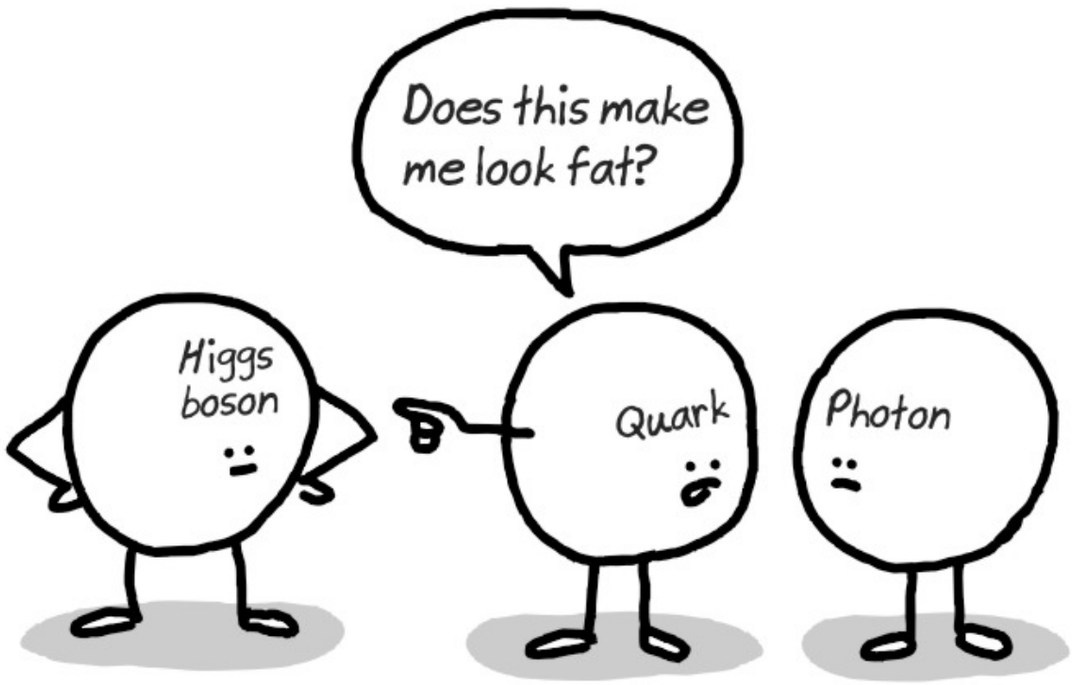
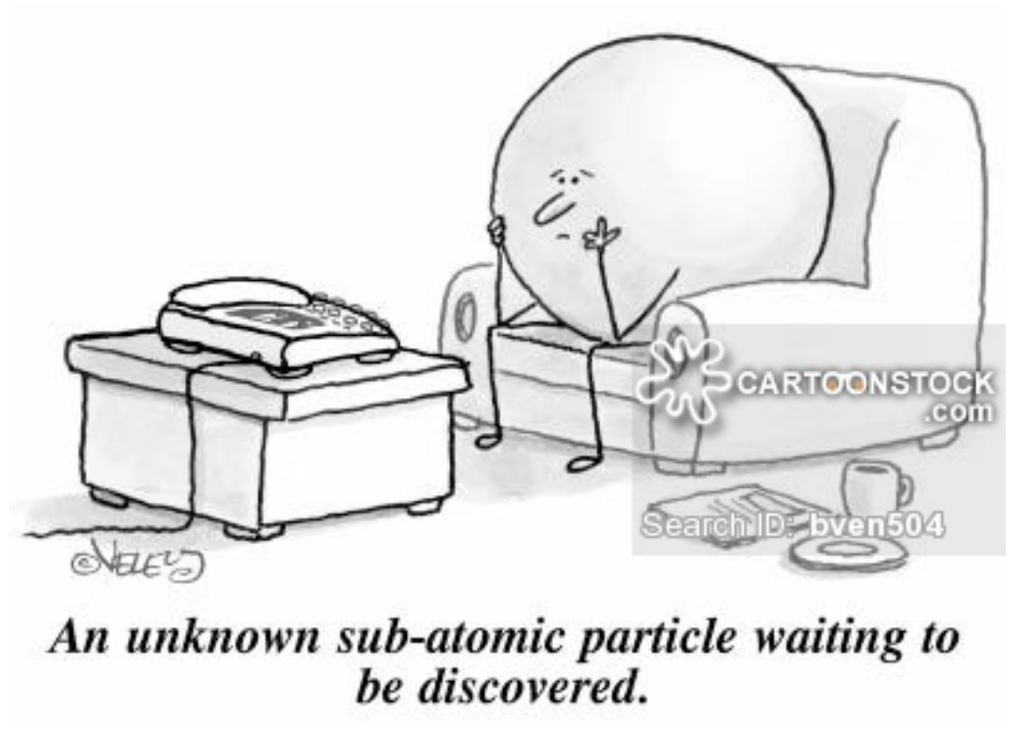
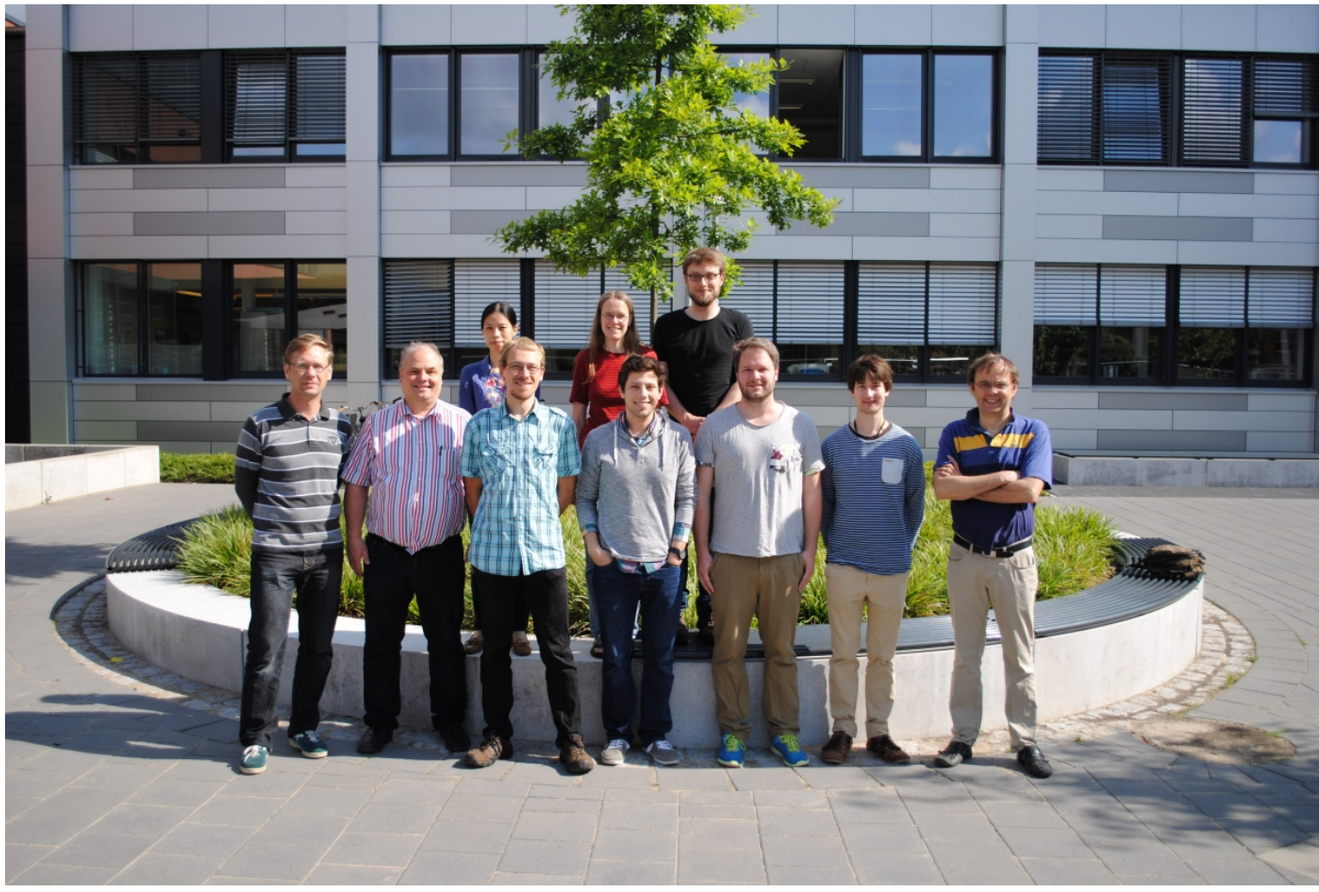






Theory activities in the context of the SFB B9 project

Georg Weiglein, DESY

B9 (Higgs) Meeting,
DESY, Hamburg, 11 / 2015

SFB B9 (Higgs) project

B9 project: Probing the nature of Higgs physics and electroweak symmetry breaking with results from the LHC

Joint activity between ATLAS (DESY), CMS (Univ HH and DESY) and theory (DESY) in the third phase of the SFB (2014-2018)

What kind of topics are we addressing?

Main topics of the B9 project (from the proposal)

- Methods for determining the properties of the new state at about 125 GeV

  - Coherent framework for the determination of coupling and CP properties

  - Development of improved methods for property determination

  - Analysis of rare, invisible and SM-forbidden decays

Main topics of the B9 project (from the proposal)

- Interpretation of the experimental results in the Higgs sector in terms of possible scenarios of electroweak symmetry breaking

  - Confrontation of the experimental results with different models

  - Development of public tools and incorporation of other constraints

Main topics of the B9 project (from the proposal)

- Strategies for probing BSM interpretations with future analyses at the LHC
  - Information from the state observed at about 125 GeV
  - Phenomenology of additional Higgs states
  - Phenomenology involving other states of new physics

Some theory activities during phase 2 of the SFB

SFB-funded postdocs: *O. Stål, F. Domingo*

Main focus: BSM phenomenology + interpretation

- A light Higgs in SUSY cascades? *[O. Stål, G. W. '11]*

  Example: NMSSM scenario, light $\mathcal{CP}$-even Higgs,
  $20\ \mathrm{GeV} < M_{\mathrm{h}_1} < 110\ \mathrm{GeV}$, in agreement with all search limits
  (large singlet component)

  $\mu_{\mathrm{eff}} = -200\ \mathrm{GeV},\ M_1 = 300\ \mathrm{GeV},\ M_2 = 600\ \mathrm{GeV}$

  $M_{\mathrm{SUSY}} = 750\ \mathrm{GeV},\ m_{\tilde{\mathrm{g}}} = 1\ \mathrm{TeV}$

  ⇒ Higgs production in chargino and neutralino decays
  in SUSY cascades

$$\tilde{q} \to q\tilde{\chi}_i^0 \to q\tilde{\chi}_1^0 h_k \to q\tilde{\chi}_1^0 b\bar{b}$$

$$\tilde{g} \to g\tilde{q} \to gq\tilde{\chi}_i^0 \to gq\tilde{\chi}_1^0 h_k \to gq\tilde{\chi}_1^0 b\bar{b}$$

⇒ Could lead to a signal of SUSY + BSM Higgs at the same time

⟶ Analysis in DESY CMS group: *PhD thesis G. Mittag '15 + CMS pub.*

Interpretation of the signal at 125 GeV in extended Higgs sectors (SUSY): signal interpreted as light state h

- Most obvious interpretation: signal at about 125 GeV is interpreted as the lightest Higgs state h in the spectrum

- Additional Higgs states at higher masses

- Differences from the Standard Model (SM) could be detected via:

  - properties of h(125): deviations in the couplings, different decay modes, different CP properties, ...

  - detection of additional Higgs states: H, A → $\tau\tau$, H → hh, H, A → $\chi\chi$, ...

