Higgs physics: where are we and what next?

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Outline

- Introduction
- The Higgs-boson mass as a test for BSM physics
- Higgs phenomenology in extended Higgs sectors
- What next?
- Conclusions

Introduction

Experimental situation (in a nutshell):

- Higgs signal at 125 GeV:
  the discovered particle looks SM-like so far

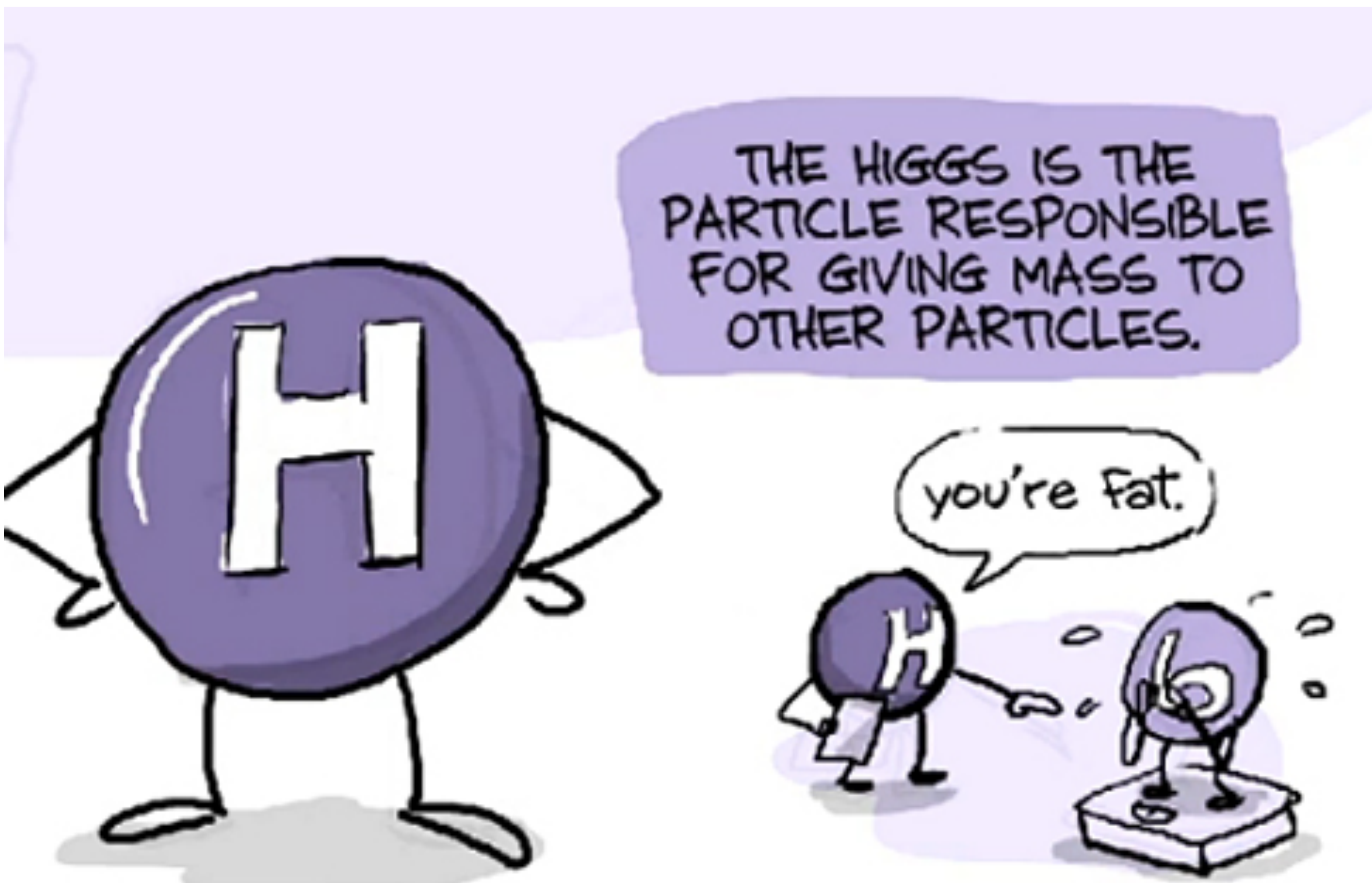
- No further clear sign of new physics so far

Higgs physics:

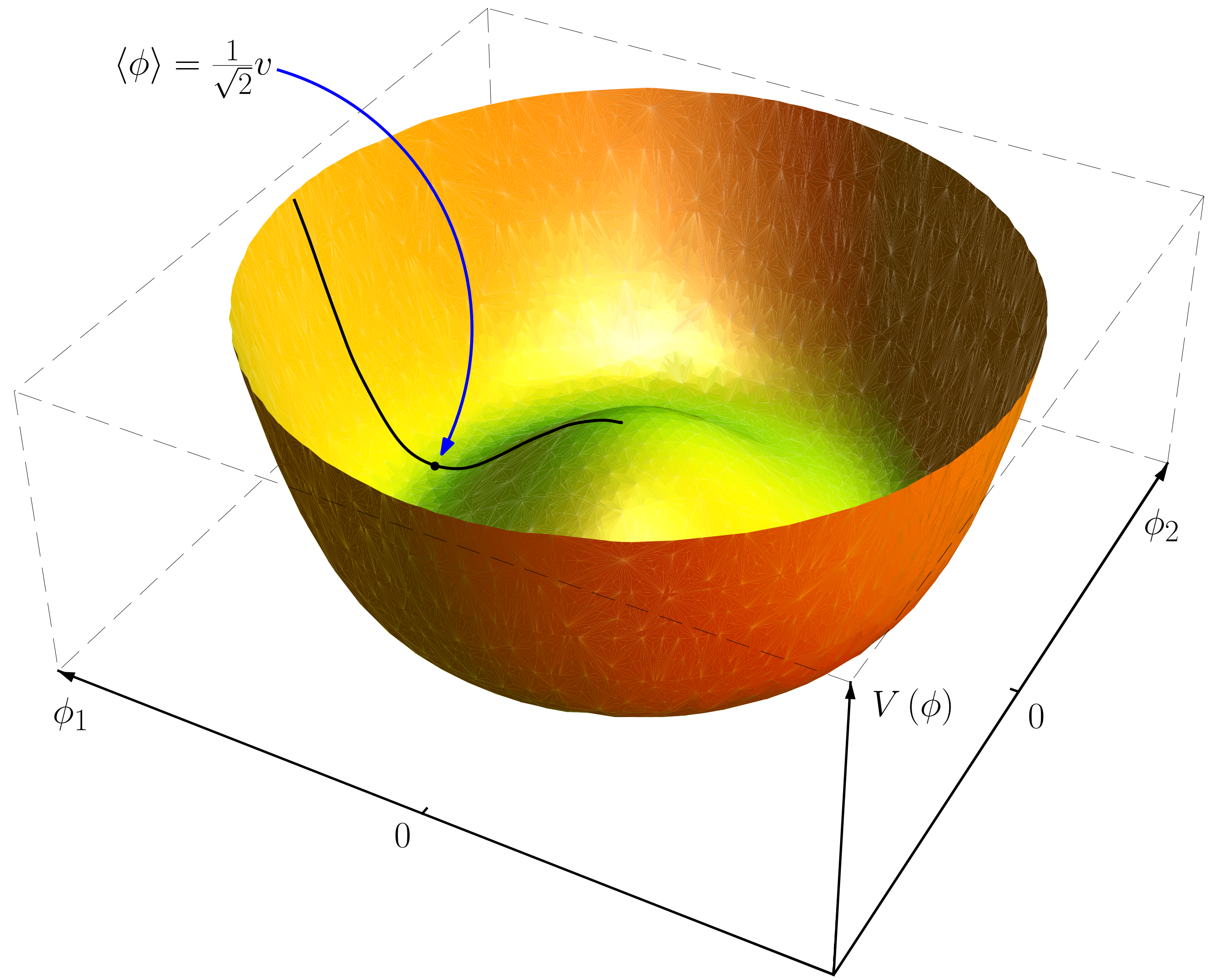
- Use the information from the properties of the detected signal, from search limits, as well as from electroweak precision observables, flavour physics, etc. to explore the mechanism of electroweak symmetry breaking

