Extended Higgs sector phenomenology and interference effects

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Introduction

- The discovered signal is so far compatible with a SM-like Higgs, but a variety of interpretations is possible, corresponding to very different underlying physics: extended Higgs sectors, composite Higgs, …

- Extended Higgs sectors: one SM-like Higgs boson (not necessarily the lightest one in the spectrum) at 125 GeV + additional Higgs states: 2HDM, MSSM, NMSSM, …

- Test of extended Higgs sectors: search for / limits on additional Higgses + compatibility with the signal at 125 GeV

Search for additional Higgs bosons

In a large variety of models with extended Higgs sectors the squared couplings to gauge bosons fulfill a ``sum rule":

$$\sum_i g^2_{H_i VV} = \left(g^{\rm SM}_{HVV}\right)^2$$

$\Rightarrow$ •The SM coupling strength is ``shared" between the Higgses of an extended Higgs sector, $\varkappa_V \leqq 1$

•The more SM-like the couplings of the state at 125 GeV turn out to be, the more suppressed are the couplings of the other Higgses to gauge bosons; heavy Higgses usually have a much smaller width than a SM-like Higgs of the same mass

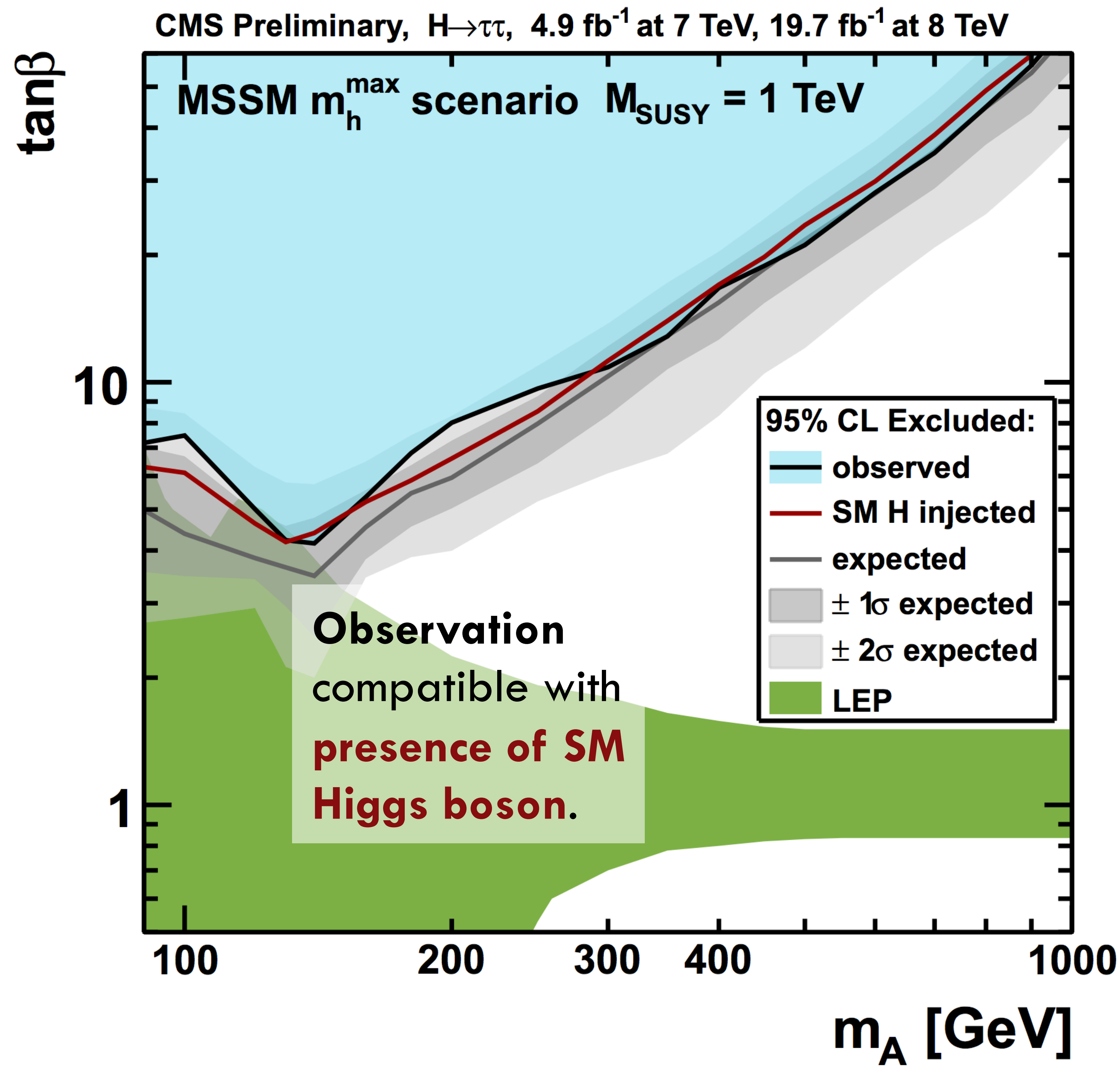
• Searches for additional Higgs bosons need to test compatibility with the observed signal at 125 GeV!

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

[CMS Collaboration '14]

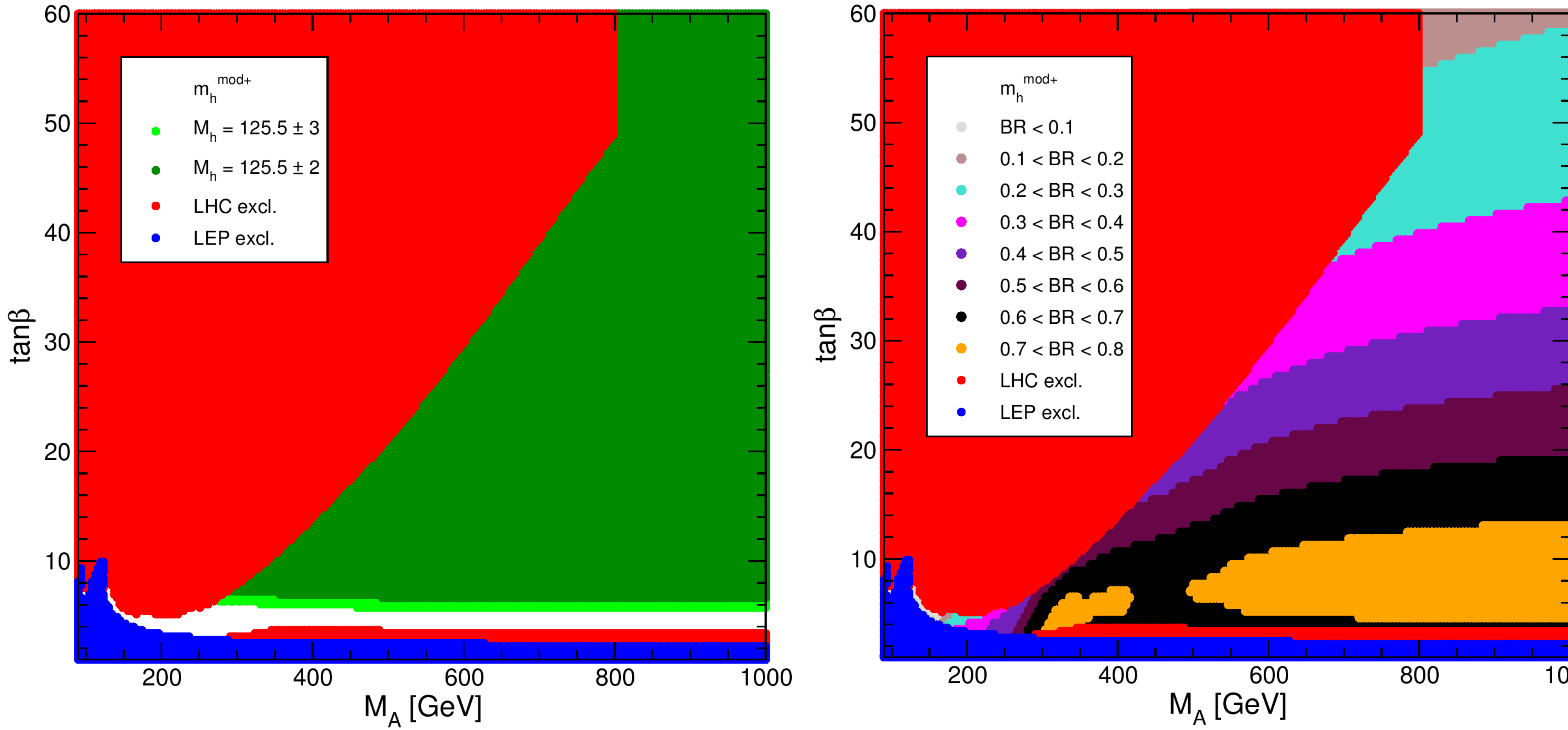
Analysis starts to become sensitive to the presence of the signal at 125 GeV

⇒ 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

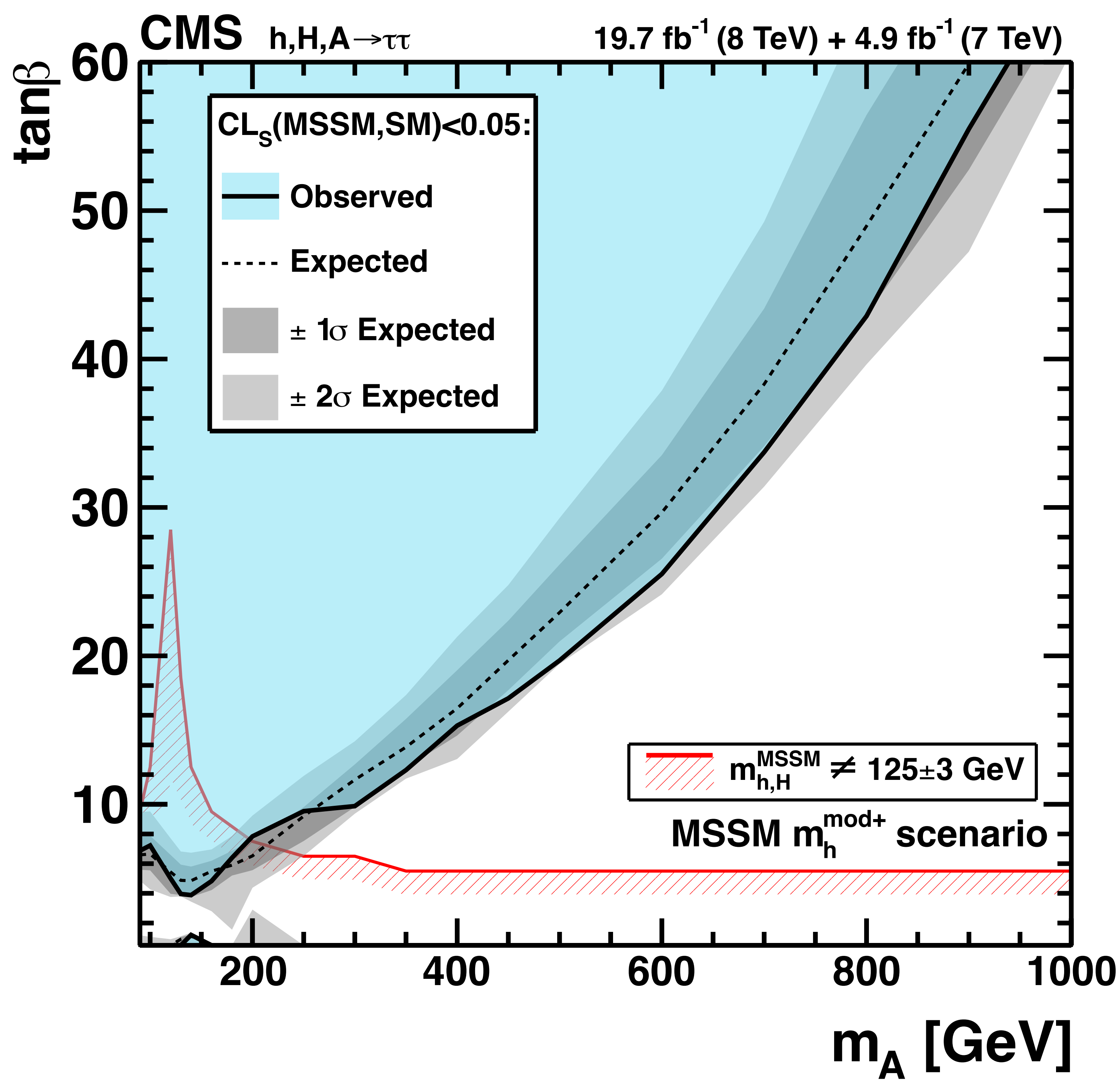
Large branching ratios into SUSY particles (right plot) and sizable BR(H → hh), up to 30%, for rel. small tanβ possible