Interpretation of the signal in terms of the light MSSM Higgs boson

- Detection of a SM-like Higgs with $M_H > 135$ GeV would have unambiguously ruled out the MSSM (with TeV-scale masses)

- Signal at 125 GeV is well compatible with MSSM prediction

- Observed mass value of the signal gives rise to lower bound on the mass of the CP-odd Higgs: $M_A > 200\ \mathrm{GeV}$

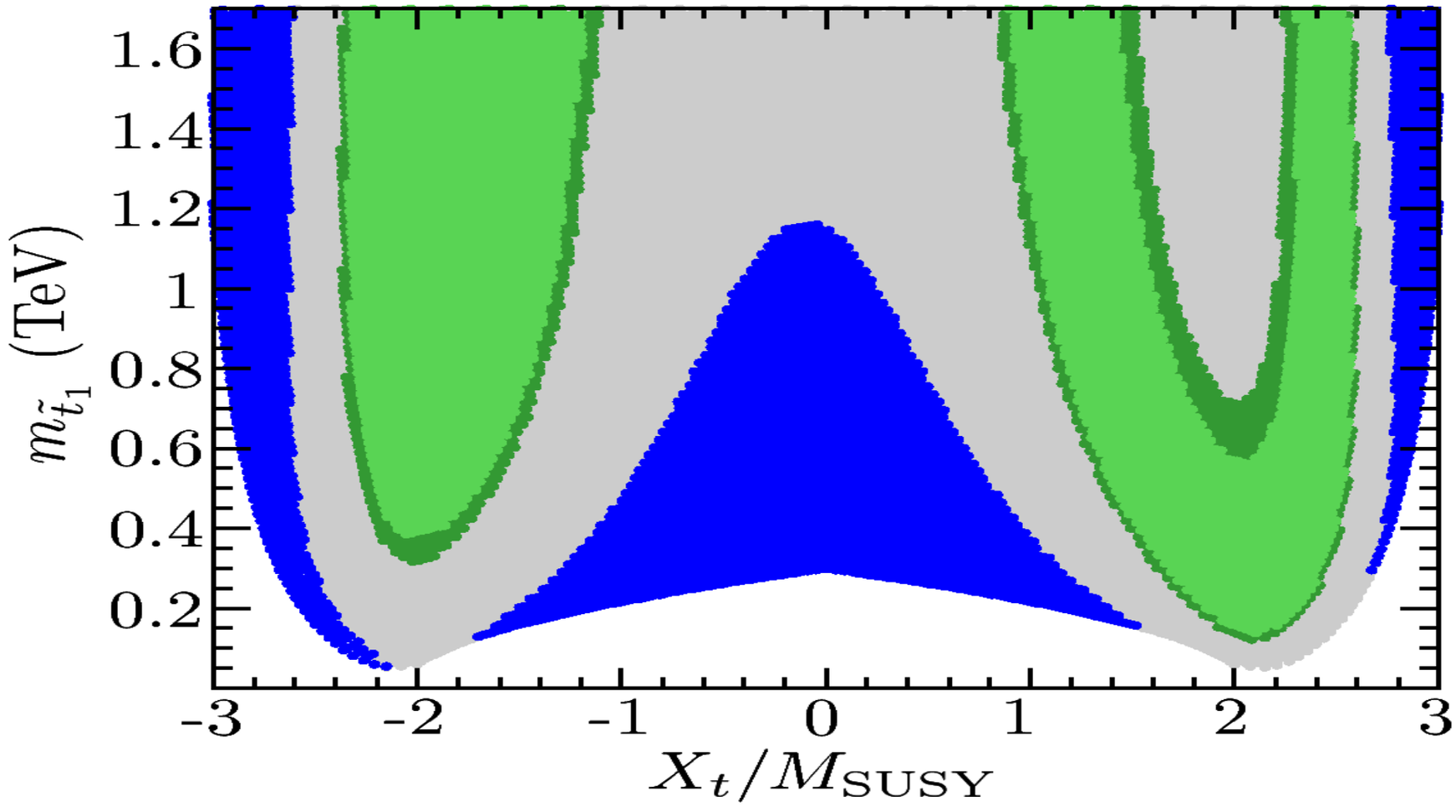
- $\Rightarrow M_A \gg M_Z$: ``Decoupling region" of the MSSM, where the light Higgs h behaves SM-like

- $\Rightarrow$ Would not expect observable deviations from the SM at the present level of accuracy

Lower bound on the lightest stop mass

- Lower bound on lightest stop mass from compatibility of the MSSM Higgs mass prediction for the lightest state h with the observed signal at 125 GeV

[S. Heinemeyer, O. Stål, G. W. '11 '12]



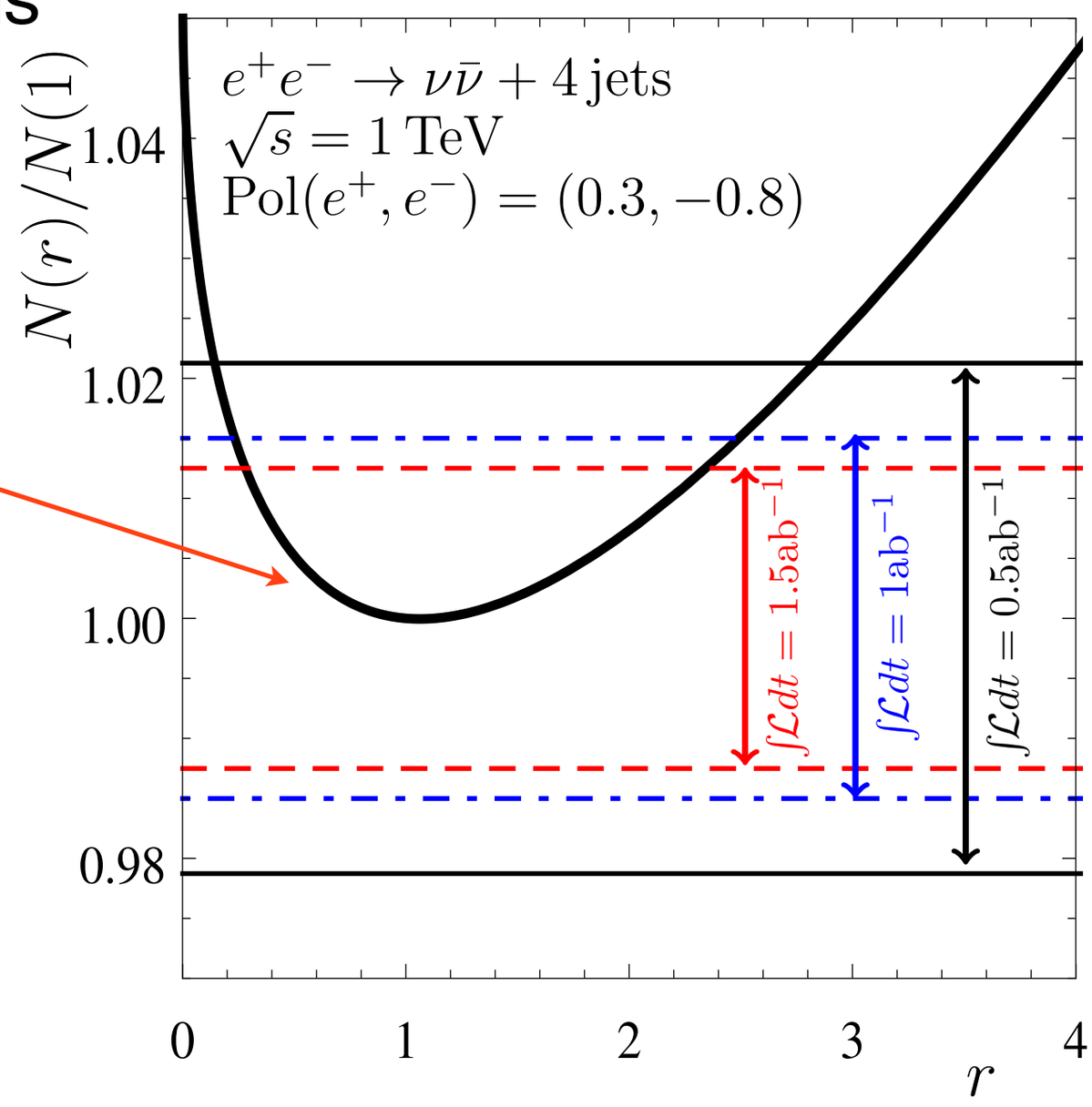
$\Rightarrow m_{\tilde{t}_1} > 150\ (300)\ \mathrm{GeV}$ for positive (negative) X_t

⇒ h(125) is compatible with a light stop!

LC: constraints on the Higgs width via off-shell effects

Same theoretical assumptions as in LHC analyses

[S. Liebler, G. Moortgat-Pick, G. Weiglein '15]



Large negative signal - background interference (reason: unitarity cancellations)

$$N(r) = N_0(1 + R_1\sqrt{r} + R_2 r)$$

$r = \Gamma/\Gamma_{SM}$

⇒ Limited sensitivity even with high integrated luminosity

Qualitative behaviour at the LHC is the same!

Incorporation of cross section limits and properties of the signal at 125 GeV: *HiggsBounds* and *HiggsSignals*

- Programs that use the experimental information on cross section limits (HiggsBounds) and observed signal strengths (HiggsSignals) for testing theory predictions *[P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein, K. Williams '08, '12, '13]*

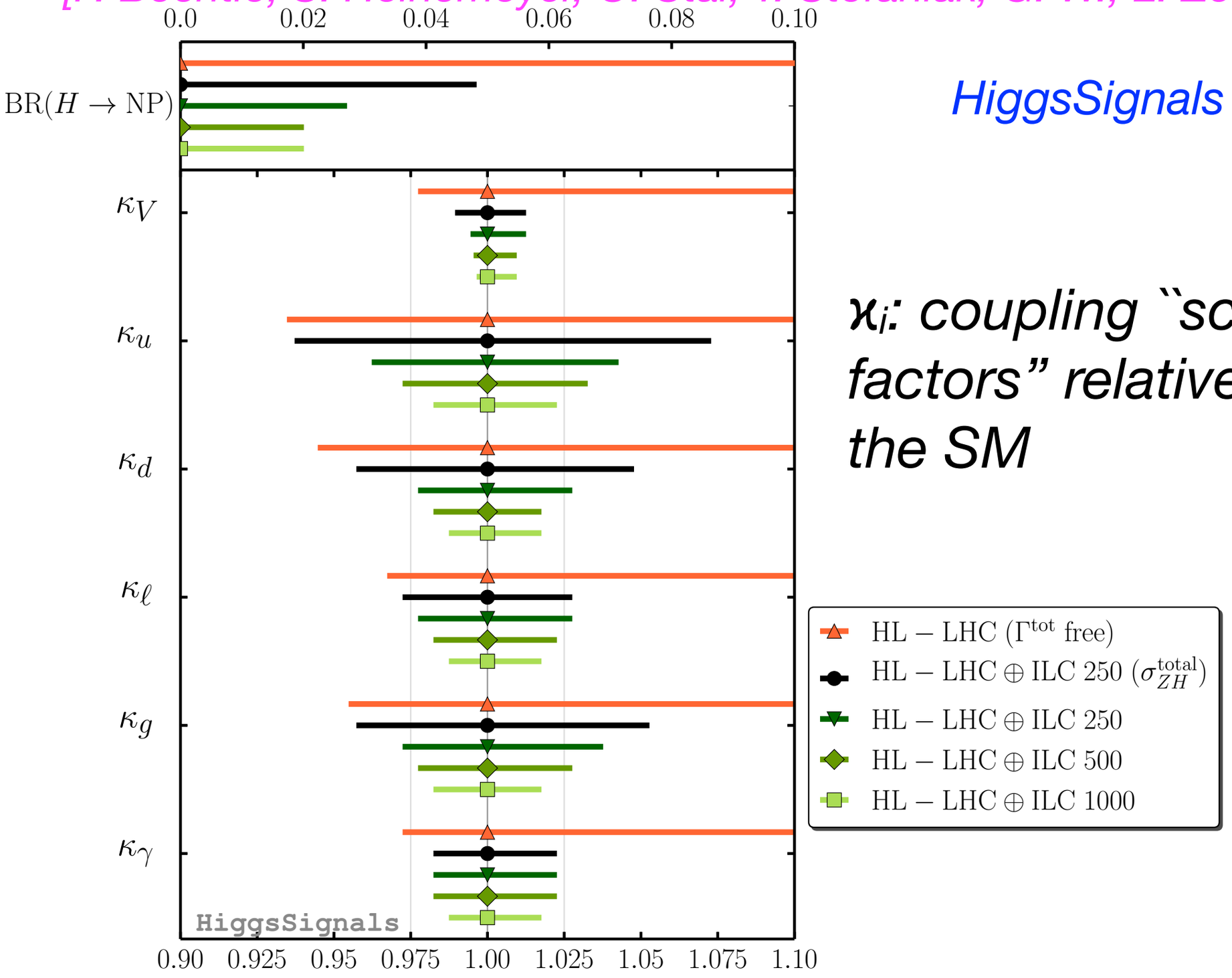
- *HiggsSignals:* *[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein '13]*