Higgs physics: origin of mass, structure of the vacuum

The fact that we can produce Higgs bosons in a controlled way at the LHC provides us access to the origin of mass of elementary particles and to the structure of the vacuum.



The structure of the vacuum



BEH mechanism, spontaneous symmetry breaking: vacuum state does not obey the underlying symmetry principle (gauge invariance)

BEH mechanism ⇔ non-trivial structure of the vacuum

Simplest version: BEH mechanism in the Standard Model (SM)

Higgs potential: $V(\Phi) = \frac{\lambda}{4}\left(\Phi^\dagger\Phi\right)^2 + \mu^2\left(\Phi^\dagger\Phi\right), \quad \lambda > 0$

$\mu^2 < 0 \quad \Rightarrow$ Minimum of the potential at $\langle\Phi\rangle = \sqrt{\frac{-2\mu^2}{\lambda}} \equiv \frac{v}{\sqrt{2}}$

SM Higgs field: scalar SU(2) doublet, complex $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

$\Rightarrow$ 4 degrees of freedom

3 components of the Higgs doublet $\longrightarrow$ longitudinal components of W^+, W^-, Z

4th component: H: elementary scalar field, Higgs boson

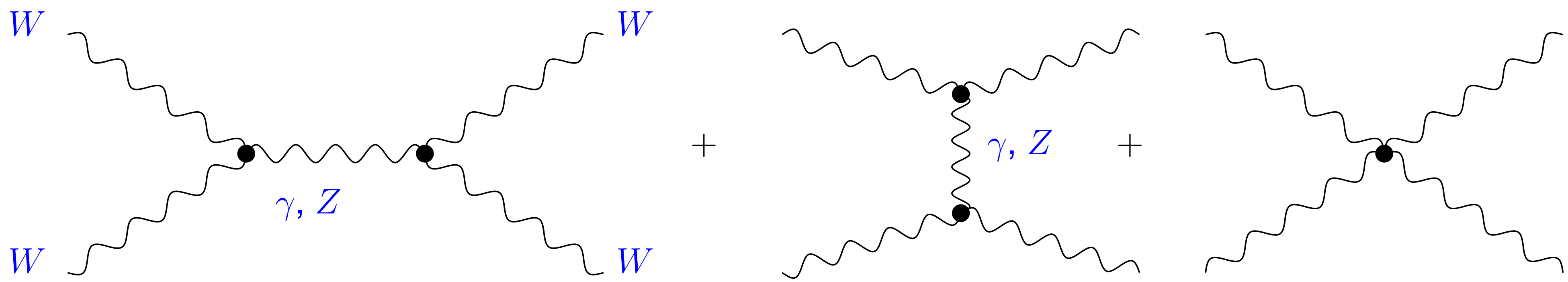
Models with two Higgs doublets (e.g. MSSM)

$\Rightarrow$ prediction: 5 physical Higgses

Unitarity cancellation in longitudinal gauge boson scattering

E.g.: WW scattering, longitudinally polarised: $W_L W_L \to W_L W_L$

$\mathcal{M}_V =$

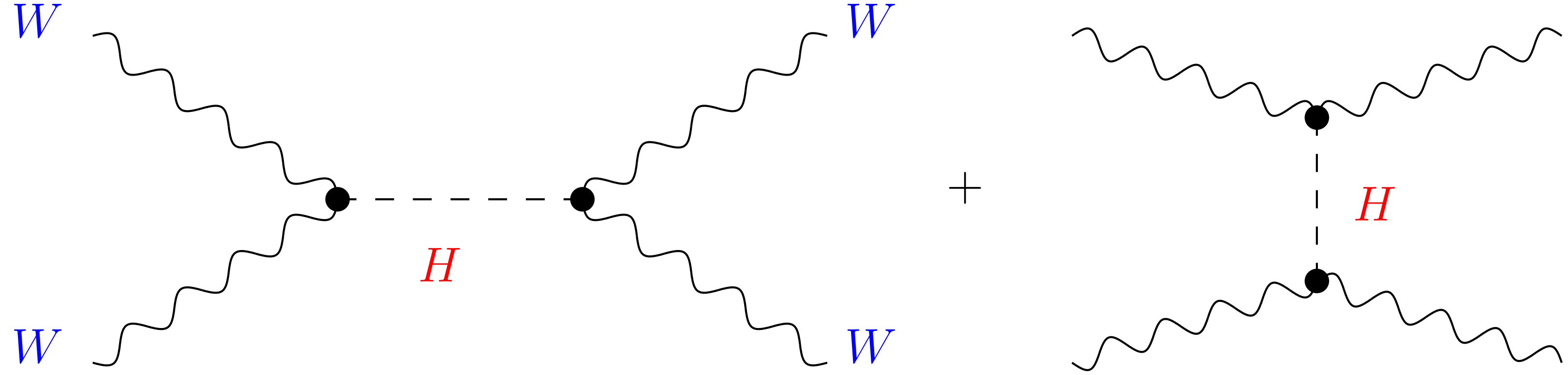


$= -g^2 \frac{E^2}{M_{\mathrm{W}}^2} + \mathcal{O}(1)$ for $E \gg M_{\mathrm{W}}$