CMS result for h, H, A → ττ 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



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]*

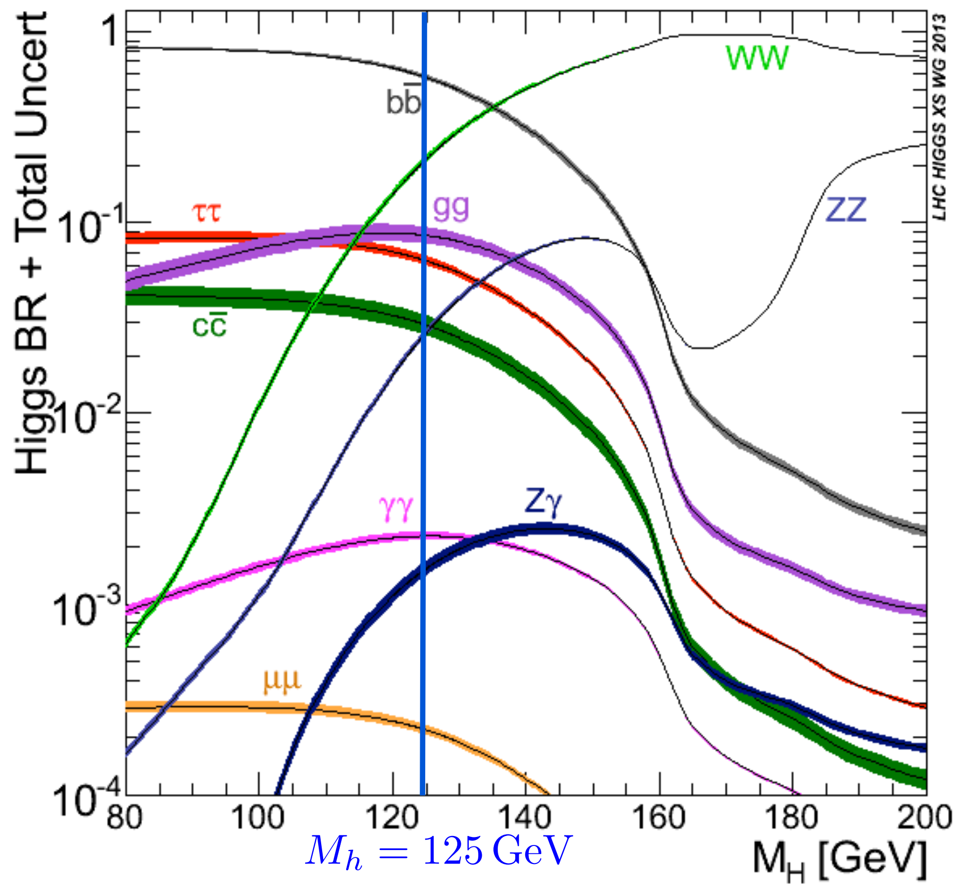
- Test of Higgs sector predictions in arbitrary models against measured signal rates and masses

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

Relevance of off-shell effects for Higgs physics

Reason for importance of off-shell effects (and high sensitivity to Higgs mass value) for BR(H → ZZ*), BR(H → WW*):

SM Higgs branching fractions:



[LHC Higgs XS WG ’14]

For a 125 GeV Higgs boson the branching ratios into BR(H → ZZ*), BR(H → WW*) are far below threshold

⇒ Strong phase-space suppression, steep rise with M_H

[N. Kauer, G. Passarino ’12]

⇒ Sensitive dependence on M_H, off-shell effects are important

Total Higgs width: recent analyses from CMS and ATLAS

- Exploit different dependence of on-peak and off-peak contributions on the total width in Higgs decays to $ZZ^{(*)}$

- CMS quote an upper bound of $\Gamma/\Gamma_{SM} < 5.4$ at 95% C.L., where 8.0 was expected, ATLAS: $\Gamma/\Gamma_{SM} < 5.7$ at 95% C.L., 8.5 expect.
[CMS Collaboration '14] *[ATLAS Collaboration '14]*

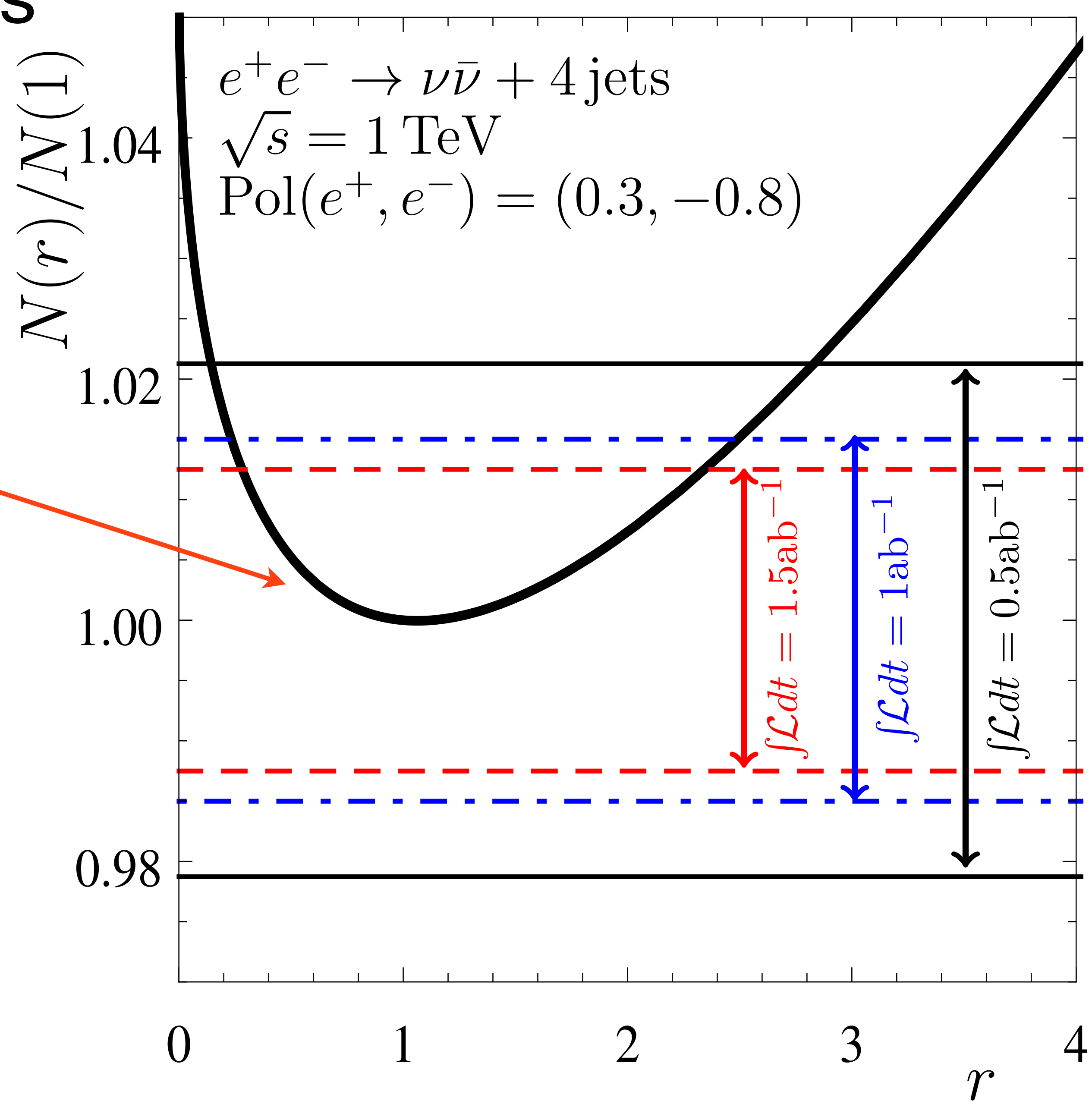
- Problem: equality of on-shell and far off-shell couplings assumed; relation can be severely affected by new physics contributions, in particular via threshold effects (note: effects of this kind may be needed to give rise to a Higgs-boson width that differs from the SM one by the currently probed amount)
[C. Englert, M. Spannowsky '14]

⇒ SM consistency test rather than model-independent bound
Destructive interference between Higgs- and gauge-boson contributions (unitarity cancellations) ⇒ difficult to reach $\Gamma/\Gamma_{SM} \approx 1$ even for high statistics

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

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

Same theoretical assumptions as in LHC analyses



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

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

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

⇒ Limited sensitivity even with high integrated luminosity

Qualitative behaviour at the LHC is the same!

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 $\to$ $\tau\tau$, H $\to$ hh, H, A $\to$ $\chi\chi$, ...

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)

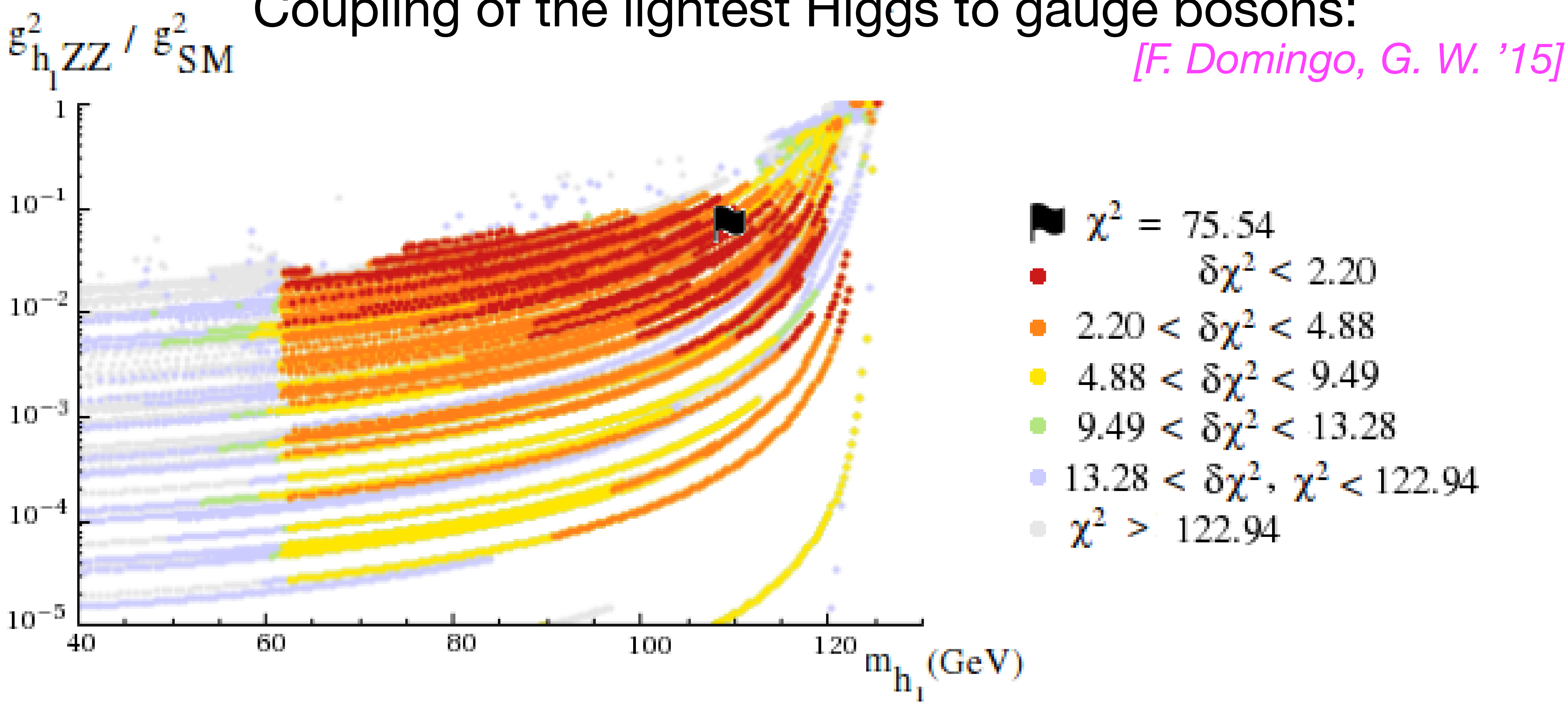
Possible realisations: 2HDM, MSSM, NMSSM, ...

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.