- Test of Higgs sector predictions in arbitrary models against measured signal rates and masses

- Systematic uncertainties and correlations of signal rates, luminosity and Higgs mass predictions taken into account

Prospects for Higgs-coupling determinations at HL-LHC, ILC without theory assumption on total width

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '14]



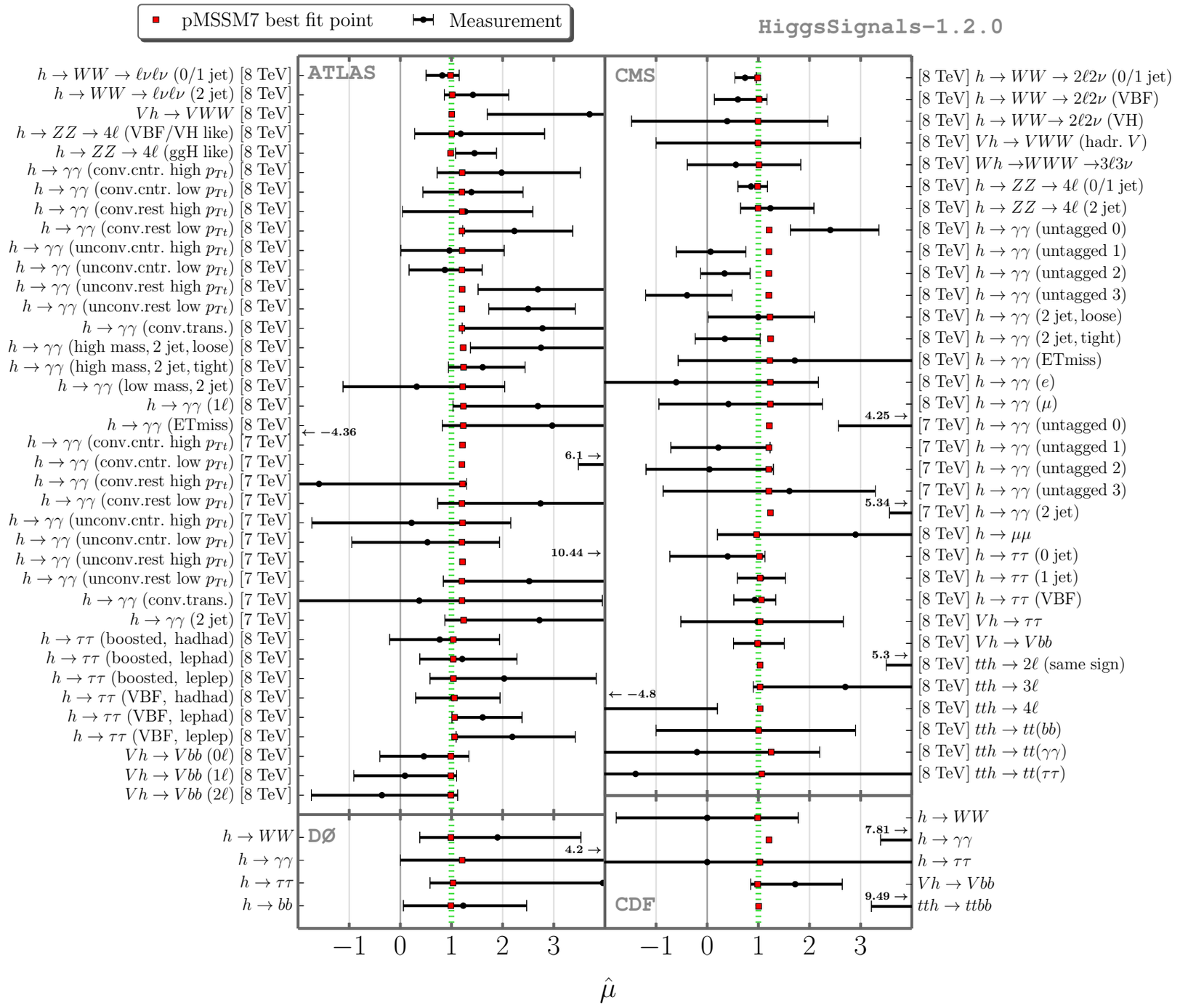
HiggsSignals

κ_i: coupling ``scale factors" relative to the SM

SUSY interpretation of the observed Higgs signal: light Higgs h
Fit to LHC data, Tevatron, precision observables: SM vs. MSSM

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '14]

Observables:



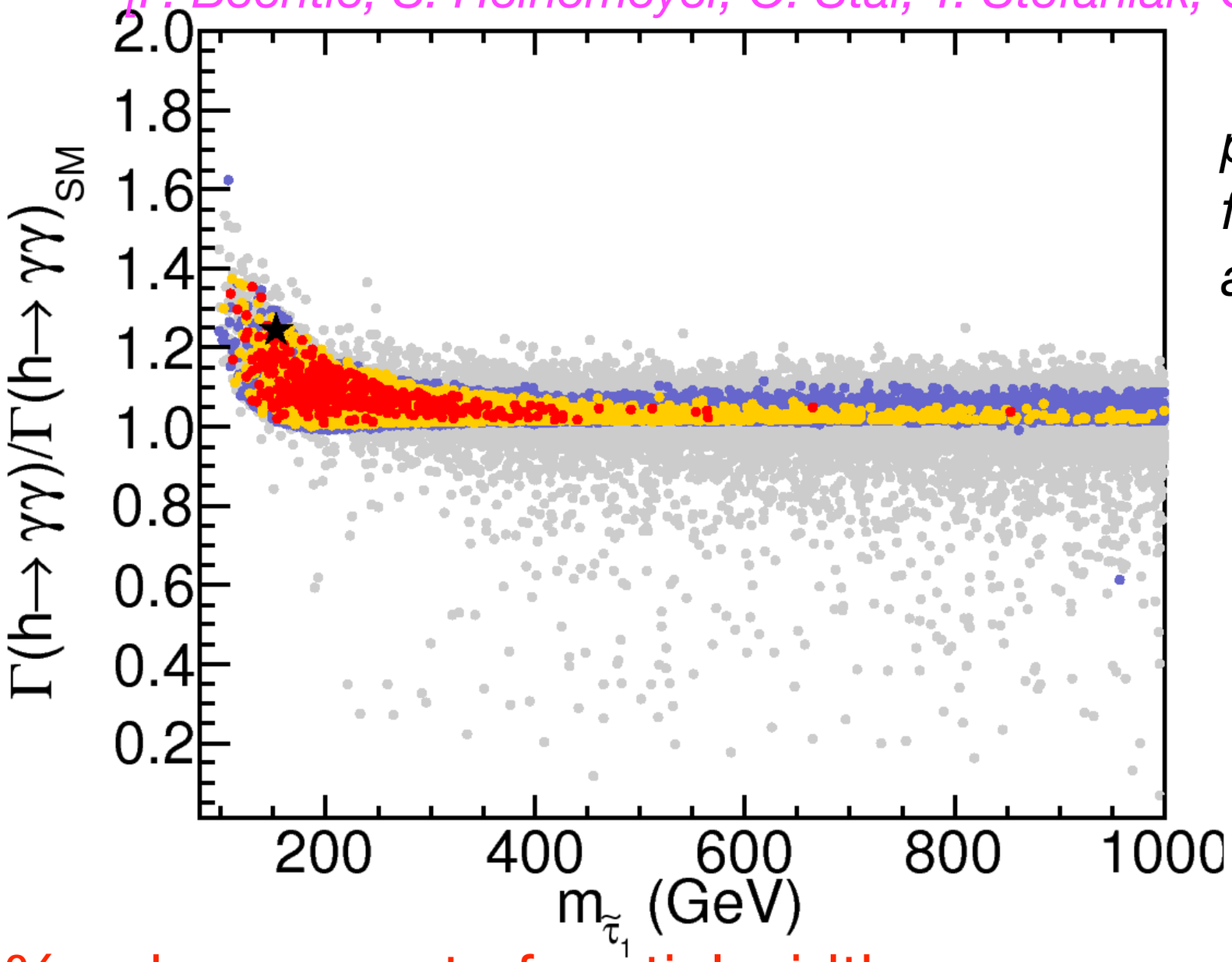
HiggsSignals

$$\mu_i = \frac{(\sigma \times \mathrm{BR})_i}{(\sigma \times \mathrm{BR})_i^{\mathrm{SM}}}$$

⇒ χ^2 reduced compared to the SM, (slightly) improved fit quality

Best fit prefers enhanced $\gamma\gamma$ rate from light staus

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '14]



pre-ICHEP data from ATLAS and CMS

⇒ ≈20% enhancement of partial width

Fit assumes slepton mass universality: $M_{\tilde{E}_{1,2}} = M_{\tilde{L}_{1,2}} = M_{\tilde{l}_3}$

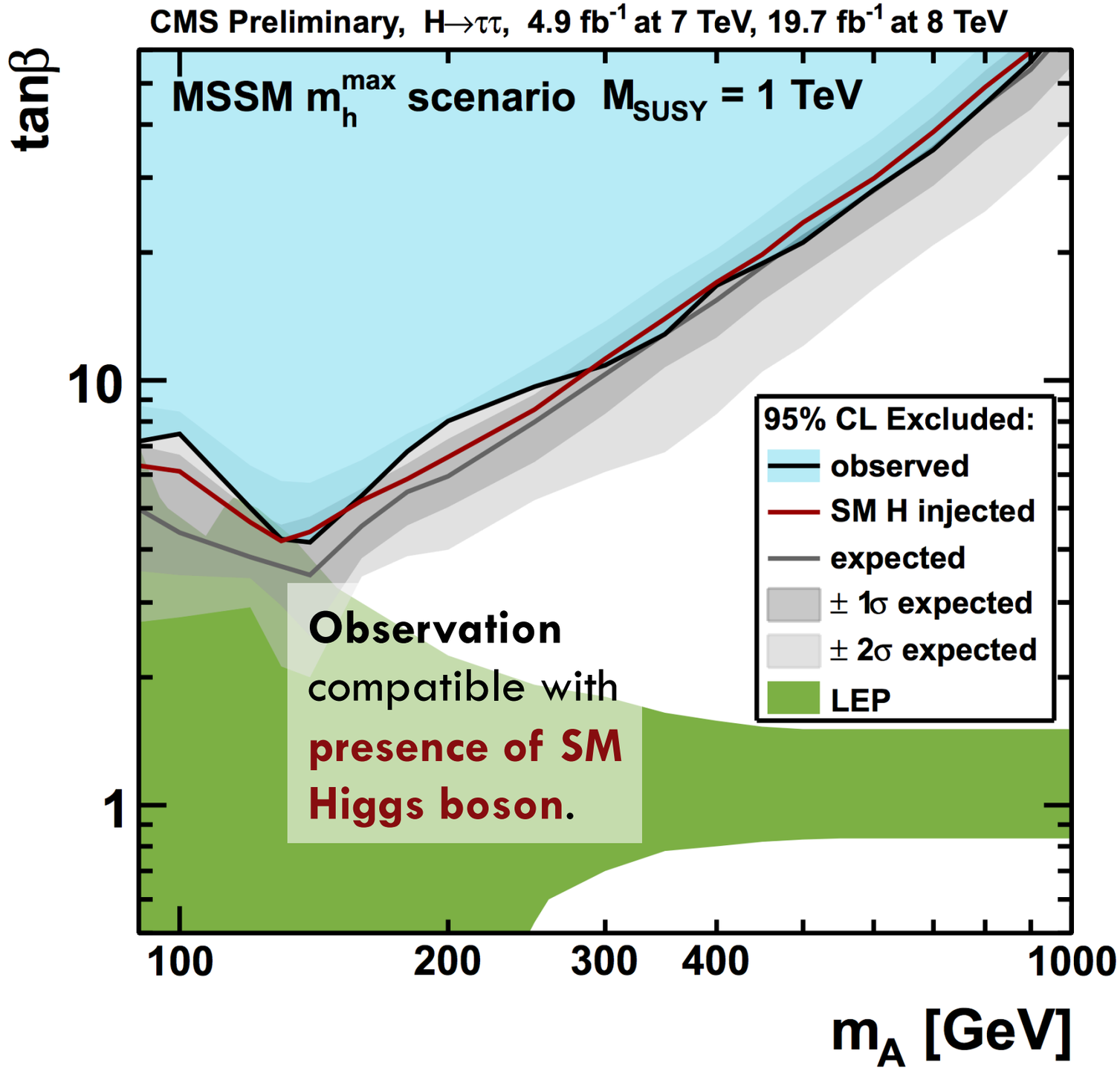
⇔ Also impact from $g_\mu - 2$

CMS result for h, H, A → $\tau\tau$ search

[CMS Collaboration '14]