$\Rightarrow$ violation of probability conservation

Compensated by Higgs contribution:

$\mathcal{M}_S =$



$= g_{WWH}^2 \frac{E^2}{M_{\mathrm{W}}^4} + \mathcal{O}(1)$ for $E \gg M_{\mathrm{W}}$, $g_{WWH} = g_2 \, M_{\mathrm{W}}$

Properties of the discovered signal

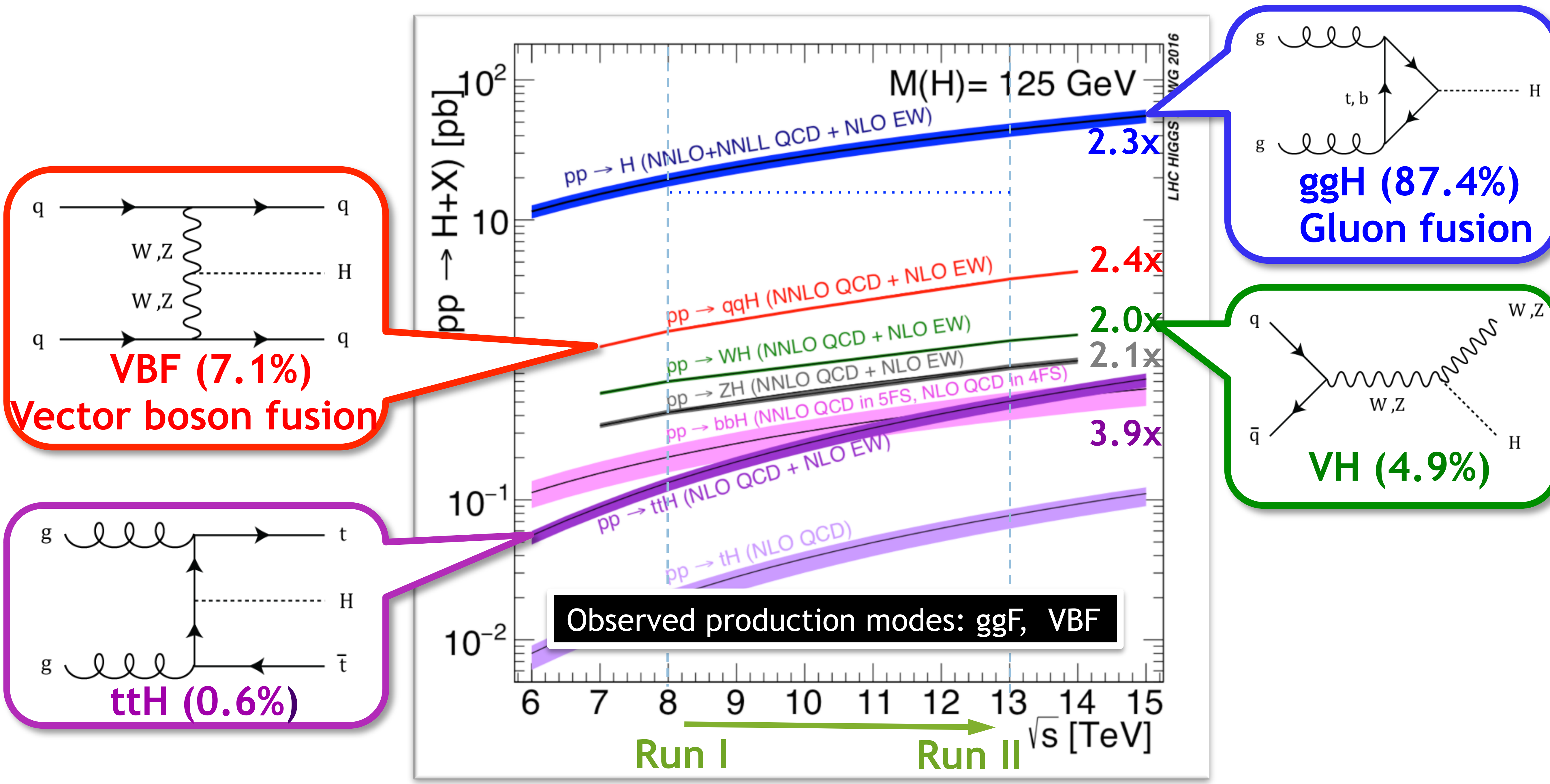
- Mass: ATLAS + CMS ⇒ $M_H = 125.1 \pm 0.2$ GeV : already a precision observable (0.16%)

- Spin: can be determined by discriminating between distinct hypotheses 0, 1, 2, ... unless signal consists of superposition of more than one states ⇒ spin 0 preferred

- CP properties: compatible with pure CP-even state (SM case), pure CP-odd state excluded, only very weak bounds so far on an admixture of CP-even and CP-odd components

Production of a SM Higgs at the LHC

[F. Canelli, ICHEP 2016]