Example: NMSSM with a light Higgs singlet

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

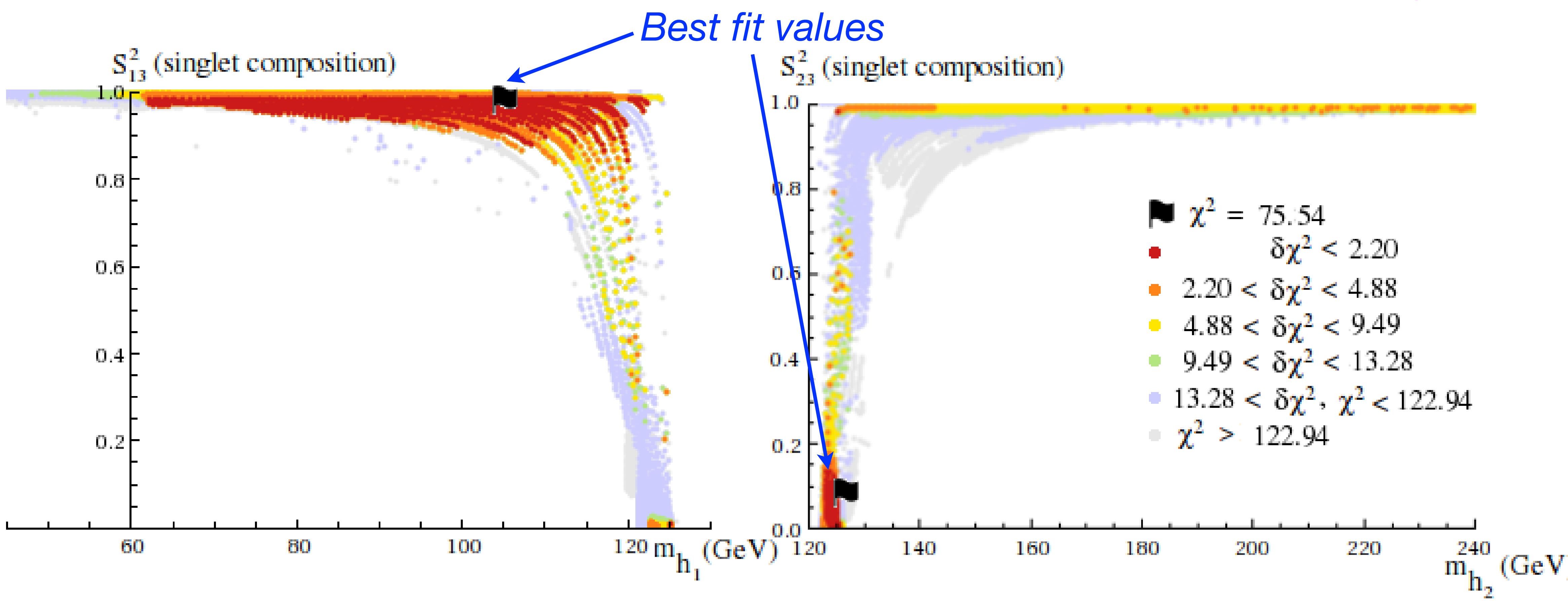
The case where the signal at 125 GeV is not the lightest Higgs arises generically if the Higgs singlet is light

⇒ Strong suppression of the coupling to gauge bosons

NMSSM 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

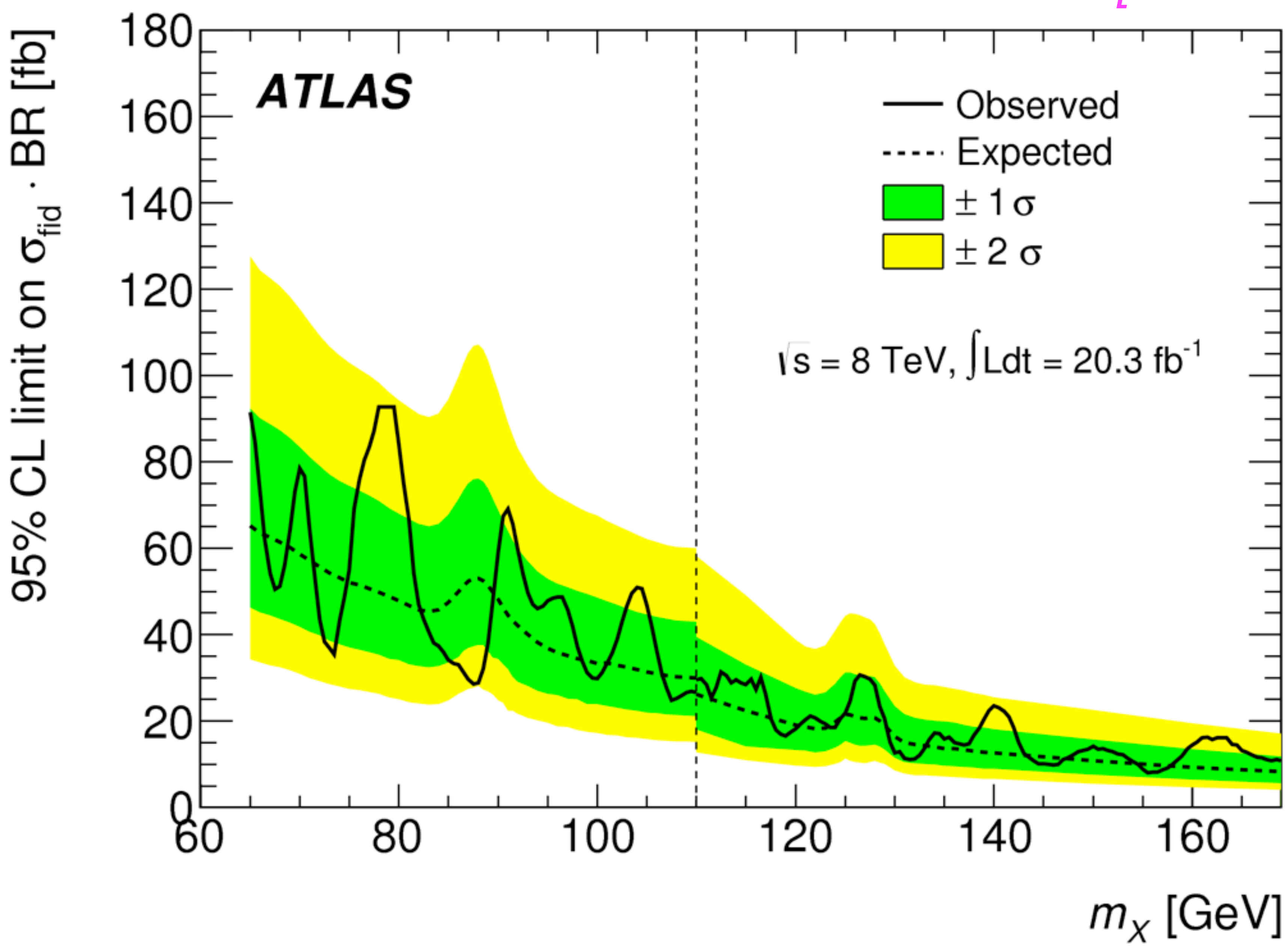
[F. Domingo, G. W. ’15]



⇒ 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?

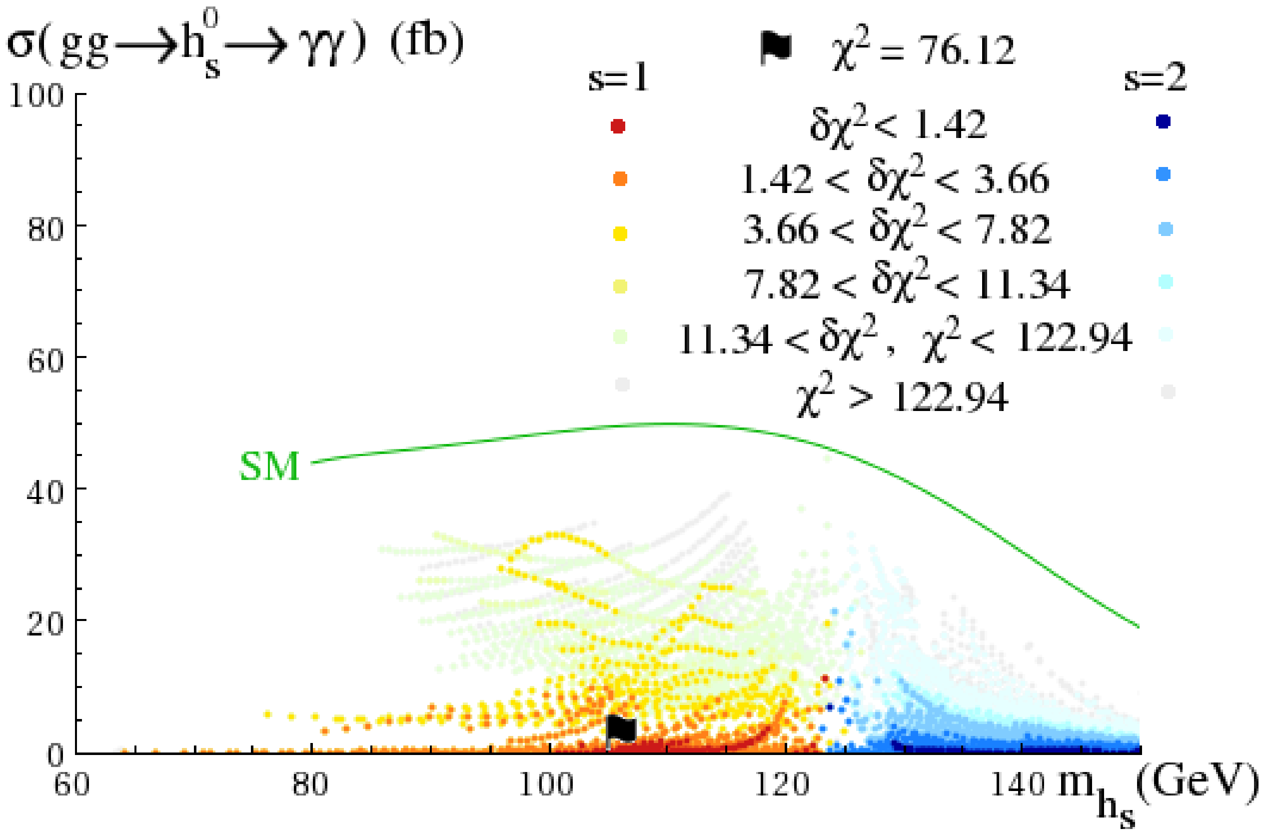
ATLAS h → $\gamma\gamma$ searches in the low-mass region: *[ATLAS Collaboration '14]*

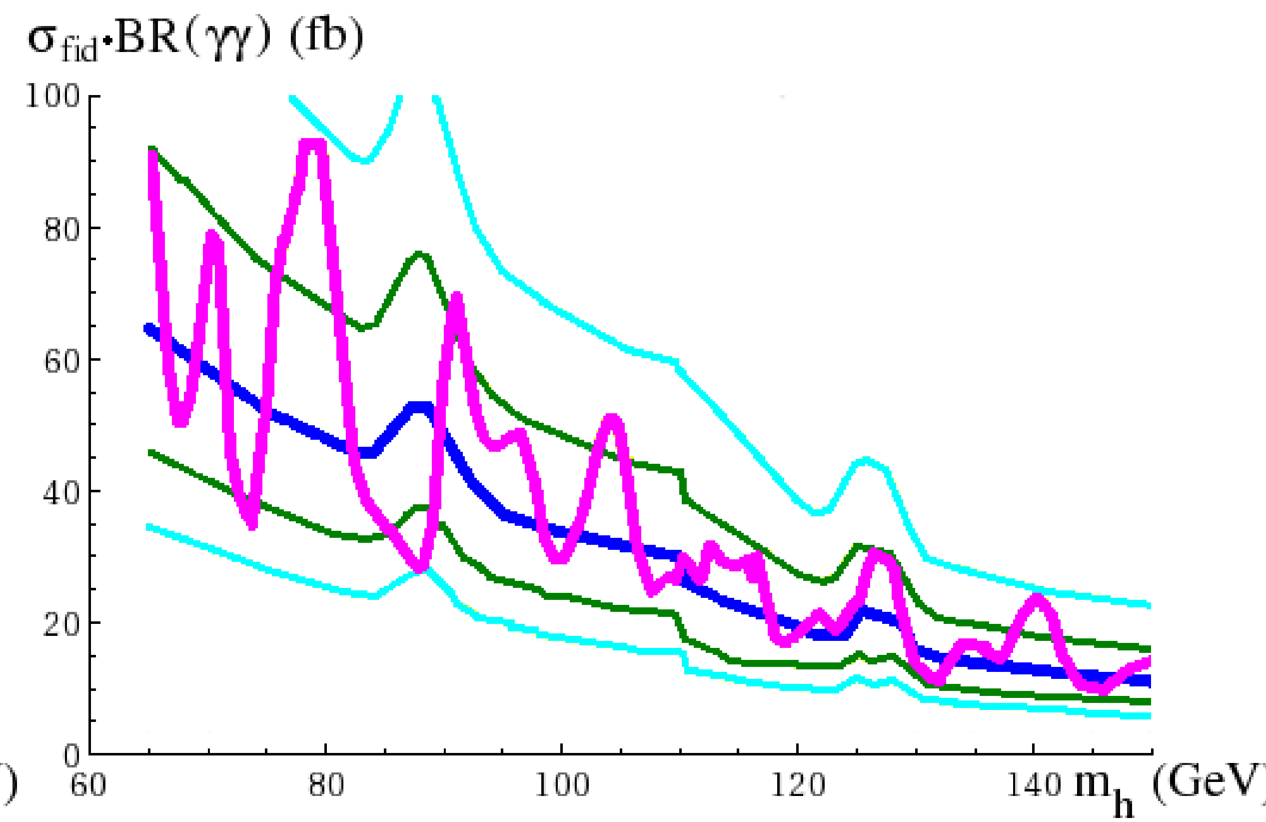


Example: MSSM, H(125) case: BR($h_1 \to \gamma\gamma$) = 8.5 10^{-7}, three orders of magnitude below BR for a SM-like Higgs of this mass (65 GeV)