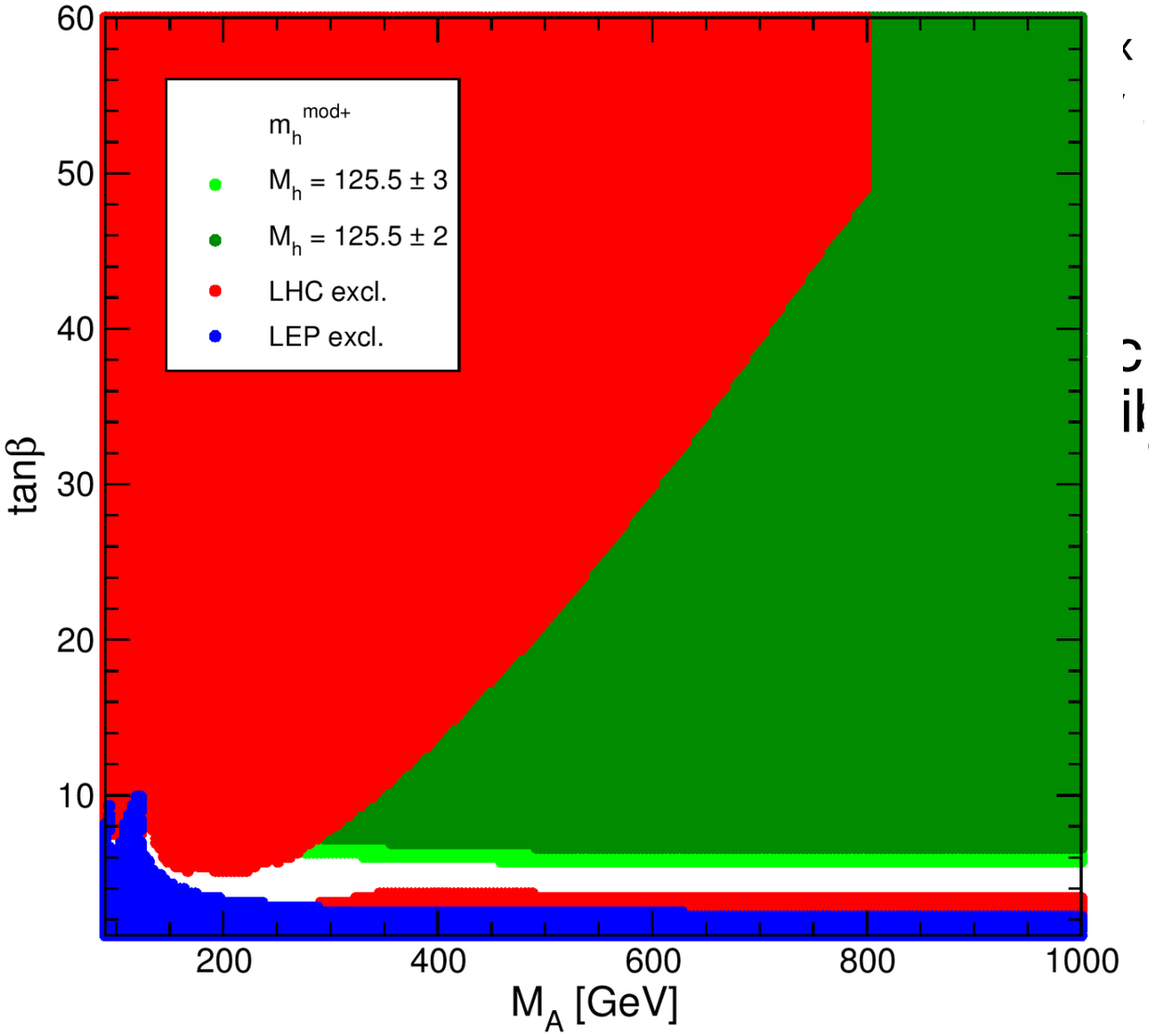
Analysis starts to become sensitive to the presence of the signal at 125 GeV

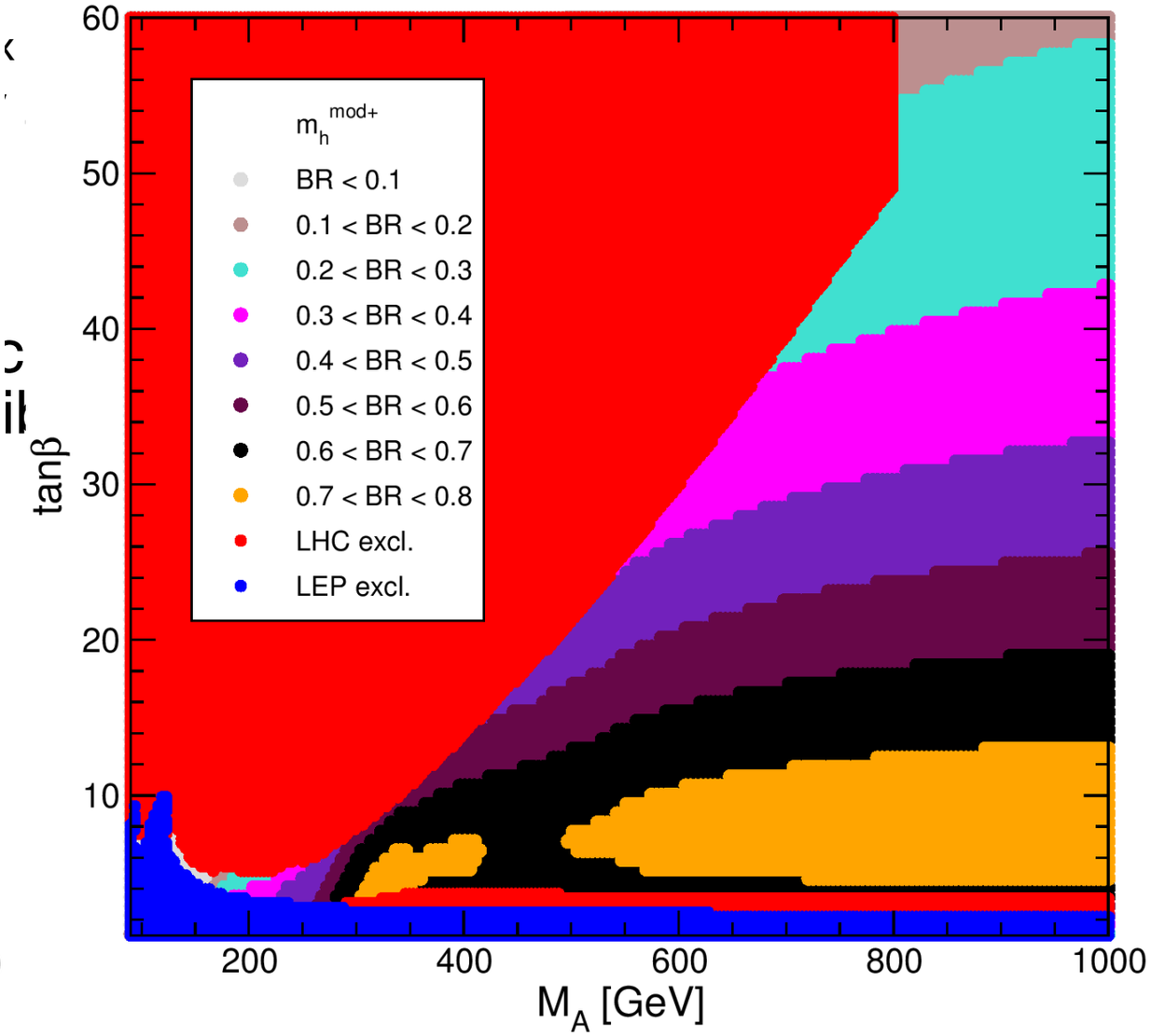
⇒ Searches for Higgs bosons of an extended Higgs sector need to test compatibility with the signal at 125 GeV (→ appropriate benchmark scenarios) and search for additional states



m_h^{mod} benchmark scenario

[M. Carena, S. Heinemeyer, O. Stål, C. Wagner, G. W. '14]





Small modification of well-known m_h^{max} scenario where the light Higgs h can be interpreted as the signal at 125 GeV over a wide range of the parameter space

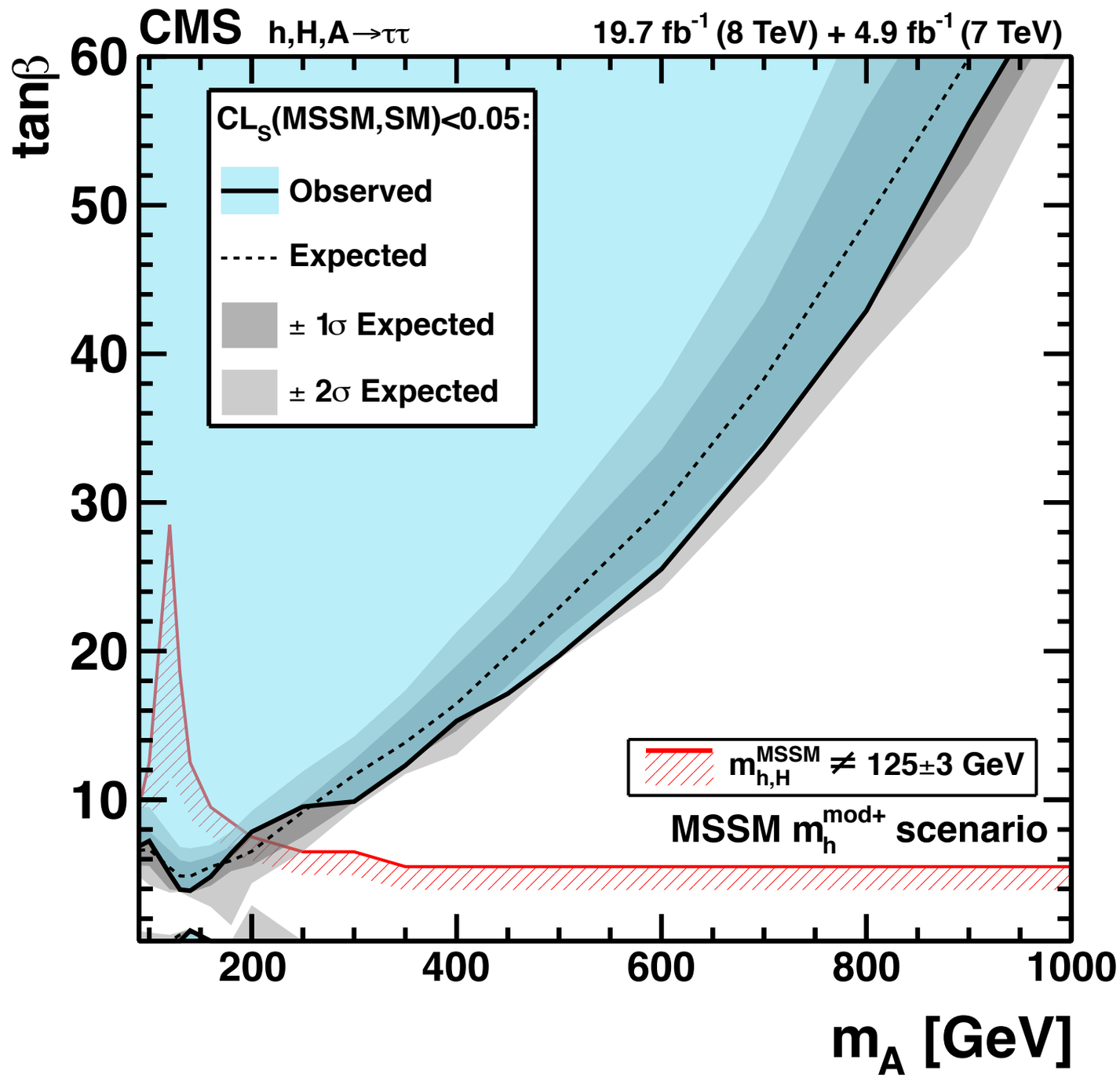
Large branching ratios into SUSY particles (right plot) and sizable BR(H → hh), up to 30%, for rel. small tanβ possible