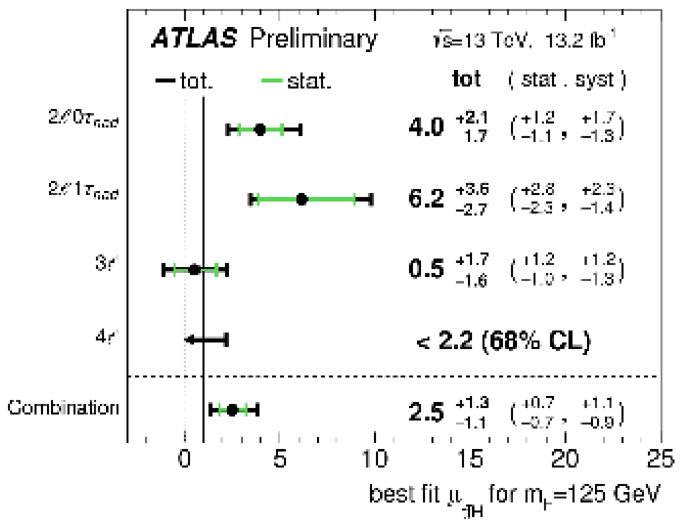


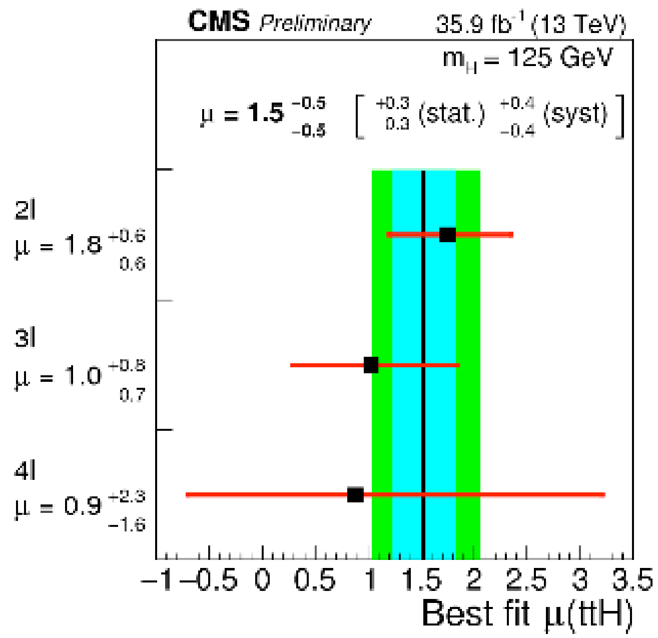
7/8 TeV (2011/2012) **13 TeV (>2015)**

ttH production: experimental status

[T. Gershon, Moriond 2017]

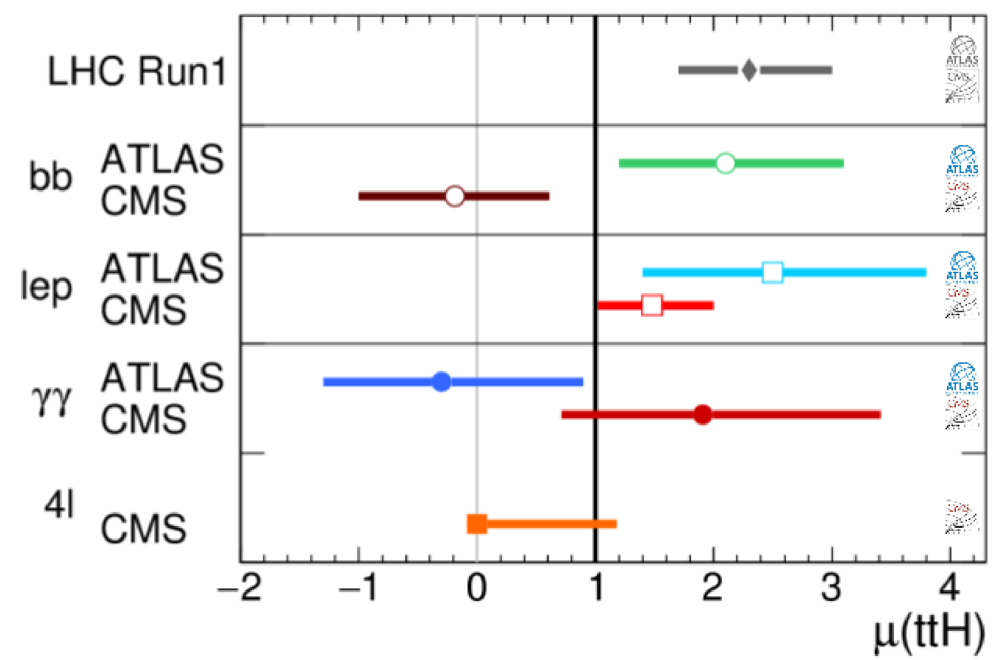
multilepton results





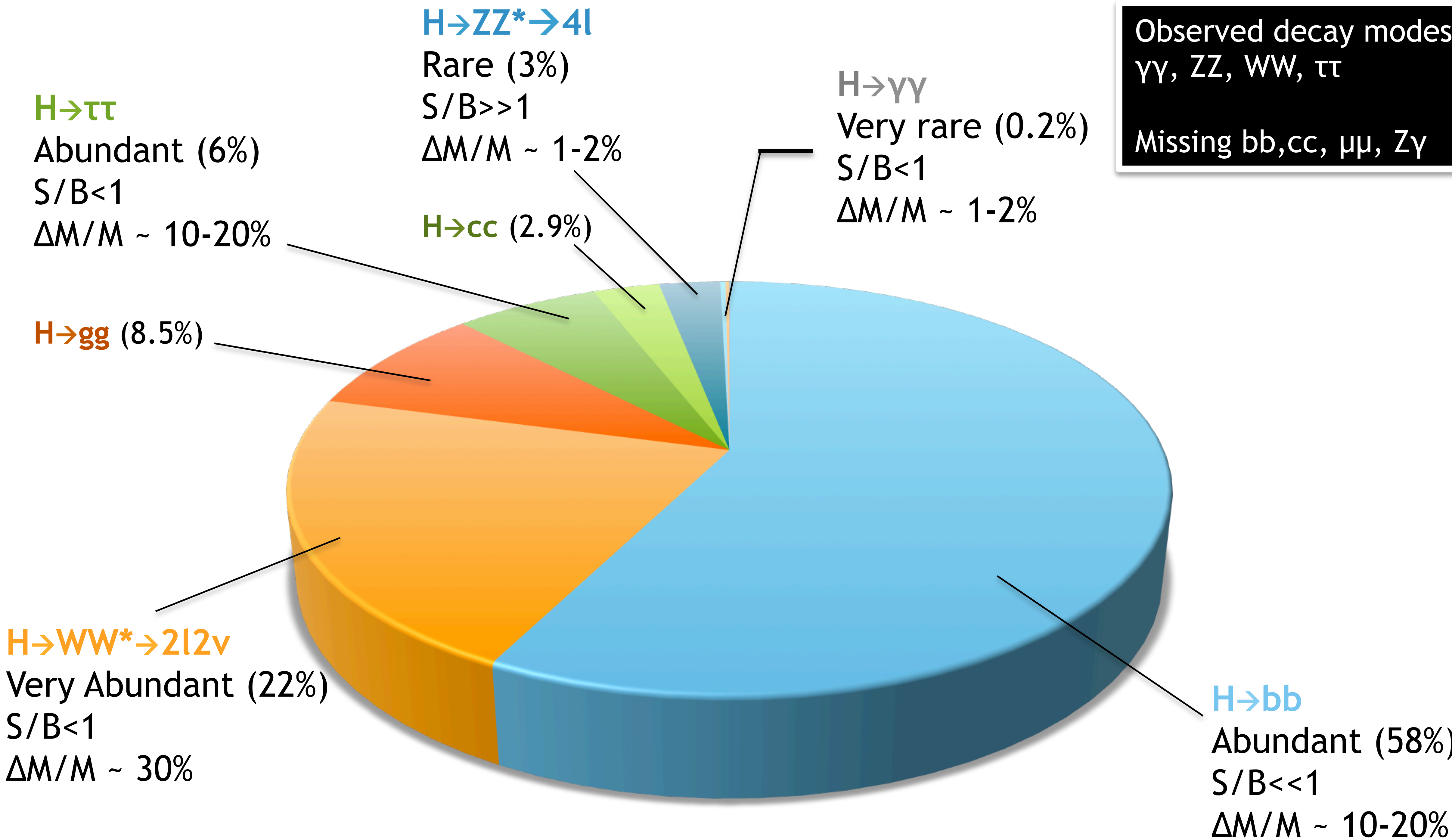
- Both results compatible with SM within about 1σ.
- Significance wrt μ(ttH) = 0 hypothesis:
  - ATLAS: 2.2 σ (expected for SM ttH: 1.0 σ)
  - CMS: 3.3 σ (expected for SM ttH: 2.5 σ)