Light NMSSM Higgs: comparison of gg → h₁ → $\gamma\gamma$ 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

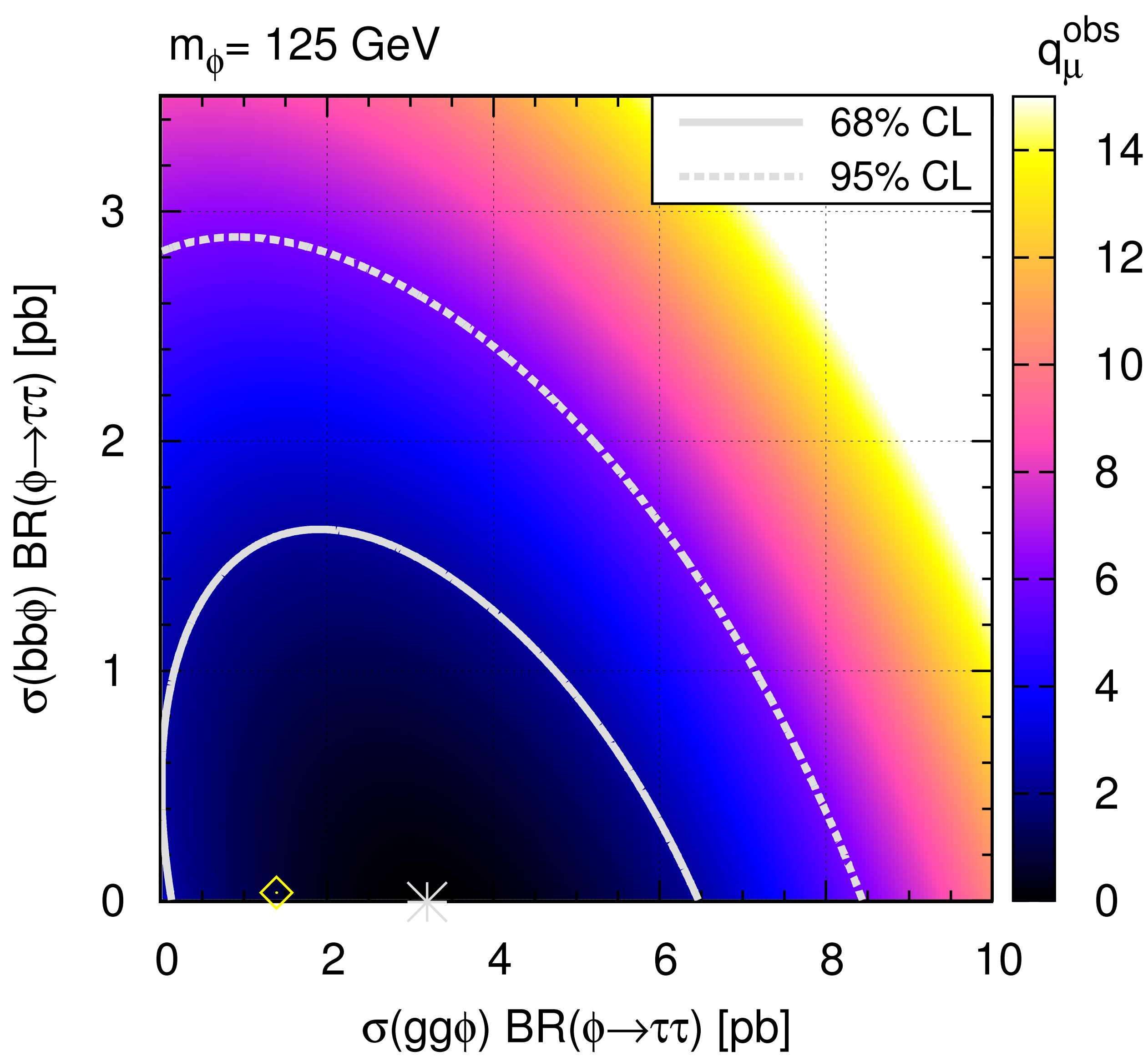
Such a light Higgs could be produced in a SUSY cascade, e.g.
$\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 h$ *[O. Stål, G. W. '11]* *[CMS Collaboration '15]*

Heavy non-standard Higgses: application of CMS result in $\tau\tau$ channel

- 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*

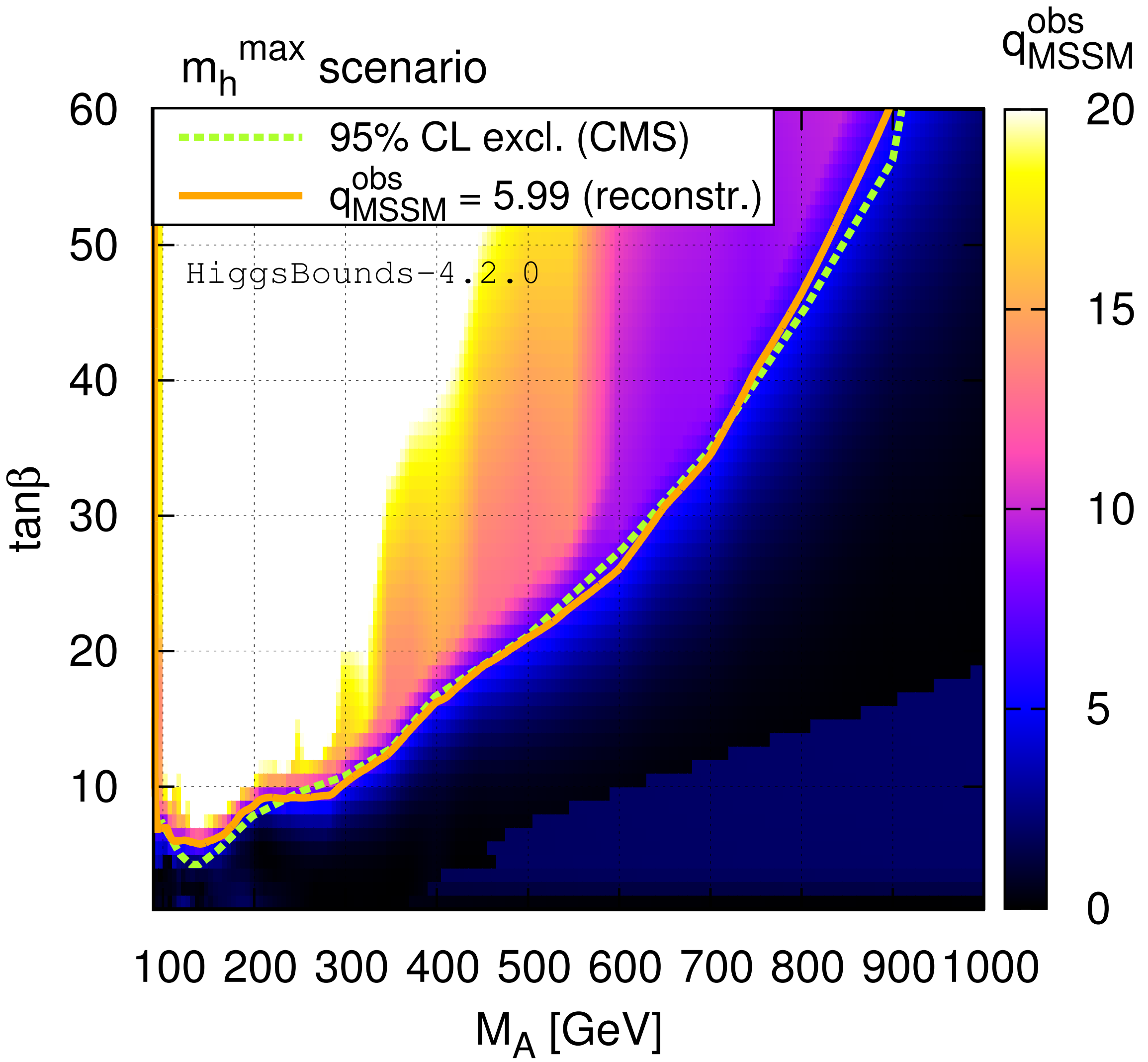
[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W. '15]



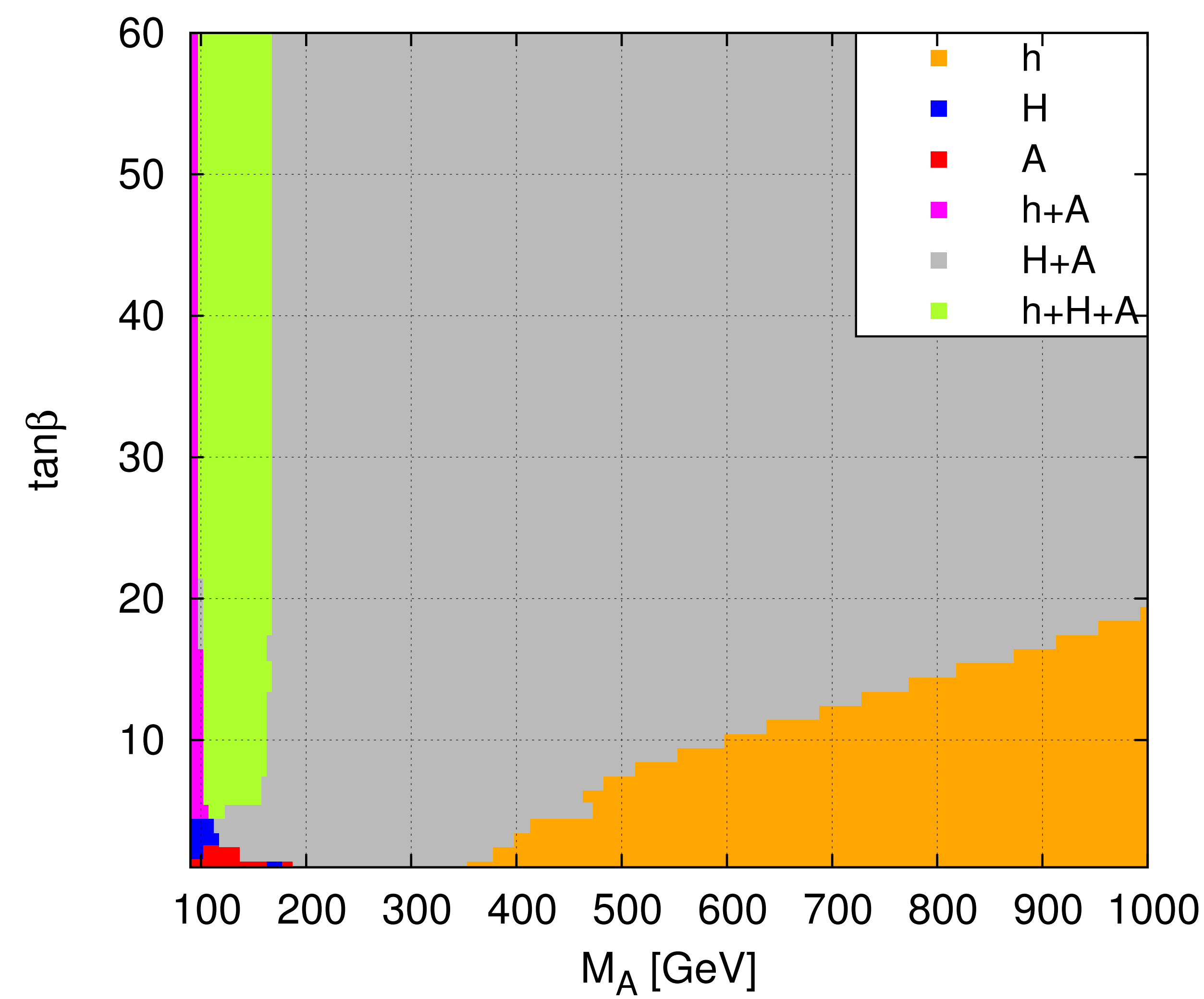
Validation: comparison with exclusion limit from dedicated CMS analysis in m_h^{max} benchmark scen.