CMS result for h, H, A → $\tau\tau$ search

[CMS Collaboration '14]

m_h^{mod} benchmark scenario

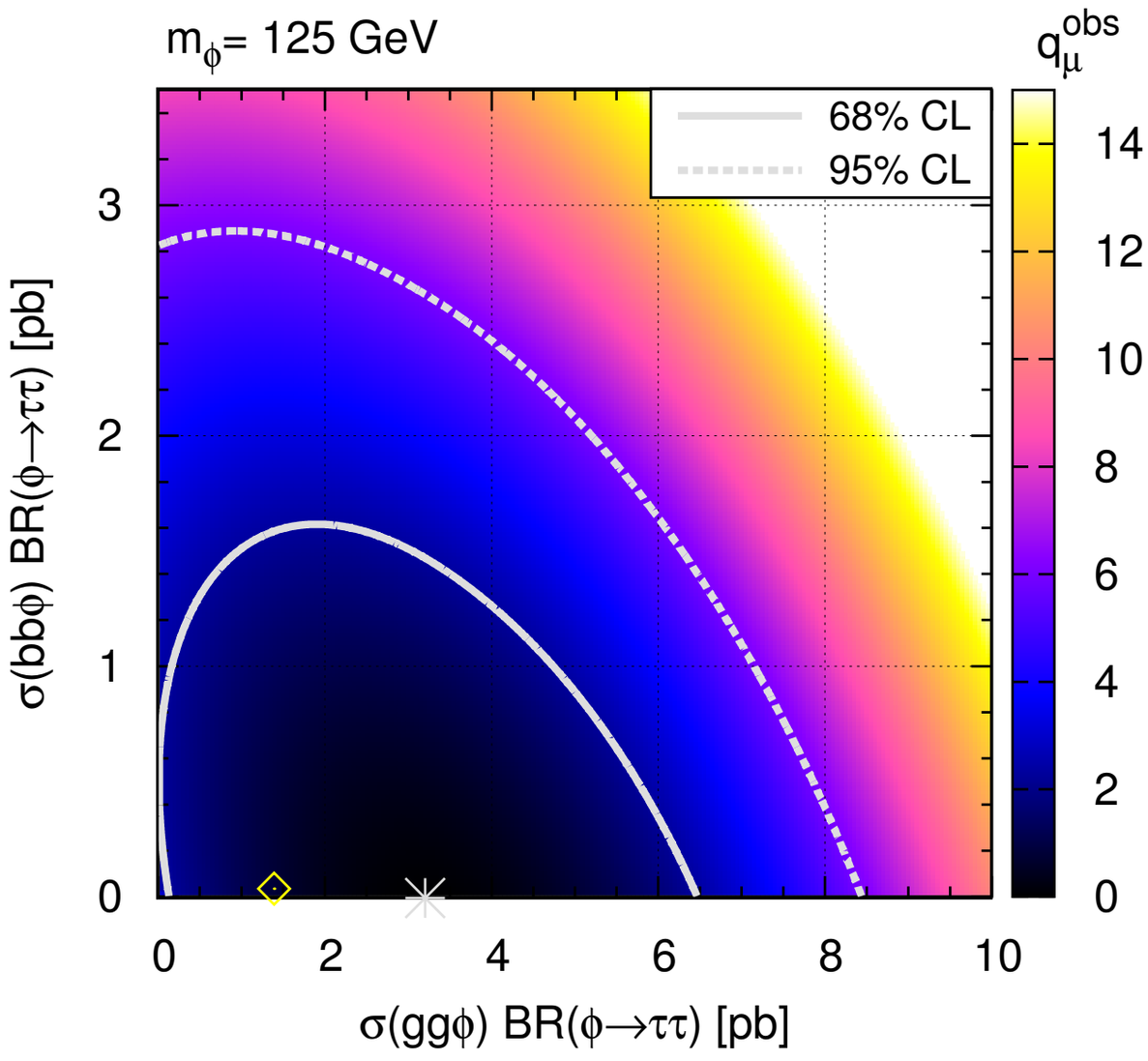
Test of compatibility of the data to the signal of h, H, A (MSSM) compared to SM Higgs boson hypothesis



Heavy non-standard Higgses: application of CMS result in $\tau\tau$ channel and impact of interference contributions

- CMS has published likelihood information for searches for a narrow Higgs resonance in $\tau\tau$ channel as function of the two production channels gluon fusion and b associated production
  [CMS Collaboration '14]
- Simple algorithm for mapping arbitrary models with several Higgses to narrow resonance model, incorporation into *HiggsBounds*

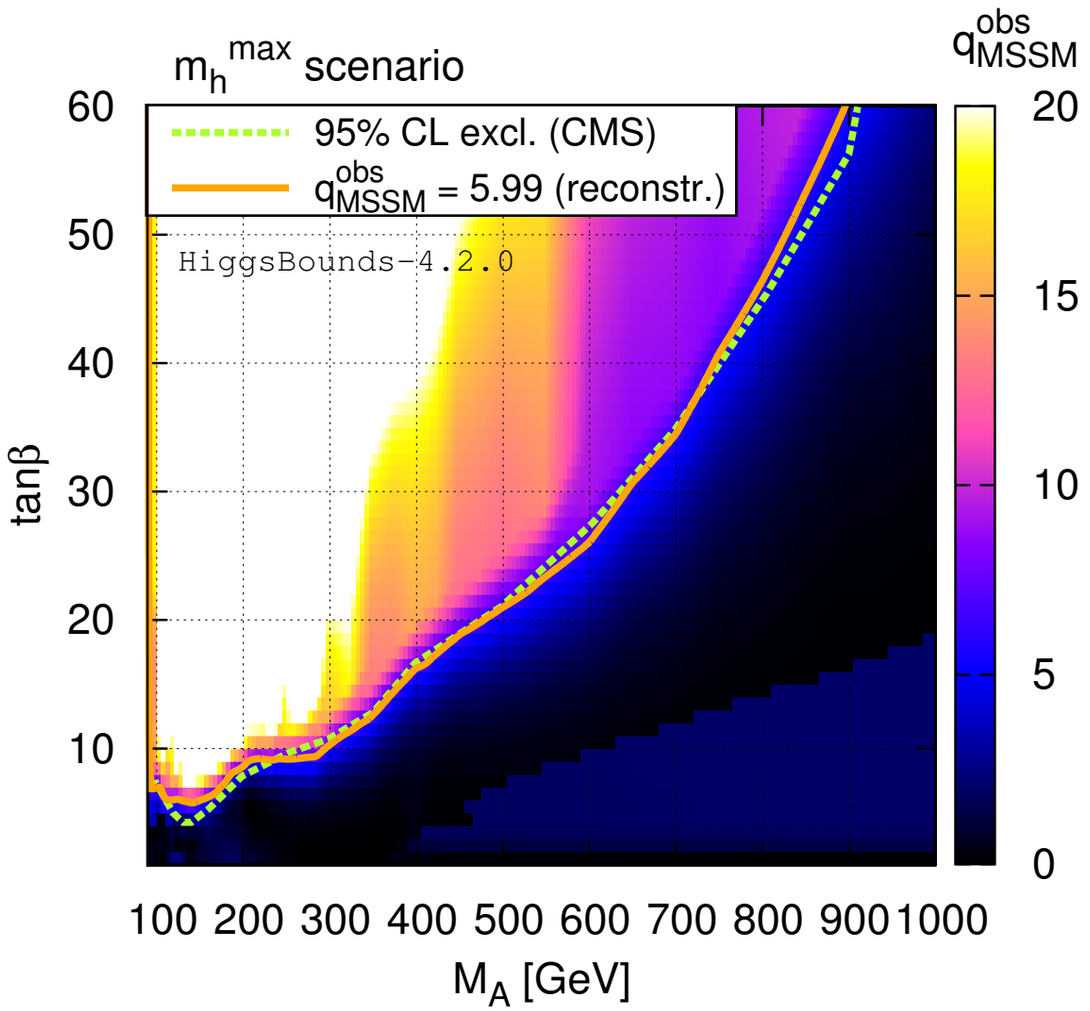
[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W. '15]



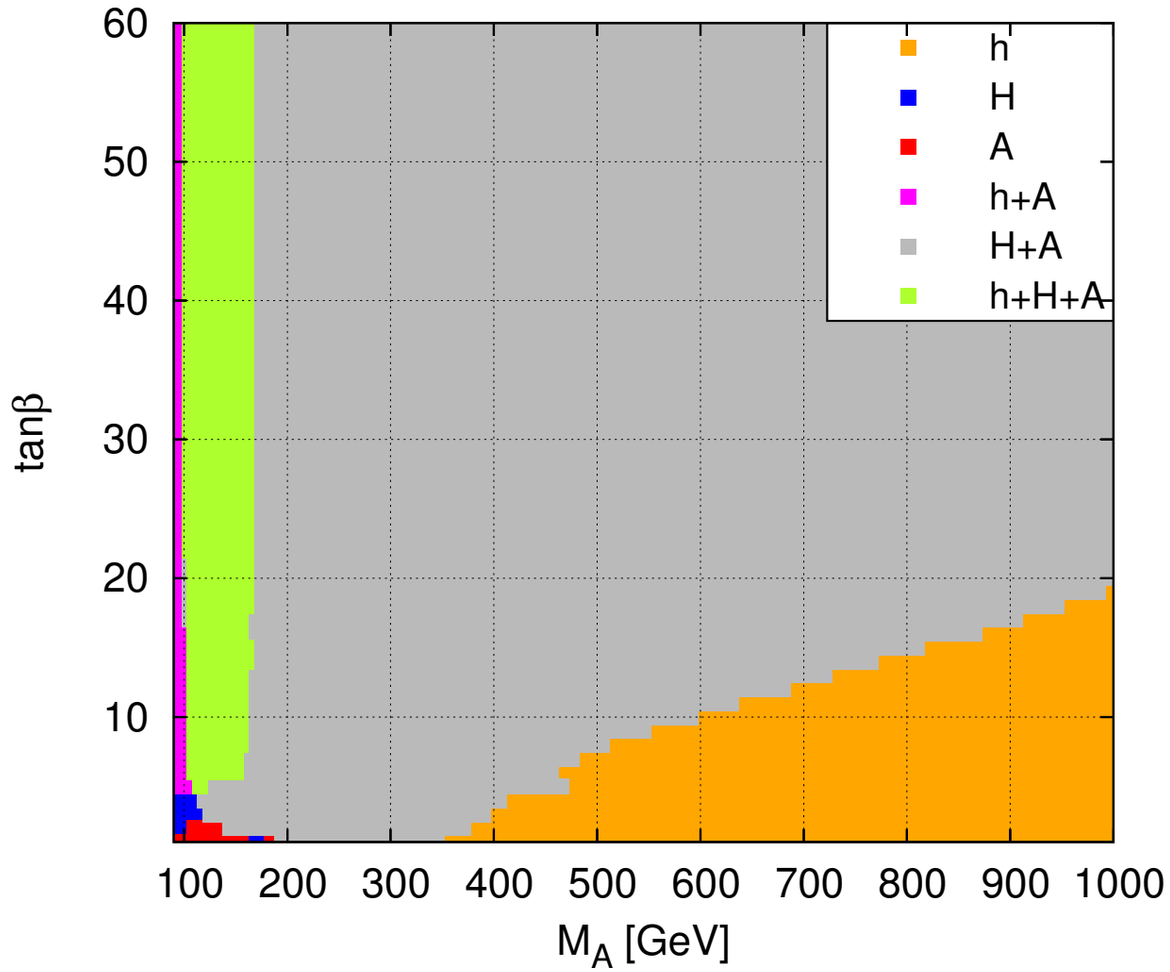
Validation: comparison with exclusion limit from dedicated CMS analysis in m_h^{max} benchmark scen.