all results



Decay modes of a SM Higgs at 125 GeV

[F. Canelli, ICHEP 2016]

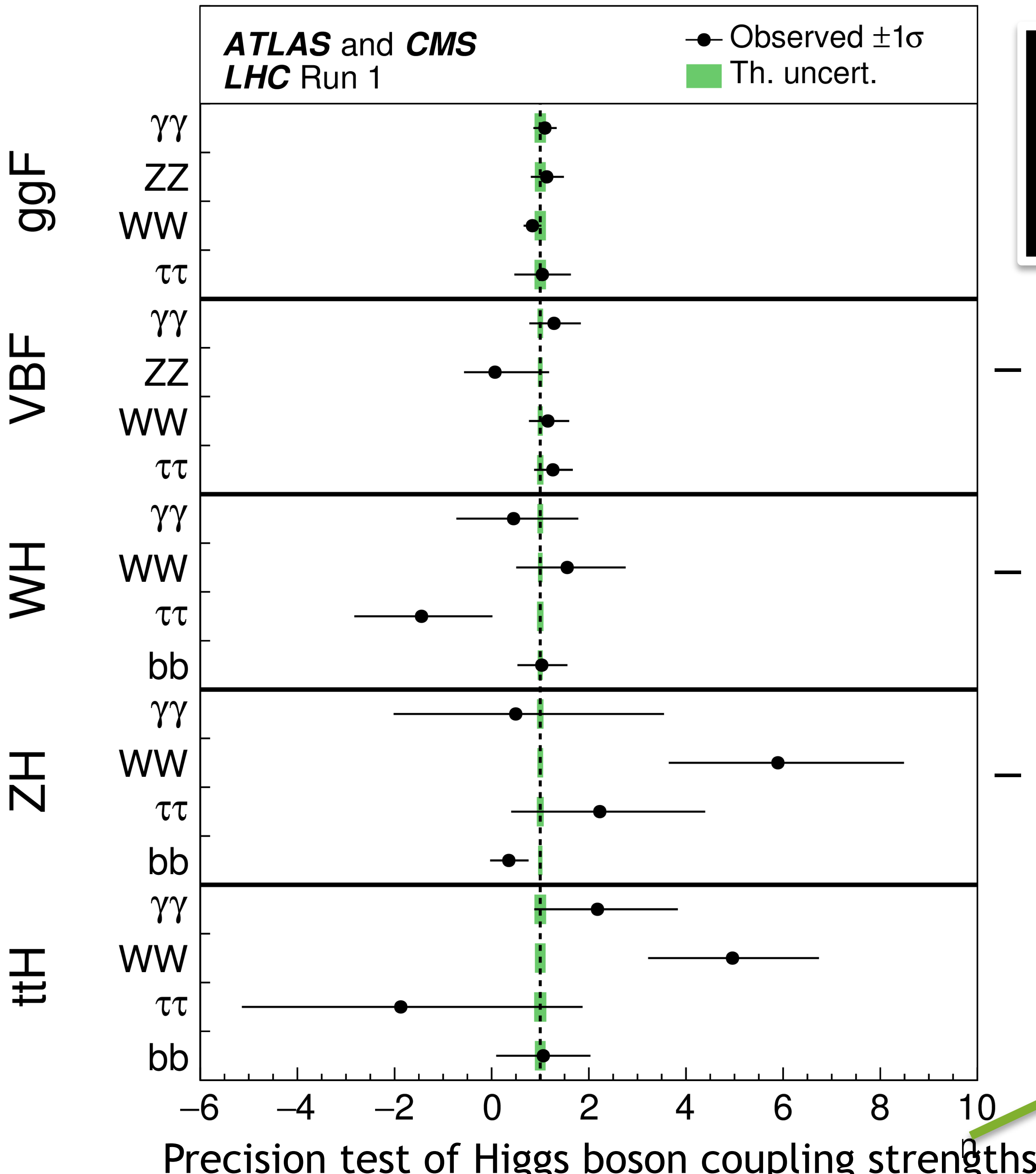


Observed decay modes:
γγ, ZZ, WW, ττ

Missing bb,cc, μμ, Zγ

Signal strengths from Run 1: ATLAS + CMS

[F. Canelli, ICHEP 2016]



CMS and ATLAS combined 7 and 8 TeV results Run 1 legacy papers:

Mass: Phys. Rev. Lett. 114, 191803
Rates and couplings: arXiv:1606.02266

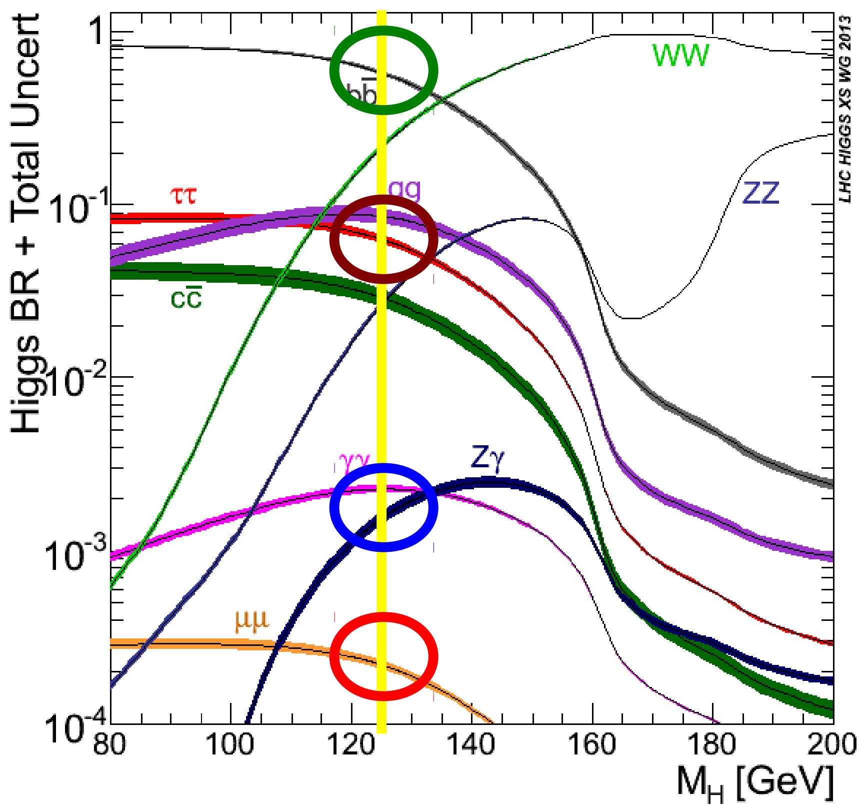
- Mass has been measured to 0.2% precision m_H=125.09±0.24 GeV
- Angular distributions consistent with spin 0 and even parity
- All couplings are consistent with SM within 2.5σ

Coupling strengths
$$\mu = \frac{\sigma}{\sigma_{SM}}$$

$$\mu = \frac{\sigma \times Br}{(\sigma \times Br)_{SM}}$$

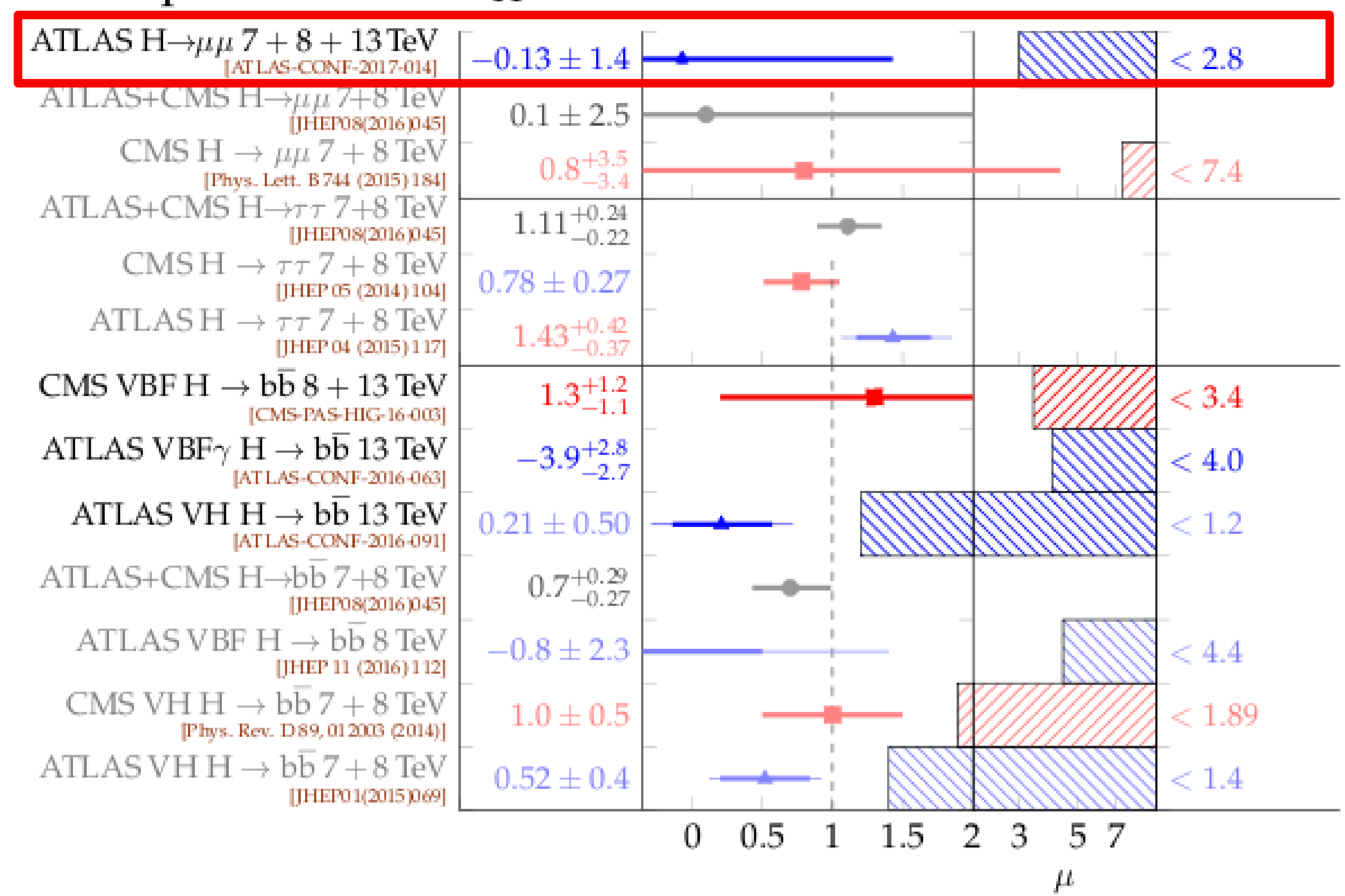
Higgs couplings to fermions: ττ, bb, μμ

[T. Gershon, Moriond 2017]