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

Likelihood distribution and excl. limits:



Signal combinations (incoherent sum):



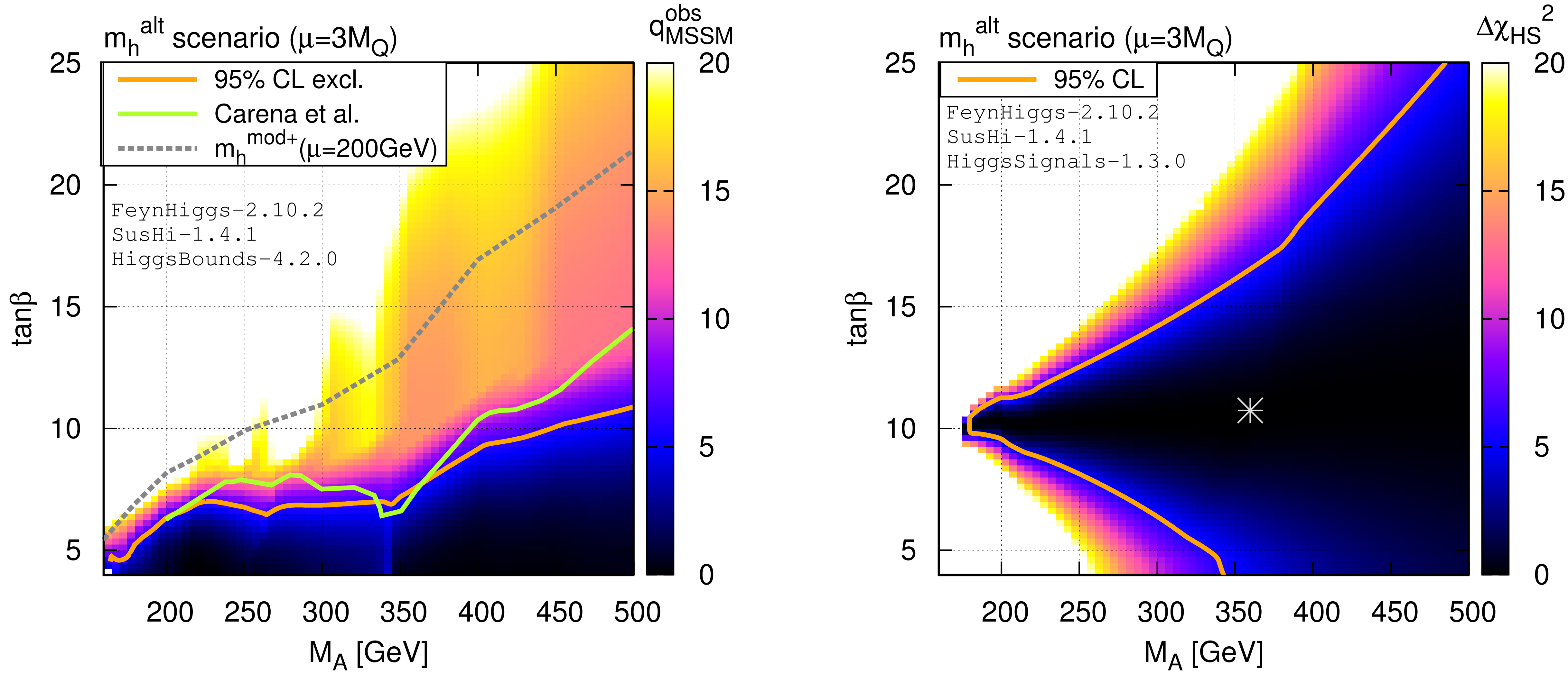
⇒ Good agreement with dedicated CMS analysis in the benchmark scenario (proper combination of channels possible)

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]

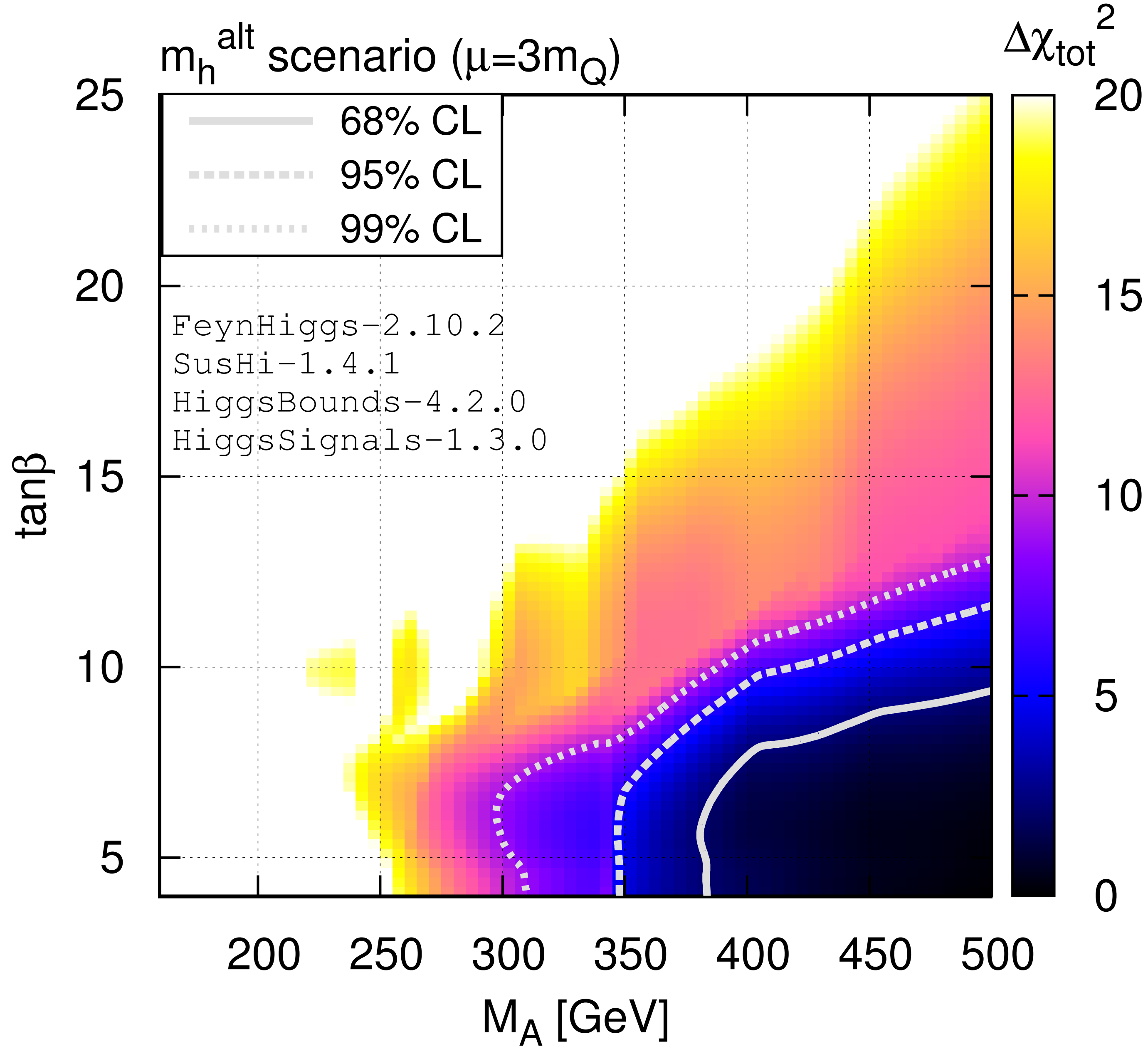
Likelihood distribution from H, A → ττ:　　Likelihood from Higgs signal rates:



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

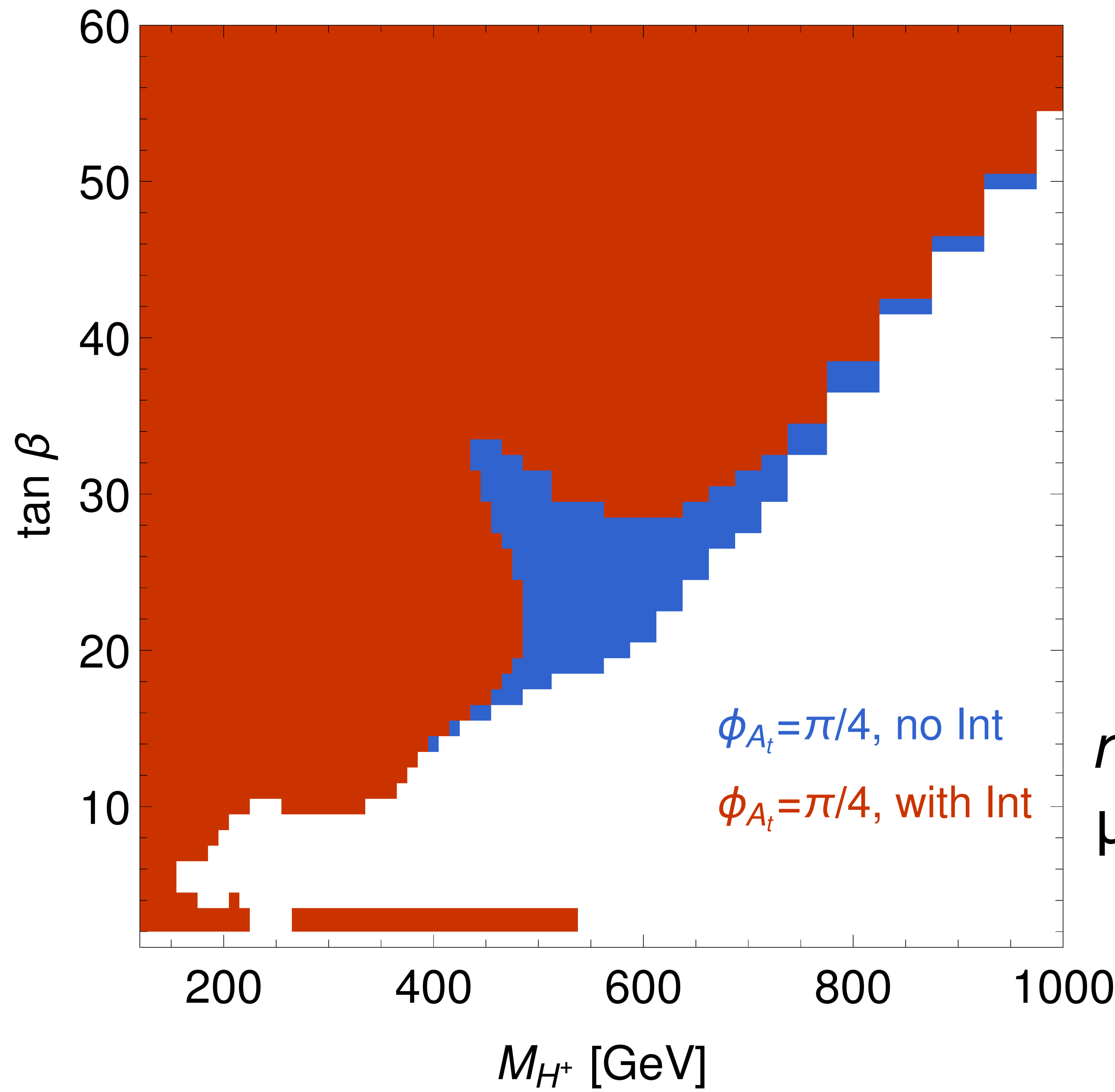
[E. Fuchs, G. W. '15]

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!