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W. '15]

Likelihood distribution and excl. limits:



Signal combinations (incoherent sum):



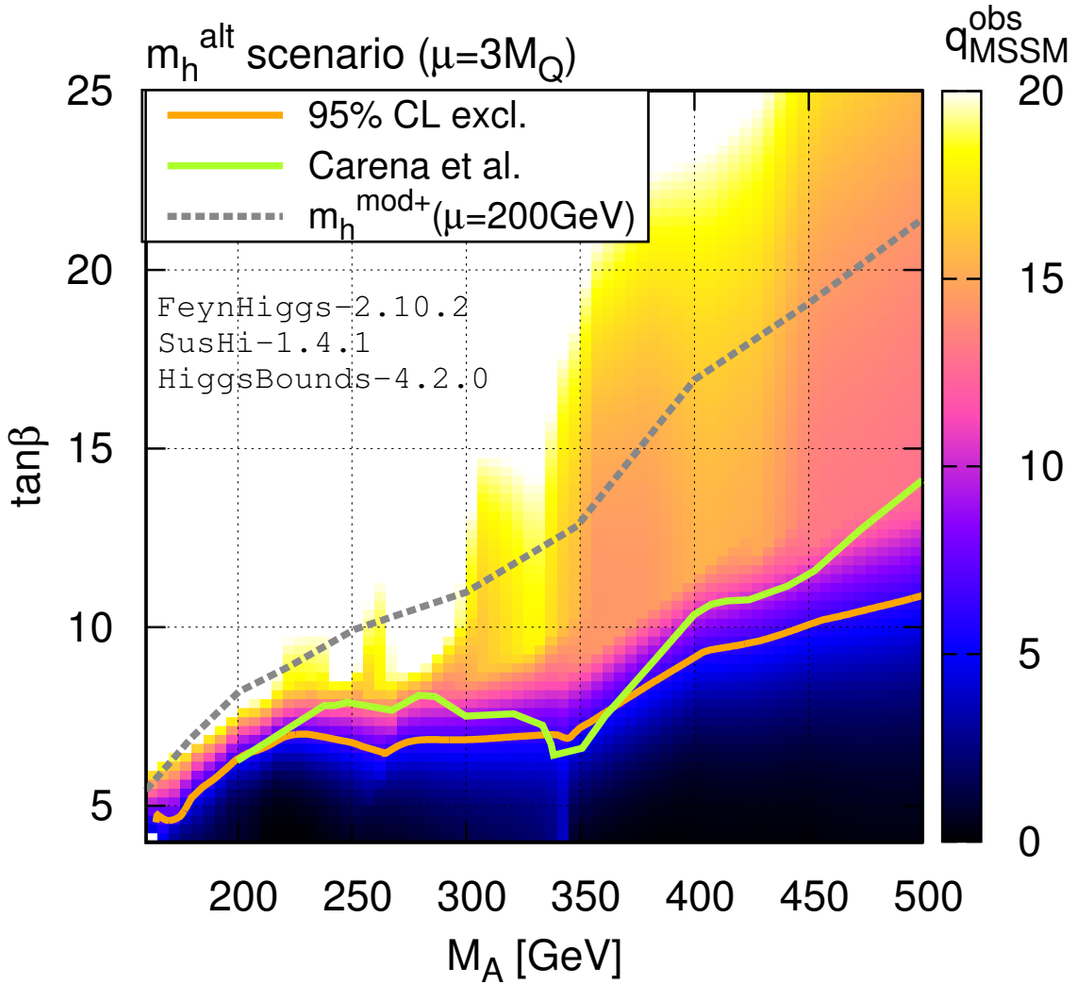
⇒ Good agreement with dedicated CMS analysis in the benchmark scenario (proper combination of channels possible)

Application to the m_h^{alt} benchmark scenario: ``alignment without decoupling"

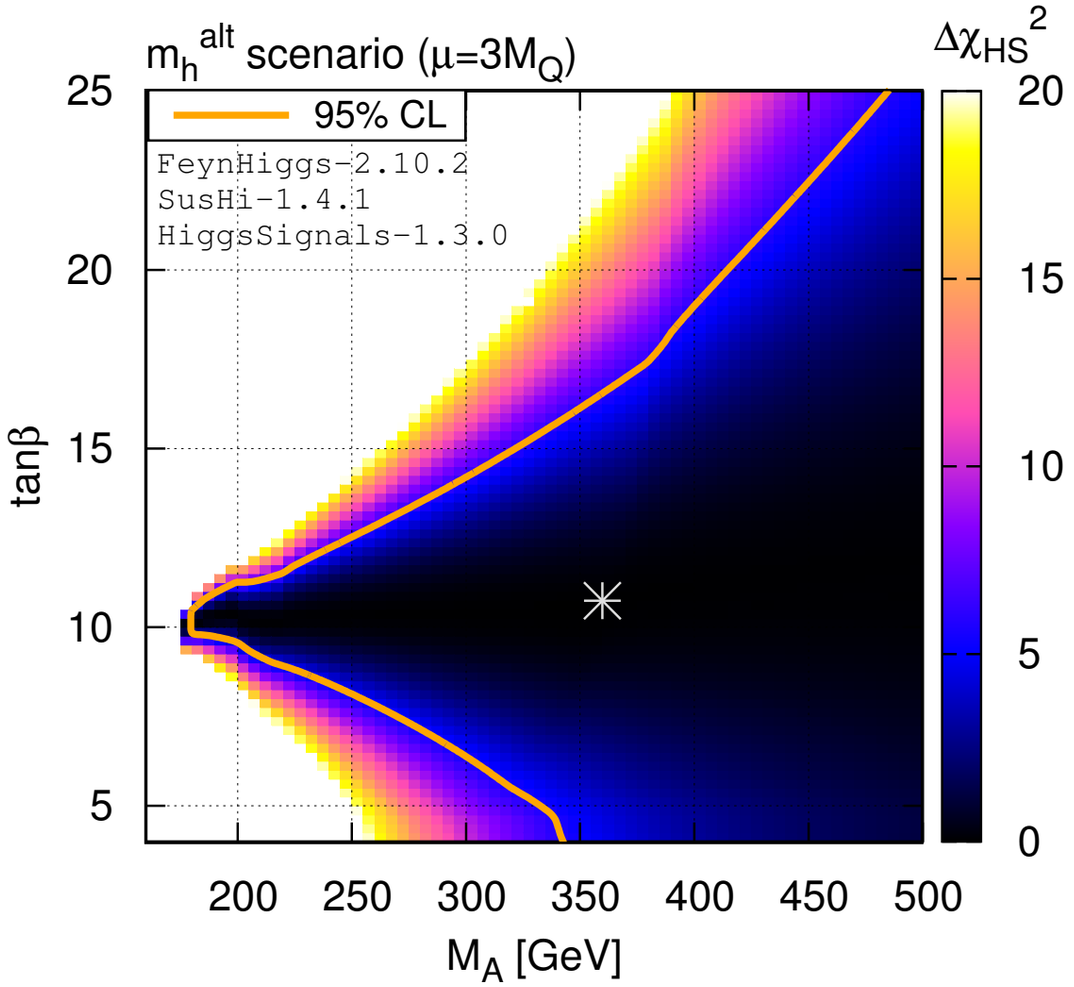
Alignment without decoupling: h in the MSSM behaves SM-like even for small values of M_A, m_h^{alt} scen. *[M. Carena, H. Haber, I. Low, N. Shah, C. Wagner'15]*

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W. '15]

Likelihood distribution from H, A → $\tau\tau$:



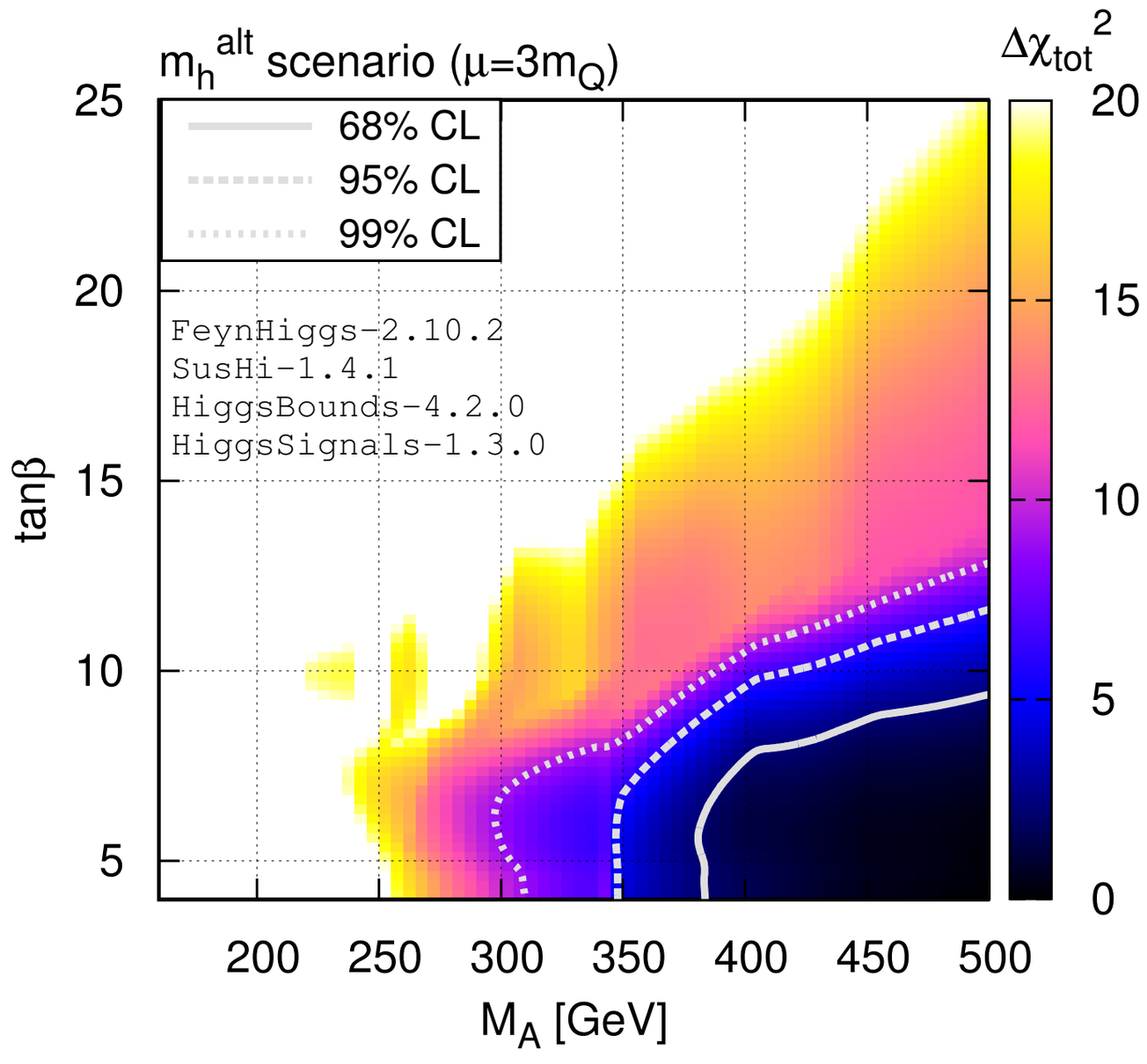
Likelihood from Higgs signal rates:



Combination of likelihood information from the Higgs signal rates and the search for heavy Higgses

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W. '15]

Public tools
HiggsBounds
and
HiggsSignals



⇒ Large impact on parameter space of the model
Lower limit on M_A from searches for heavy Higgses!