Exciting prospects for improved H → $b\bar{b}$, ττ & Zγ results soon

Measured signal strength μ and 95% CL limit on $\sigma \times$ Br relative to the SM expectation for $m_H = 125\,\mathrm{GeV}$:

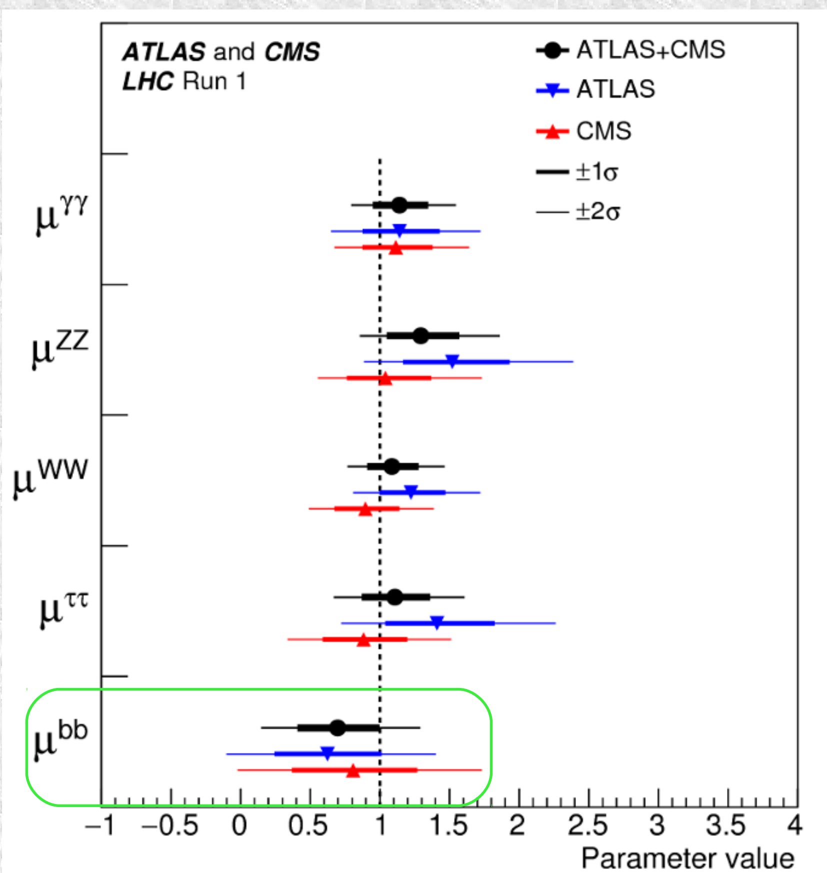


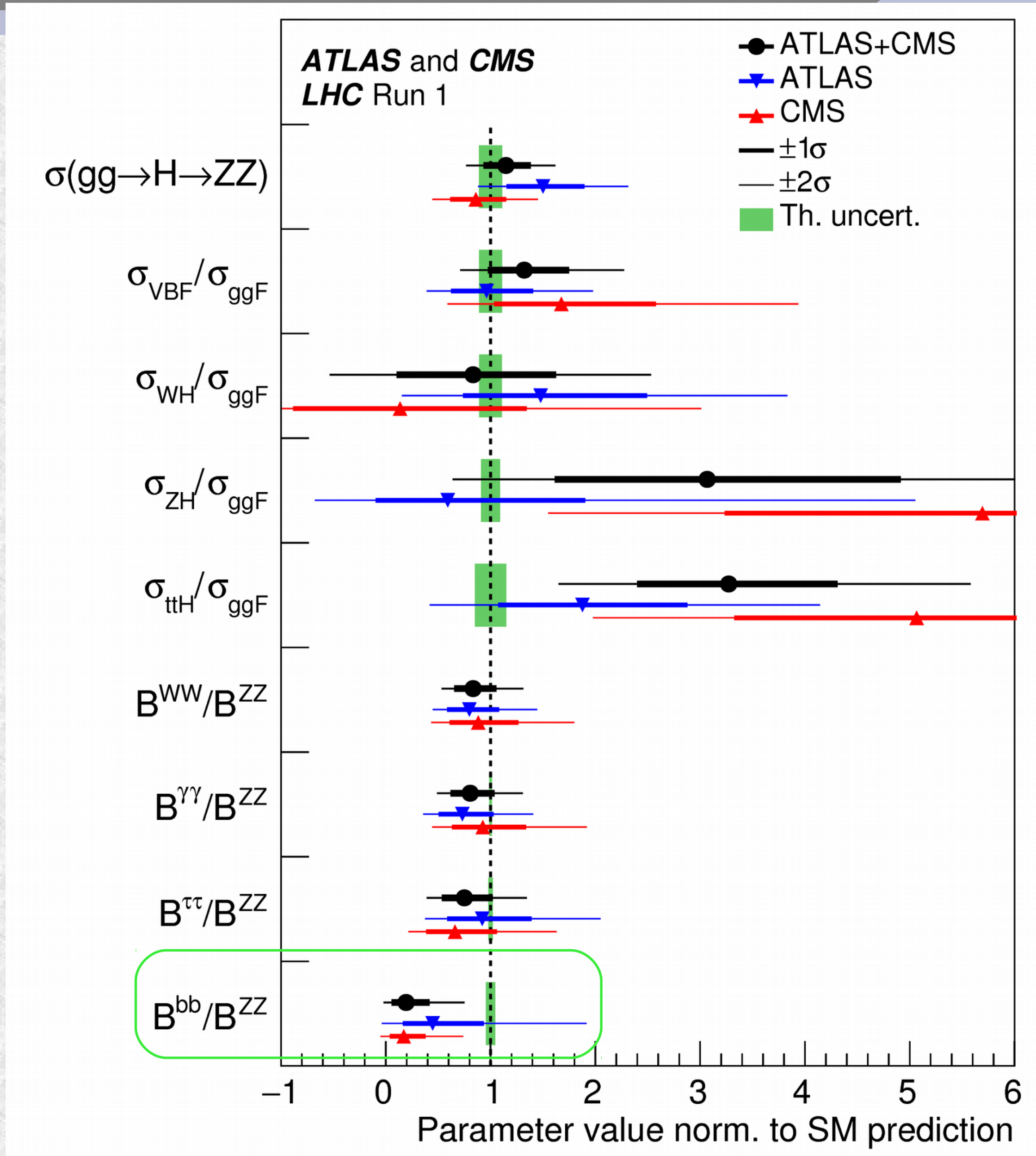
A possible hint for a deviation in H → bb?