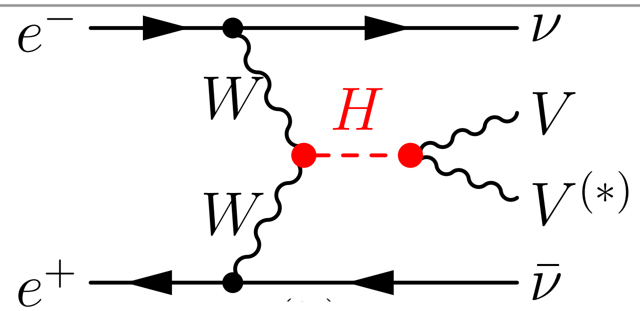
Incoherent sum is not sufficient!



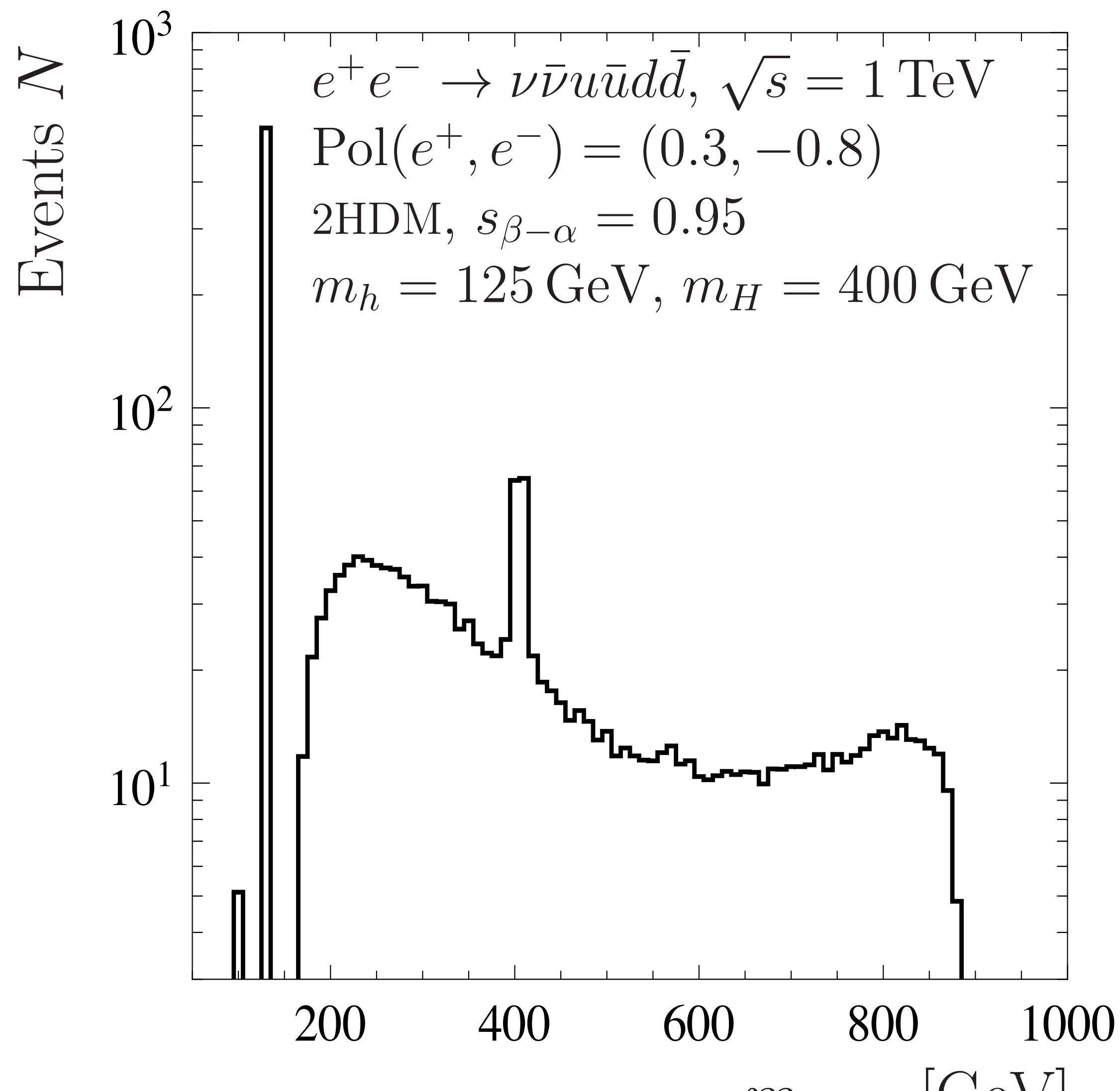
m_h^{mod+} scenario, μ = 1000 GeV

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

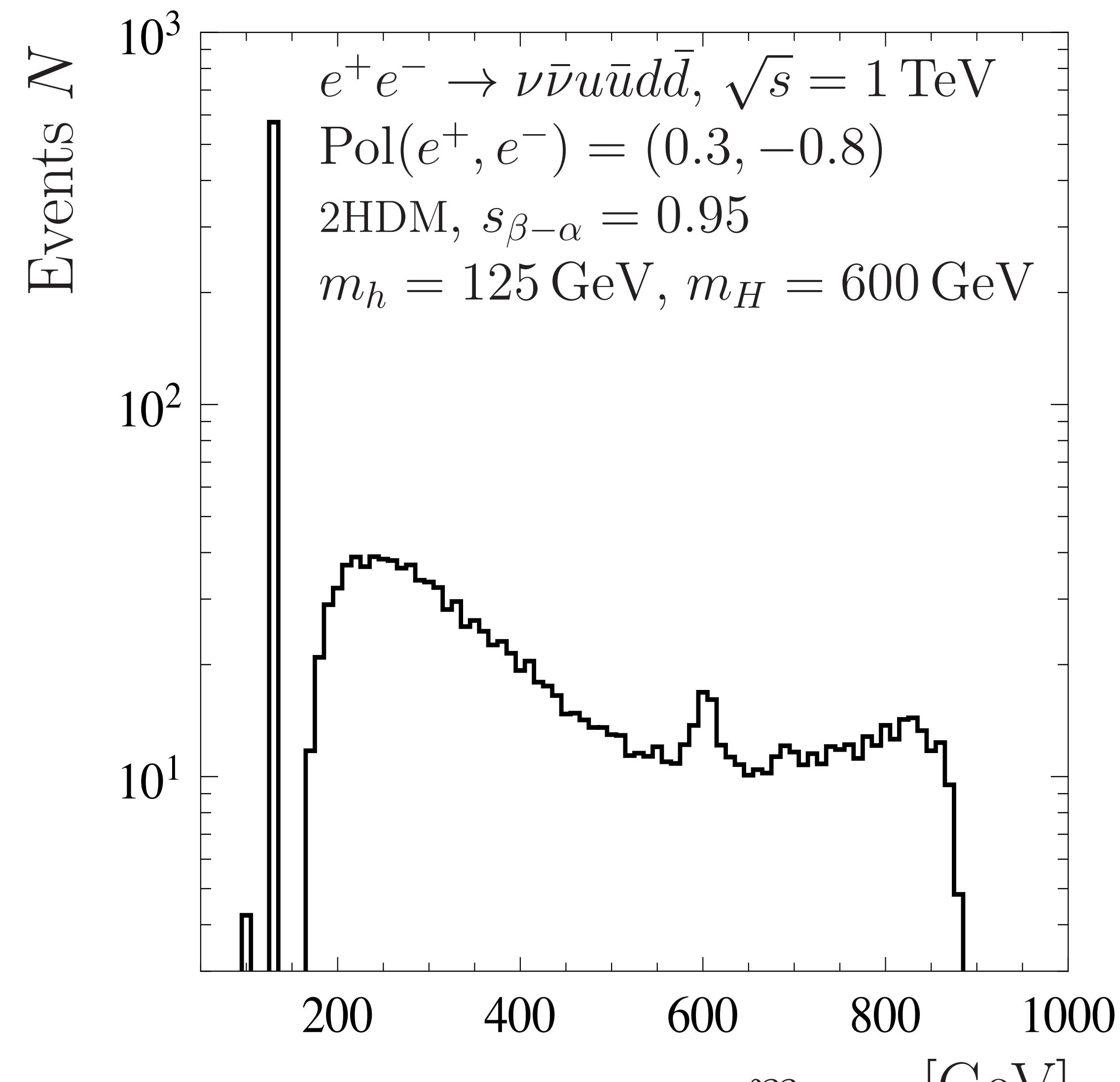
Sensitivity to the small signal of an additional heavy Higgs boson in a Two-Higgs-Doublet model (2HDM)



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



(a)



(b)

⇒ ILC: Potential sensitivity beyond the kinematic reach of Higgs pair production

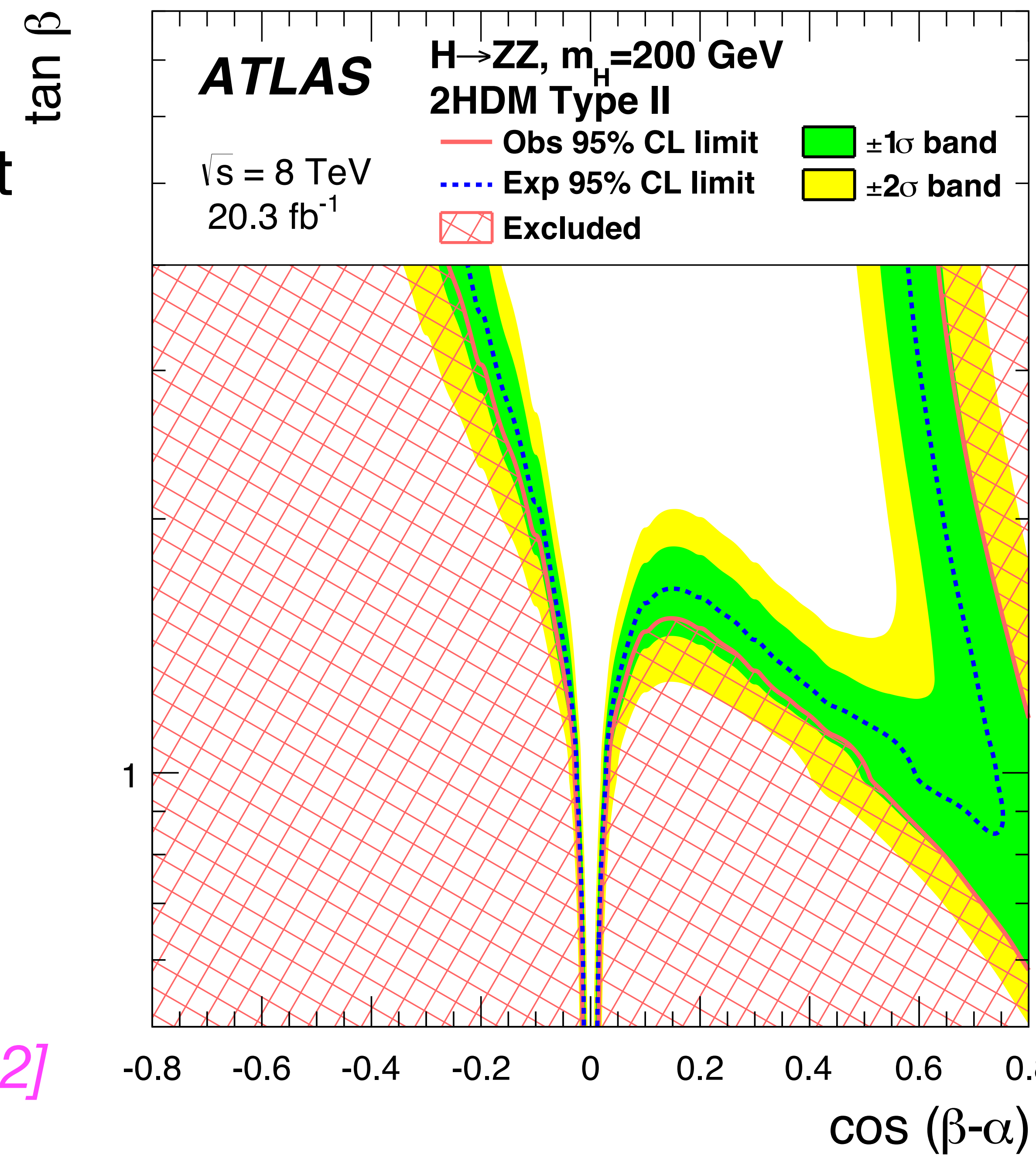
LHC: sensitivity to an additional heavy Higgs boson of a Two-Higgs-Doublet model (2HDM)