Search for heavy Higgs bosons at the LHC: impact of interference effects

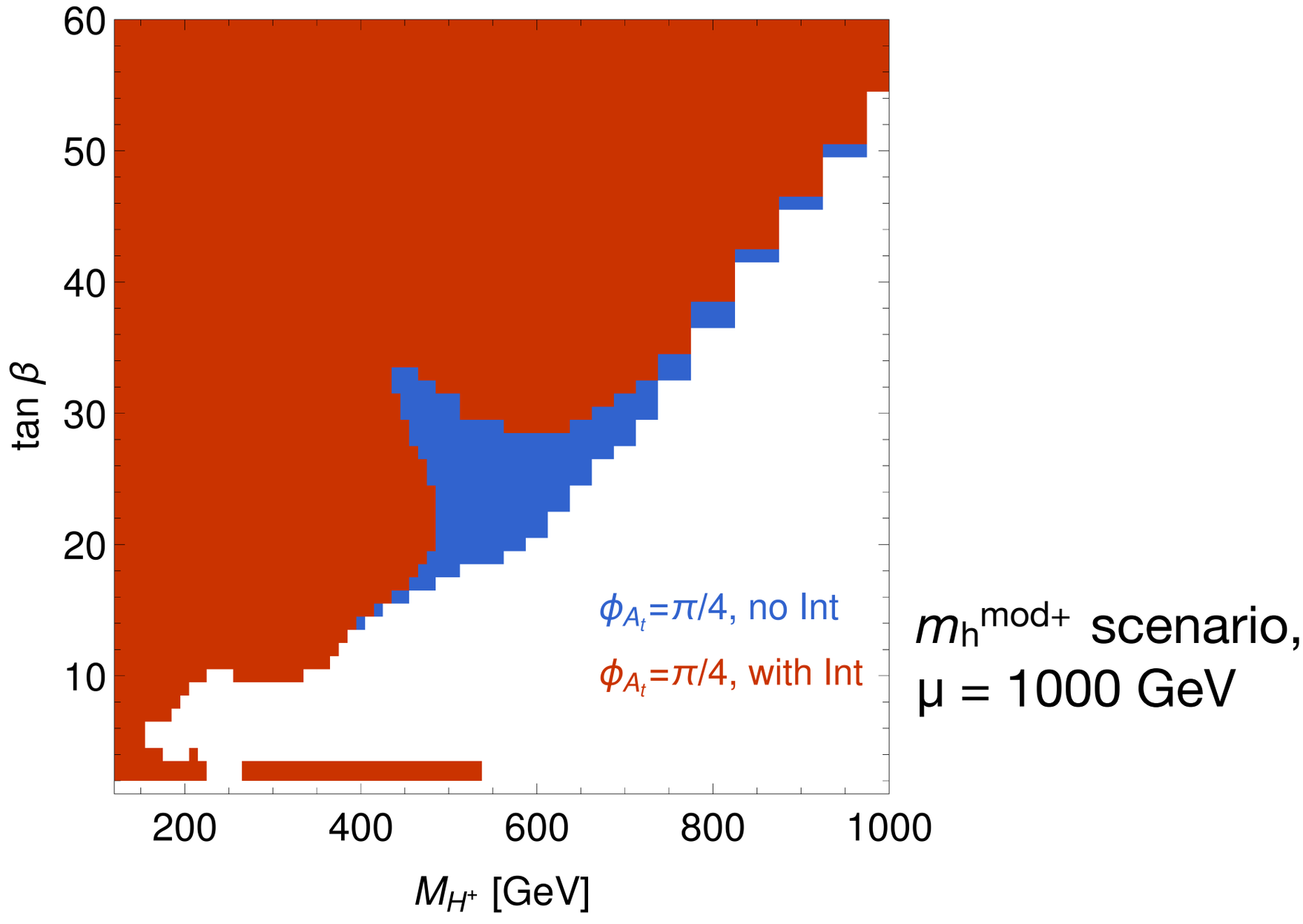
[E. Fuchs, G. W. '15]

Exclusion limits from neutral Higgs searches in the MSSM with and without interference effects:

CP-violating case,
$\Phi_{At} = \pi / 4$

H, A are nearly mass degenerate:
large mixing possible in CP-violating case!

Incoherent sum is not sufficient!



m_h^{mod+} scenario,
μ = 1000 GeV

⇒ Large CP-violating interference effects between H, A possible

Interpretation of the signal in extended Higgs sectors (SUSY): signal interpreted as next-to-lightest state H

Extended Higgs sector where the second-lightest (or higher) Higgs has SM-like couplings to gauge bosons

⇒ Lightest neutral Higgs with heavily suppressed couplings to gauge bosons, may have a mass below the LEP limit of 114.4 GeV for a SM-like Higgs (in agreement with LEP bounds)

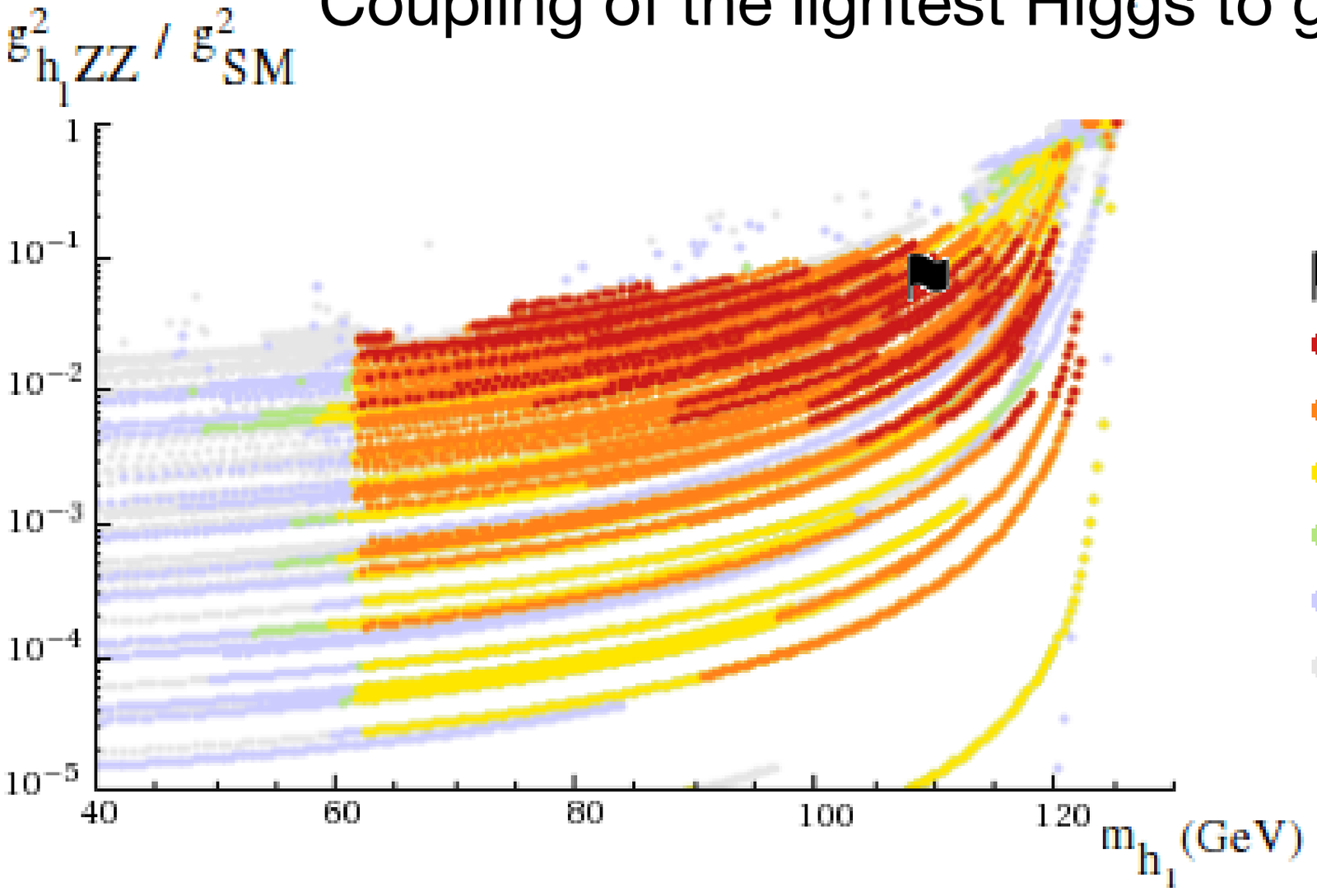
Possible realisations: 2HDM, MSSM, NMSSM, ...

A light neutral Higgs in the mass range of about 60-100 GeV (above the threshold for the decay of the state at 125 GeV into hh) is a generic feature of this kind of scenario. The search for Higgses in this mass range has only recently been started at the LHC. Such a state could copiously be produced in SUSY cascades.

In the NMSSM such a situation arises generically if the Higgs singlet is light

Coupling of the lightest Higgs to gauge bosons:

[F. Domingo, G. W. '15]



⇒ SM-like Higgs at 125 GeV + singlet-like Higgs at lower mass

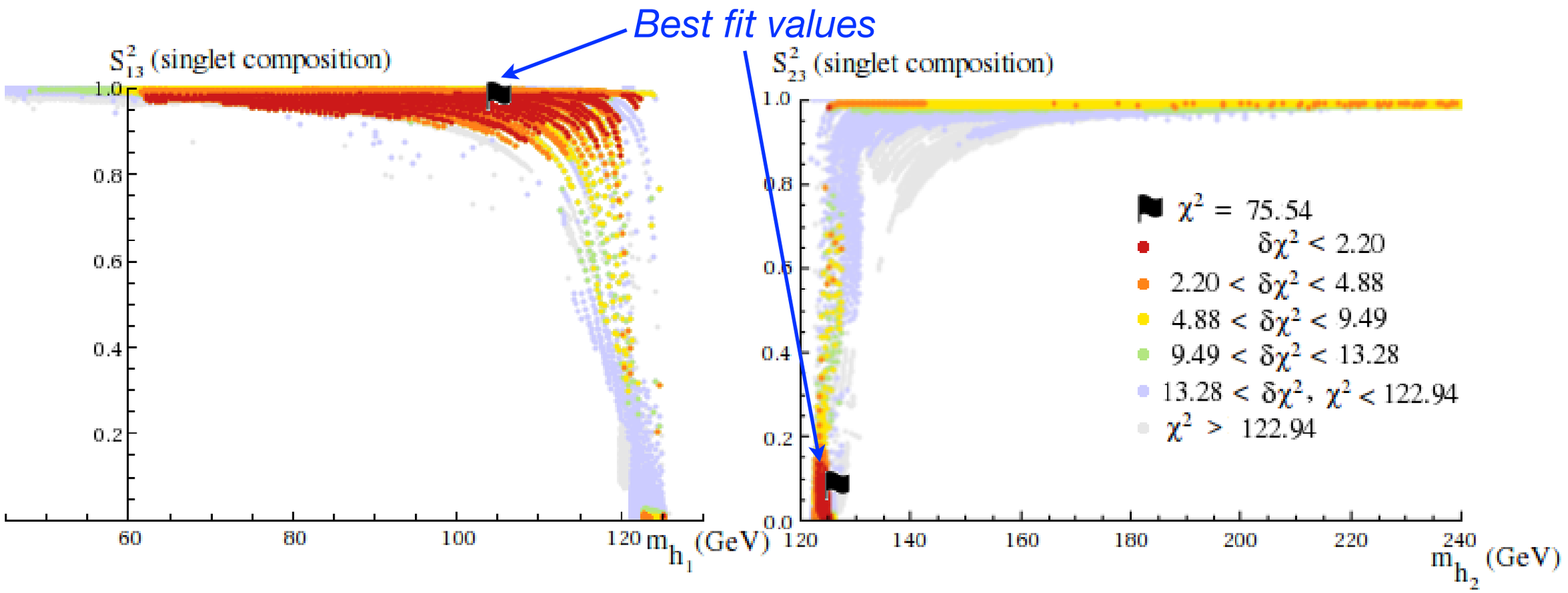
The case where the signal at 125 GeV is not the lightest Higgs arises generically if the Higgs singlet is light

⇒ Strong suppression of the coupling to gauge bosons

Theory: interpretation of the observed signal

Extended Higgs sector where h(125) is not the lightest state:
NMSSM with a SM-like Higgs at 125 GeV + a light singlet

