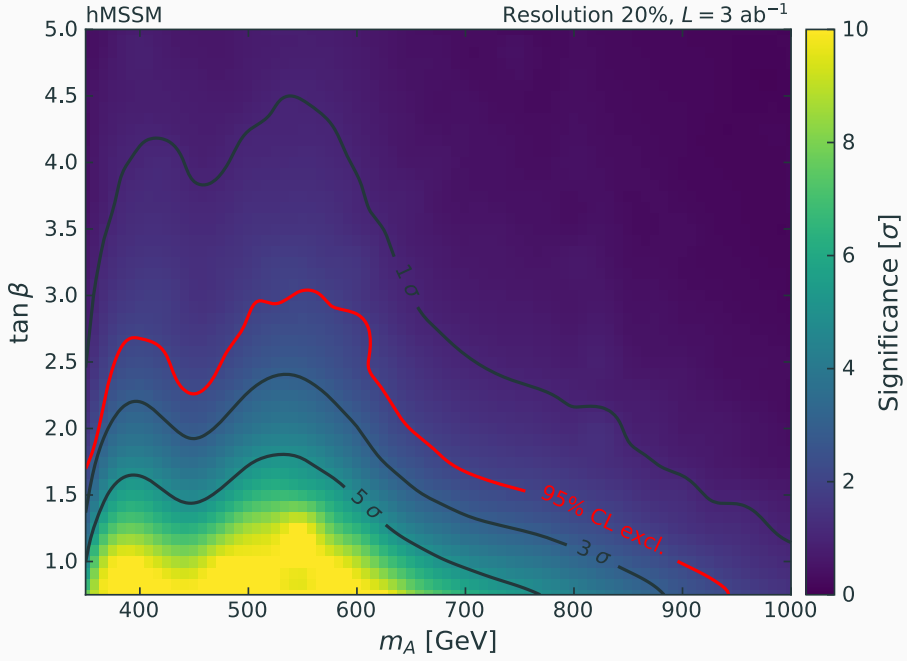
[Bahl, Sobolev, Weiglein '20]

Expected limit of $gg \to H/A \to t\bar{t}$ search in the hMSSM

LHC with 150 fb^{-1}



HL-LHC with 3 ab^{-1}



[Djouadi, Ellis, Popov, Quevillon '19]