[ATLAS Collaboration ’15]

Recent ATLAS analysis:

Interference effects of heavy Higgs with background and light Higgs contribution neglected

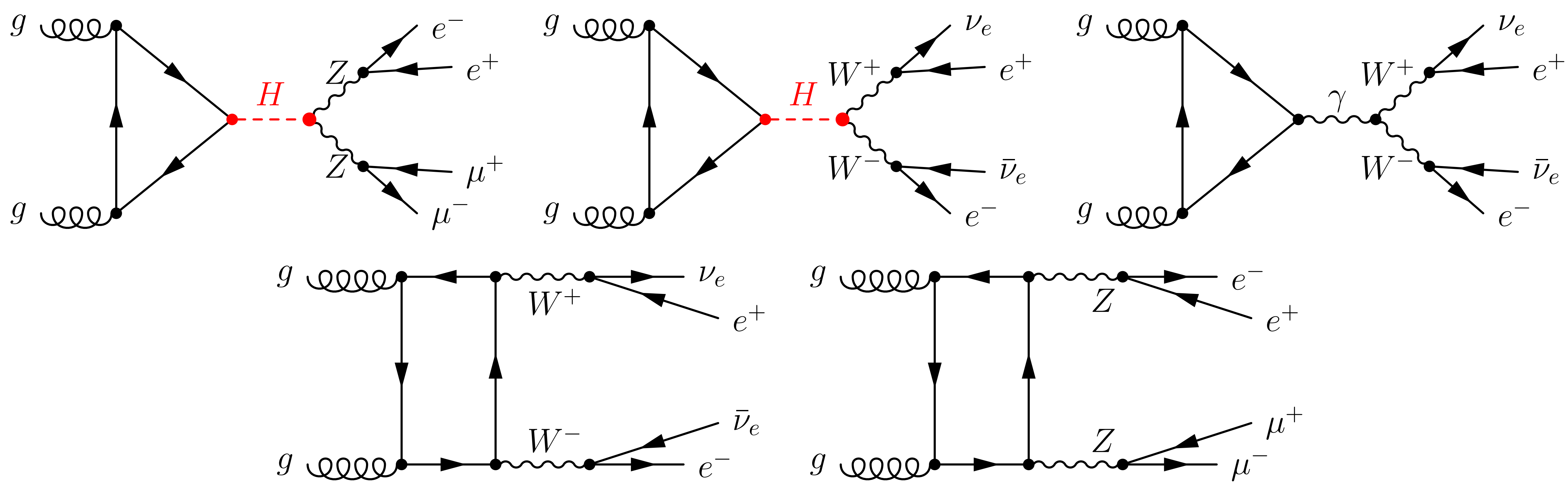
[N. Greiner, S. Liebler, G. W. ’15]
(work in progress)
Analysis of $gg \to e^+e^-\mu^+\mu^-$ and $gg \to ll\nu\nu$ including signal, background and H-h, H-background interference contributions using *GoSam* *[G. Cullen et al. ’14]* and *MadEvent* *[F. Maltoni, T. Stelzer ’02]*



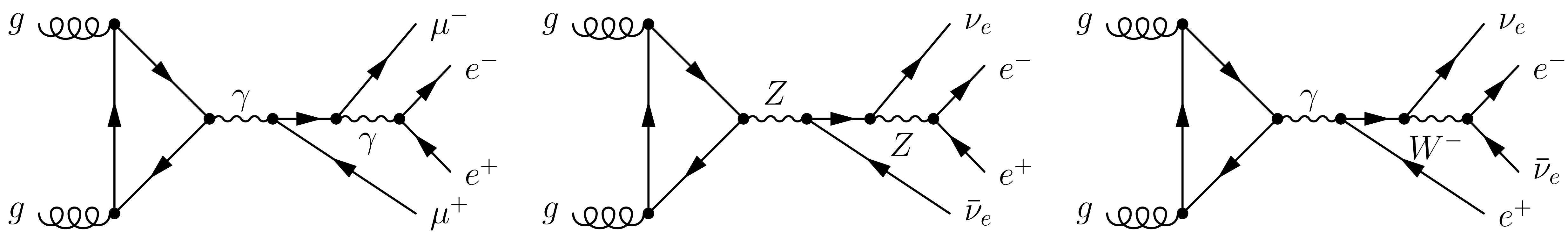
← tanβ = 2 used as example in some plots on the next slides

Sample diagrams for gg → $e^+e^-\mu^+\mu^-$

Diagrams with two resonant W/Z bosons:



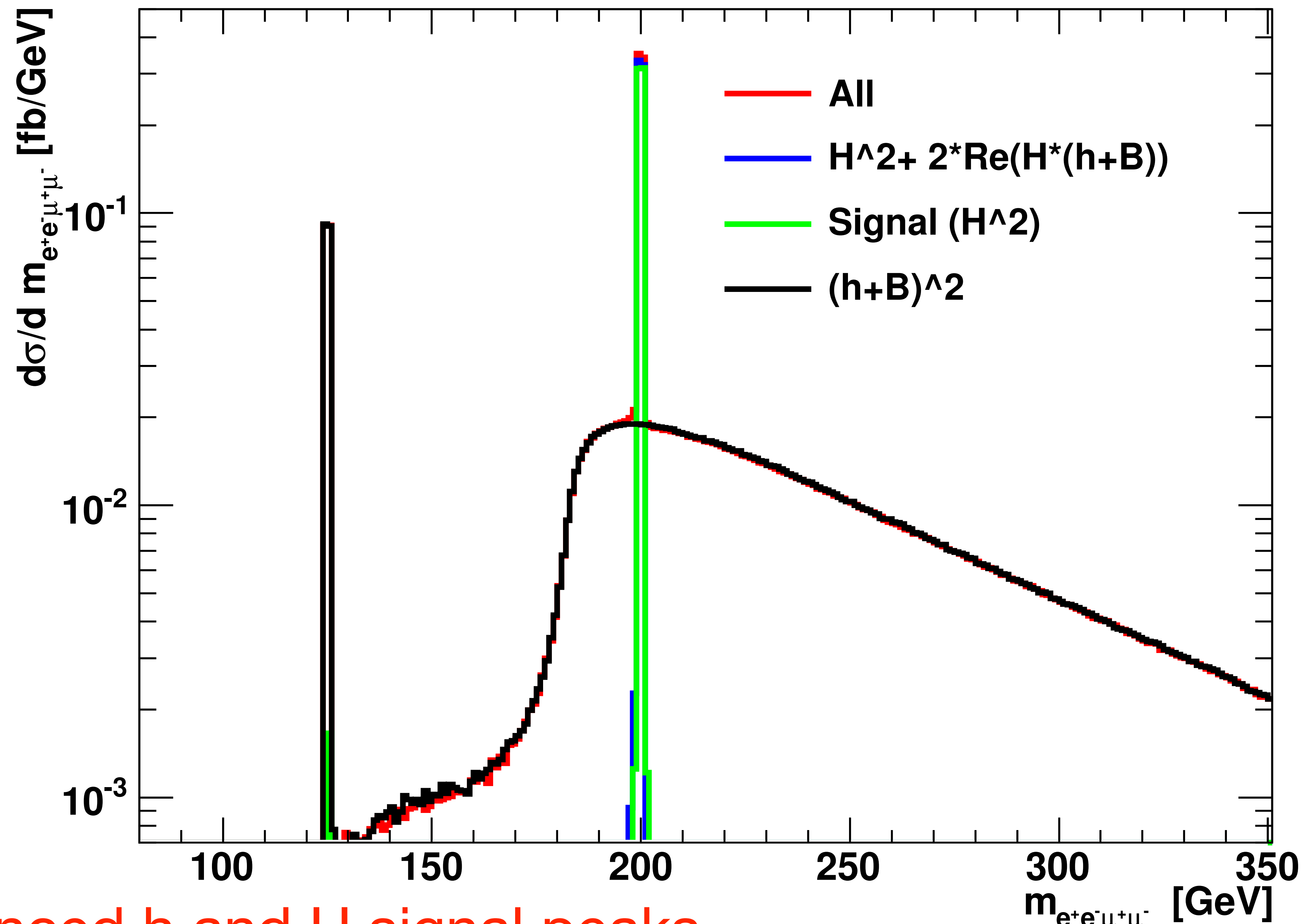
Diagrams with single-resonant W/Z bosons and non-resonant diagrams:



gg → $e^+e^-\mu^+\mu^-$, invariant mass distribution

[N. Greiner, S. Liebler, G. W. ’15]

sin(β-α) = -0.995, M_H = 200 GeV, tanβ = 2 (ATLAS scenario for 13 TeV):

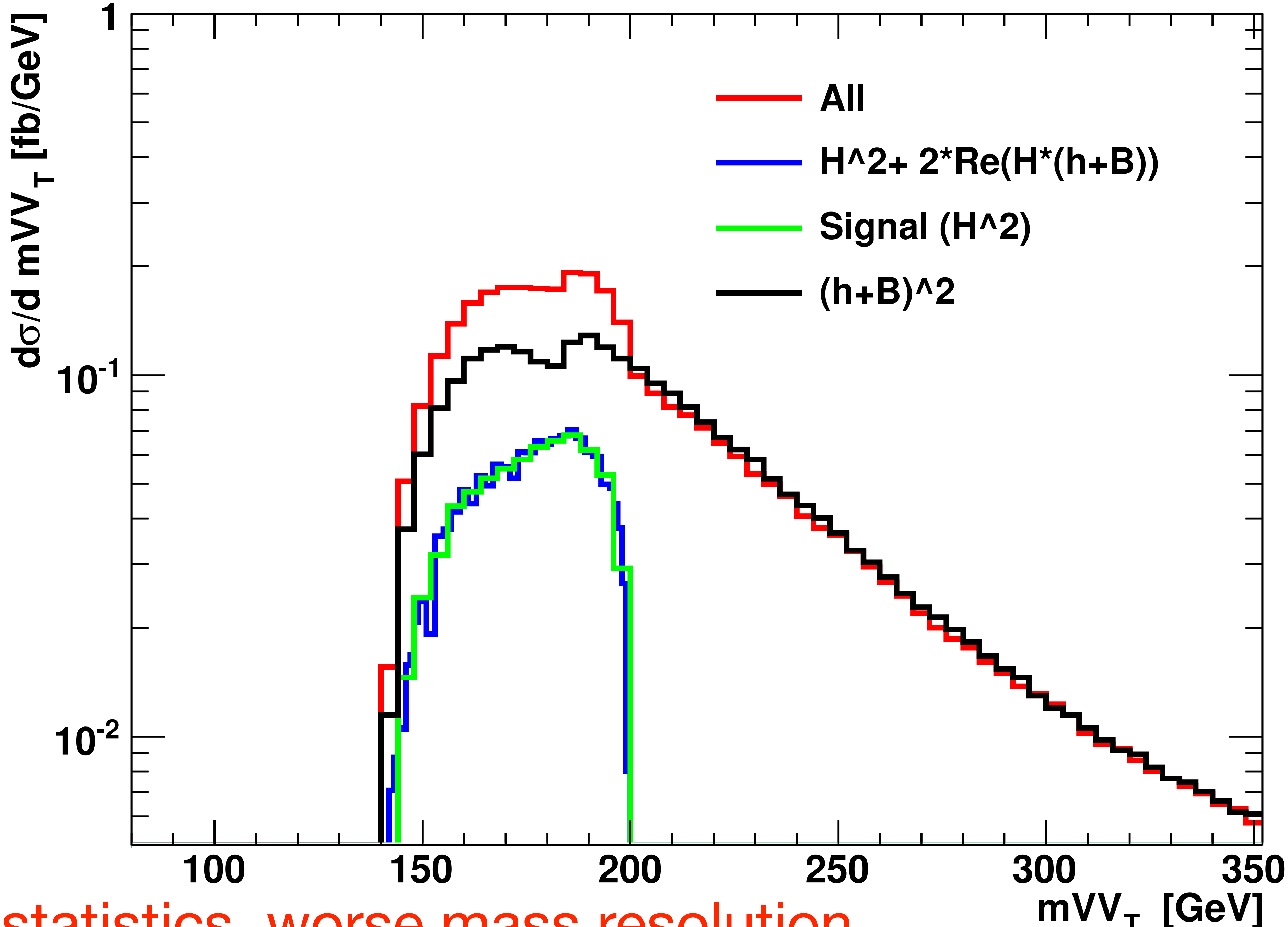


⇒ Pronounced h and H signal peaks

gg → llνν, contributions from both WW and ZZ

[N. Greiner, S. Liebler, G. W. '15]