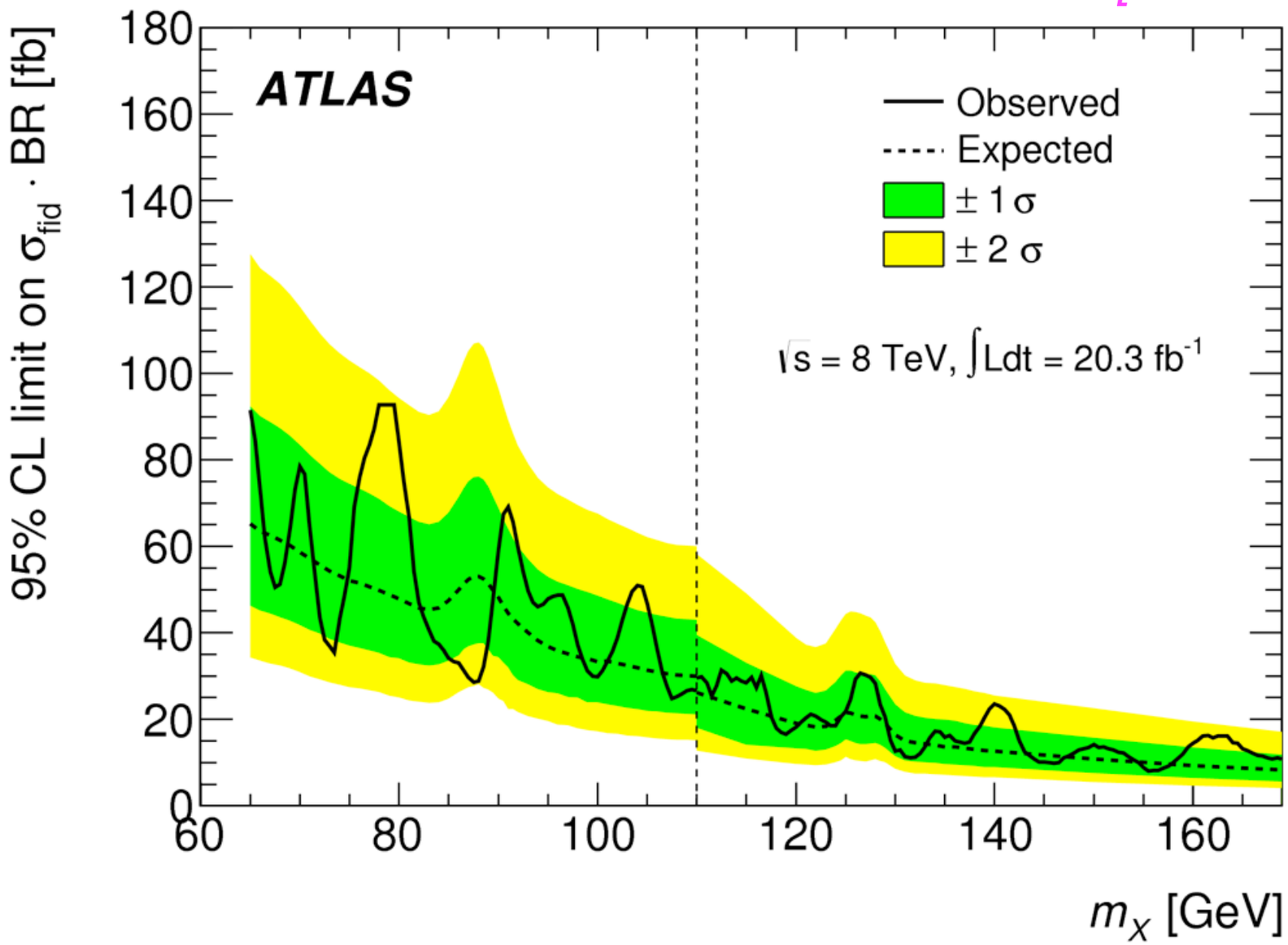
[F. Domingo, G. W. '15]



⇒ Additional light Higgs with suppressed couplings to gauge bosons, in agreement with all existing constraints

Are LHC searches sensitive to a low-mass Higgs with suppressed couplings to gauge bosons?

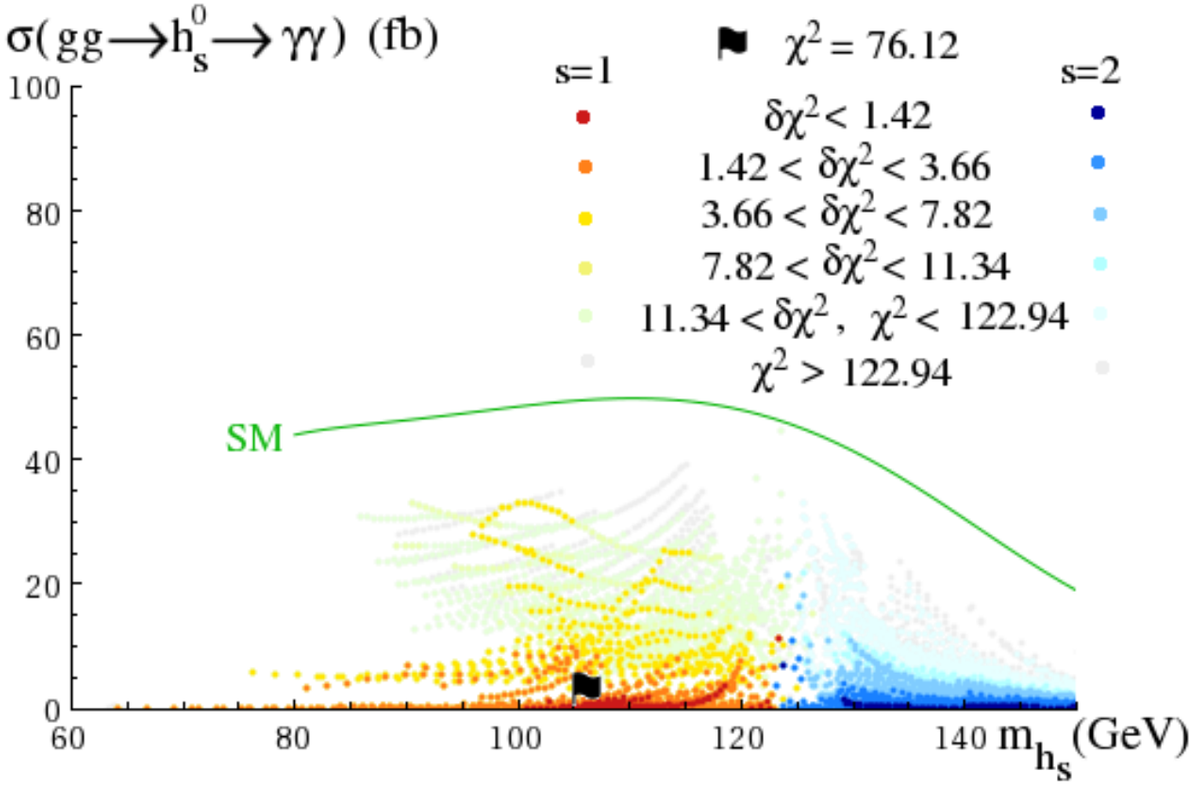
ATLAS h → $\gamma\gamma$ searches in the low-mass region: *[ATLAS Collaboration '14]*

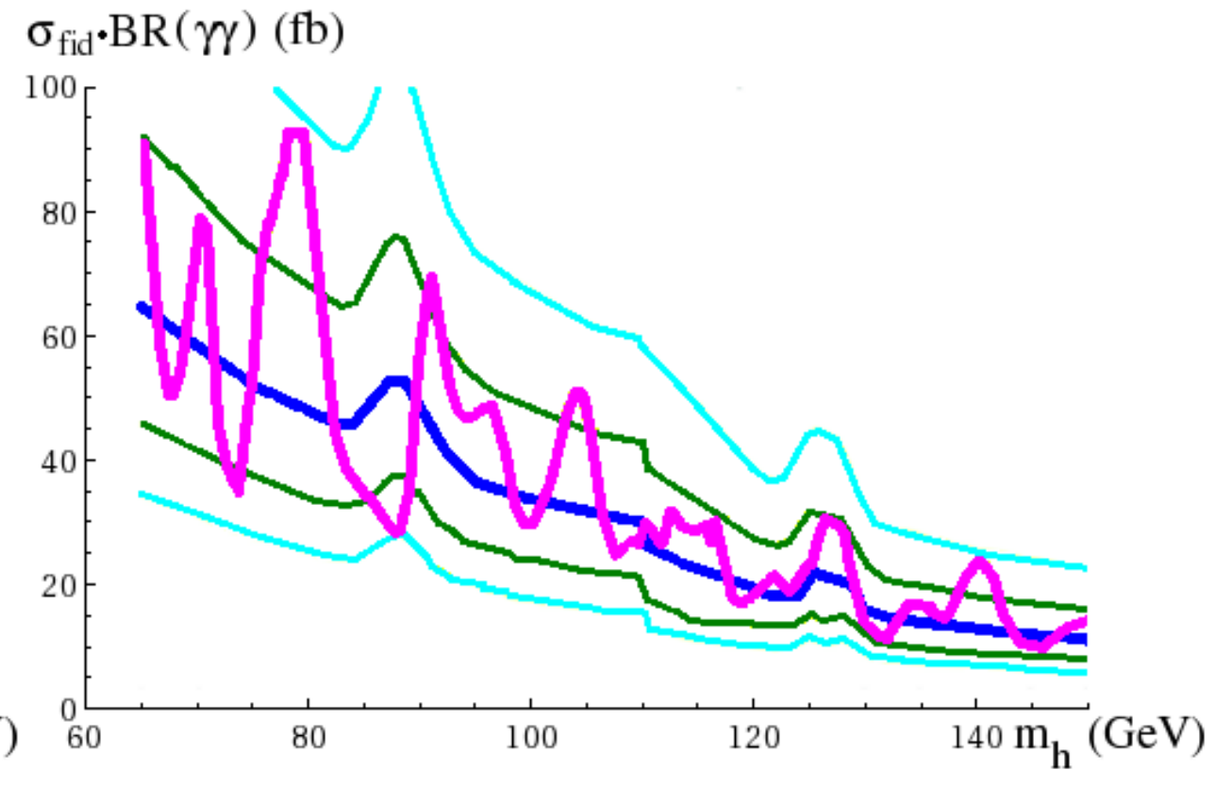


Example: MSSM, H(125) case: BR(h_1 → $\gamma\gamma$) = 8.5 10^{-7}, three orders of magnitude below BR for a SM-like Higgs of this mass (65 GeV)

Light NMSSM Higgs: comparison of gg →h_1 → $\gamma\gamma$ with the SM case and the ATLAS limit on fiducial σ

[F. Domingo, G. W. '15]





⇒ Limit starts to probe the NMSSM parameter space
But: best fit region is far below the present sensitivity

Such a light Higgs could be produced in a SUSY cascade, e.g.
$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$ *[O. Stål, G. W. '11] [CMS Collaboration '15]*

Ongoing theory activities during phase 3 within the wider context of the B9 project

Note: not a complete list, by far

- SM Higgs production processes, differential distributions, impact of jet vetoes, jet p_T resummation, … *[E. Bagnaschi, S. Liebler, J. Reuter, F. Tackmann, …]*

- Monte Carlo tools *[E. Bagnaschi, Z. Nagy, J. Reuter, F. Tackmann, …]*

- Boosted topologies *[C. Grojean, P. Pietrulewicz, F. Tackmann, …]*

- Analysis of Higgs couplings and CP properties, effective Lagrangians *[M. Chala, C. Grojean, P. Schwaller, G. Servant, G. W., …]*

- Sensitivity to an additional heavy Higgs boson of a Two-Higgs Doublet model (2HDM), impact of interference effects *[S. Liebler, N. Greiner, G. W.]*

Ongoing theory activities during phase 3 within the wider context of the B9 project

- SUSY Higgs production *[E. Bagnaschi, S. Liebler, S. Patel, G. W., …]*
- Phenomenology of Little Higgs models *[J. Reuter, …]*
- Vector-boson scattering *[J. Reuter, …]*
- Composite Higgs *[M. Chala, C. Grojean, T. Konstandin, O. Matsedonskyi, G. Servant, …]*
- Vacuum stability *[E. Bagnaschi, W. Buchmueller, S. Di Vita, G.C. Dorsch, W.G. Hollik, T. Konstandin, G.W., …]*
- Higgs-mass predictions in SUSY models: MSSM, NMSSM, … , high-scale SUSY models *[E. Bagnaschi, S. Di Vita, P. Drechsel, S. Passehr, A. Voigt, G.W., …]*

Ongoing theory activities during phase 3 within the wider context of the B9 project

- Development of tools for Higgs phenomenology: *FeynHiggs, eHDecay, HiggsBounds, HiggsSignals, SusHi, FlexibleSUSY, …* *[E. Bagnaschi, P. Drechsel, C. Grojean, S. Liebler, S. Passehr, S. Patel, A. Voigt, G. W., …]*

- Estimate of theoretical uncertainties from unknown higher-order corrections *[E. Bagnaschi, P. Drechsel, S. Passehr, A. Voigt, G. W., …]*

- Resonant Higgs mixing *[E. Fuchs, G. Weiglein]*

- Higgs-Dark matter interplay, Higgs-Axion interplay *[M. Chala, C. Grojean, A. Ringwald, K. Schmidt-Hoberg, P. Schwaller, S. Servant, …]*

- …

Conclusions

- Very rich and lively theory activities
- Great potential for interaction between experiment and theory
- For many topics there is a local expert (or more than one around)
  ⇒ Many opportunities for discussions, interaction, etc.