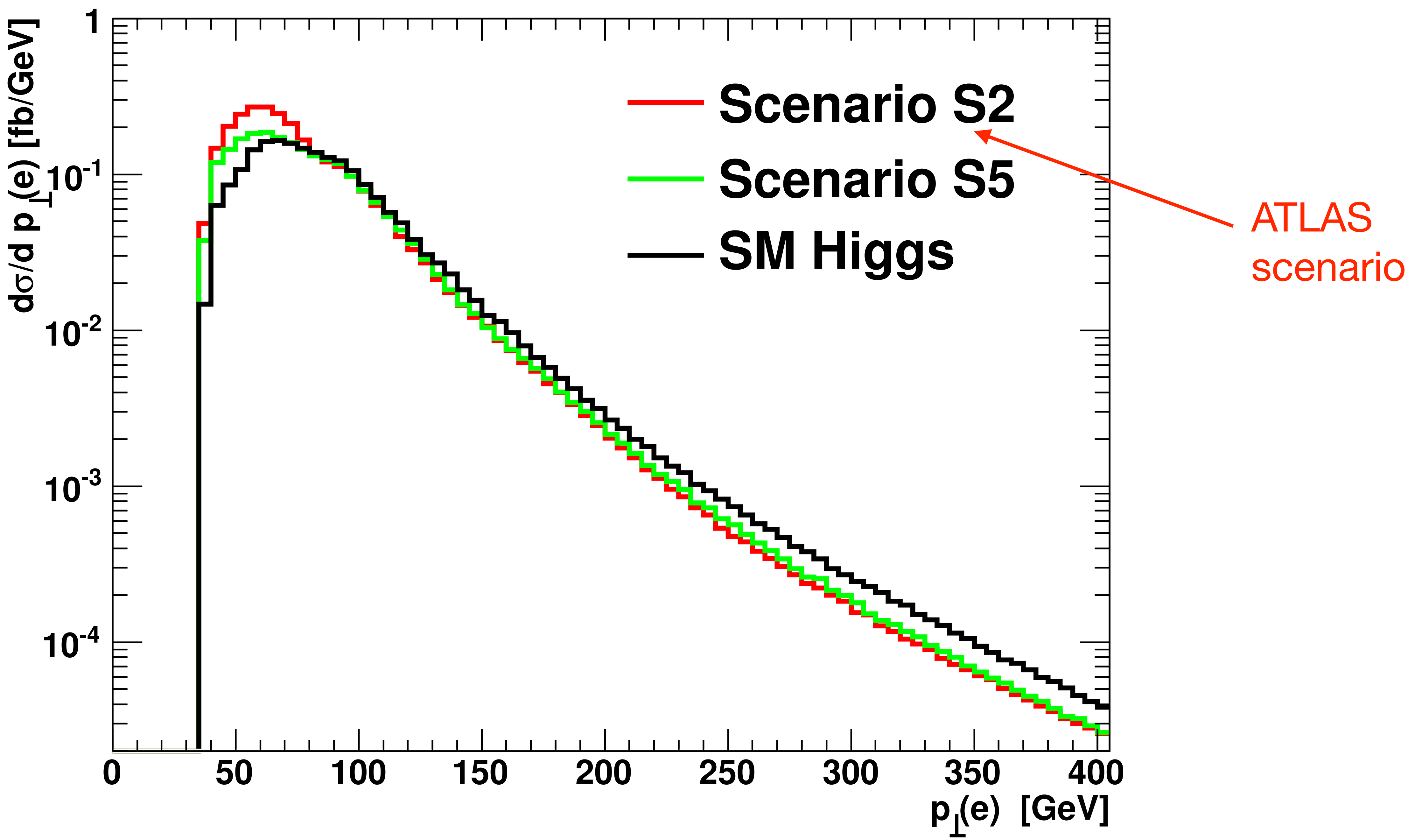
sin(β-α) = -0.995, M_H = 200 GeV, tanβ = 2 (ATLAS scenario for 13 TeV):



⇒ Higher statistics, worse mass resolution

gg → llνν, transverse momentum distribution of the hardest electron / positron

[N. Greiner, S. Liebler, G. W. '15]

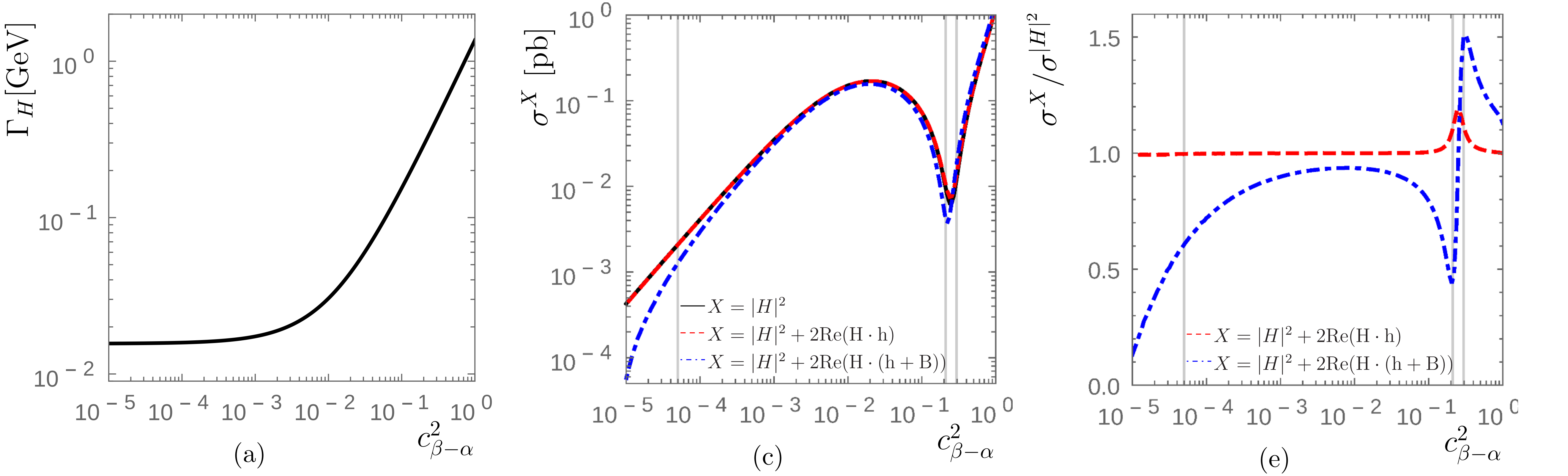


⇒ Kinematic distributions differ from SM case; larger differences are possible for other scenarios

Hadronic gg → ZZ cross sections, impact of interference contributions (ATLAS scen., tanβ = 2)

Total width of heavy Higgs H:

[N. Greiner, S. Liebler, G. W. ’15]



⇒ Interferences are small in the region where the ATLAS search was sensitive

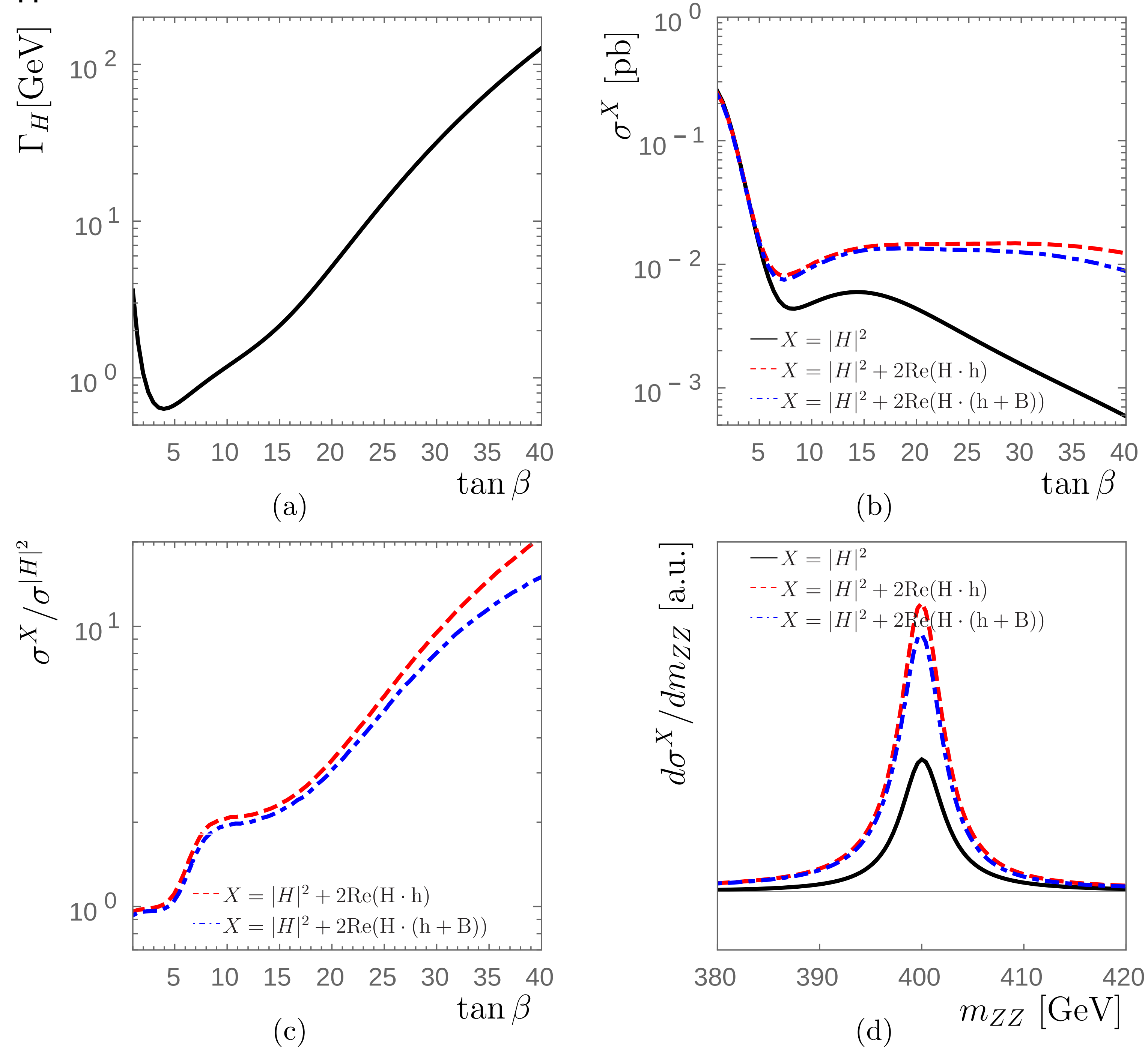
Sizable interference effects possible, not necessarily correlated with a large width

Larger interference effects possible for higher values of tanβ

Hadronic gg → ZZ cross sections, impact of interference contributions for larger values of tanβ

[N. Greiner, S. Liebler, G. W. ’15]

$\sin(\beta-\alpha) = 0.990$, $M_H = 400$ GeV:



tanβ = 20

⇒ Interference effects provide enhanced sensitivity to heavy Higgs H

Conclusions

Discovered signal is so far compatible with a SM-like Higgs, but variety of interpretations possible ⇔ very different underlying physics

Extended Higgs sector where second-lightest Higgs is identified with signal at 125 GeV: additional light Higgs with suppressed couplings to gauge bosons; can be realised generically in the NMSSM: NMSSM fit prefers singlet-like light Higgs

Heavy Higgs searches: new result from CMS allows to combine likelihood information from the Higgs signal with the one from the H, A → $\tau\tau$ searches (and from the LEP searches). Large interference effects between heavy Higgs contributions possible in the CP-violating case

Off-shell effects and interference contributions can be important for Higgs physics despite the small width of a SM-like Higgs at 125 GeV
Search for heavy Higgs in 2HDM: interference effects in the region probed so far by ATLAS are small; interference effects could enhance sensitivity to small signal of additional heavy Higgs

Backup

Higgs mass measurement: the need for high precision

Measuring the mass of the discovered signal with high precision is of interest in its own right

But a high-precision measurement has also direct implications for probing Higgs physics

M_H: crucial input parameter for Higgs physics

BR($H \to ZZ^*$), BR($H \to WW^*$): highly sensitive to precise numerical value of M_H

A change in M_H of 0.2 GeV shifts BR($H \to ZZ^*$) by 2.5%!

$\Rightarrow$ Need high-precision determination of M_H to exploit the sensitivity of BR($H \to ZZ^*$), ... for testing BSM physics