[W. Murray, Moriond 2017]

H → bb: Run 1 ATLAS+CMS

- $\mu = 0.70^{+0.29}_{-0.27}$
- $B^{bb}/B^{ZZ} = 0.20^{+0.20}_{-0.12}$
- Is all well?





A possible hint for a deviation in H → bb?

Run 2 results: *[W. Murray, Moriond 2017]*

	Luminosity, fb^{-1}	μ
ATLAS ttH	13.2	$2.1^{+1}_{-0.9}$
CMS ttH	12.9	-0.19±0.80
ATLAS VH	13.2	0.21±0.51
CMS VBF	2.3	$-3.7^{+2.4}_{-2.5}$
ATLAS VBF+γ	12.6	$-3.9+^{2.8}_{-2.7}$

- The first 3 have systematics ≥ statistics
- Last two lag in sensitivity but may catch up?
- There is a pattern of low rates of H→bb
  - Naive average 0.2±0.4
- Full statistics analyses urgently awaited!

So, where do we stand?

[Traunstein, May 1st, 2017]

⇒ Still some way to go to establish the properties of the discovered particle

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}

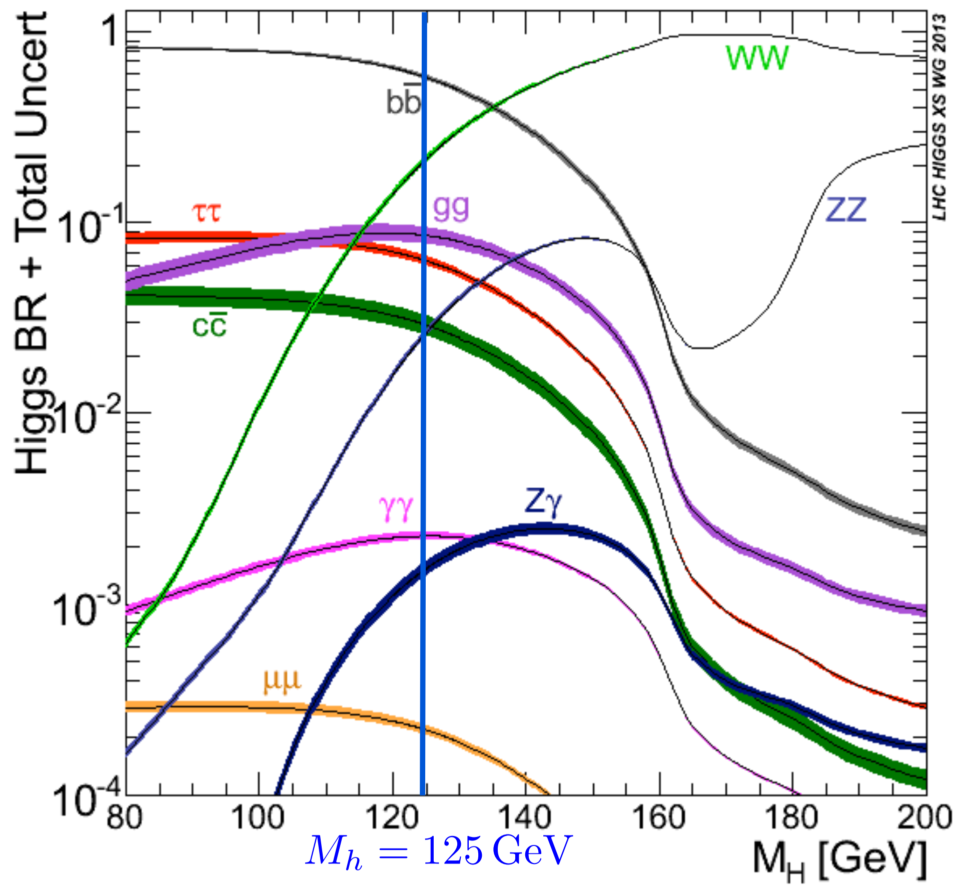
A change in M_{H} of 0.2 GeV shifts BR($H \to ZZ^*$) by 2.5%!

$\Rightarrow$ Need high-precision determination of M_{H} to exploit the sensitivity of BR($H \to ZZ^*$), ... to test BSM physics

Relevance of off-shell effects for Higgs physics

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

SM Higgs branching fractions:



[LHC Higgs XS WG '14]

For a 125 GeV Higgs boson the branching ratios into BR($H \to ZZ^*$), BR($H \to WW^*$) 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

Why the discovered particle cannot be the SM Higgs

The SM is incomplete: in particular, it describes only three of the four fundamental interactions, i.e. it does not contain gravity. Thus, the SM cannot be the ultimate theory. At best, the SM could be the low-energy limit of the (as yet unknown) more complete theory

Thus, the actual question is whether the low-energy limit of the more complete theory has just the matter content and the properties of the SM

However, this would mean that the gauge hierarchy, dark matter, the matter—anti-matter asymmetry in the Universe, … , would all have origins that are not directly related to low-scale physics

``Hierarchy problem'': Higgs mass should be affected by physics at high energy scales (e.g. Planck scale, 10^{19} GeV, where gravity is of similar strength as the other interactions)

BSM Higgs physics

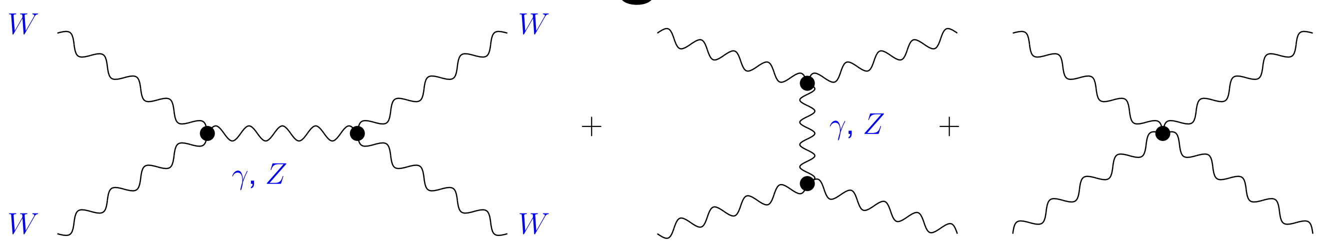
Extended Higgs sectors: where are the additional Higgses and how can we find them?

Composite Higgs: resonances, composite top partners, ... ?

…

Distinction possible via:

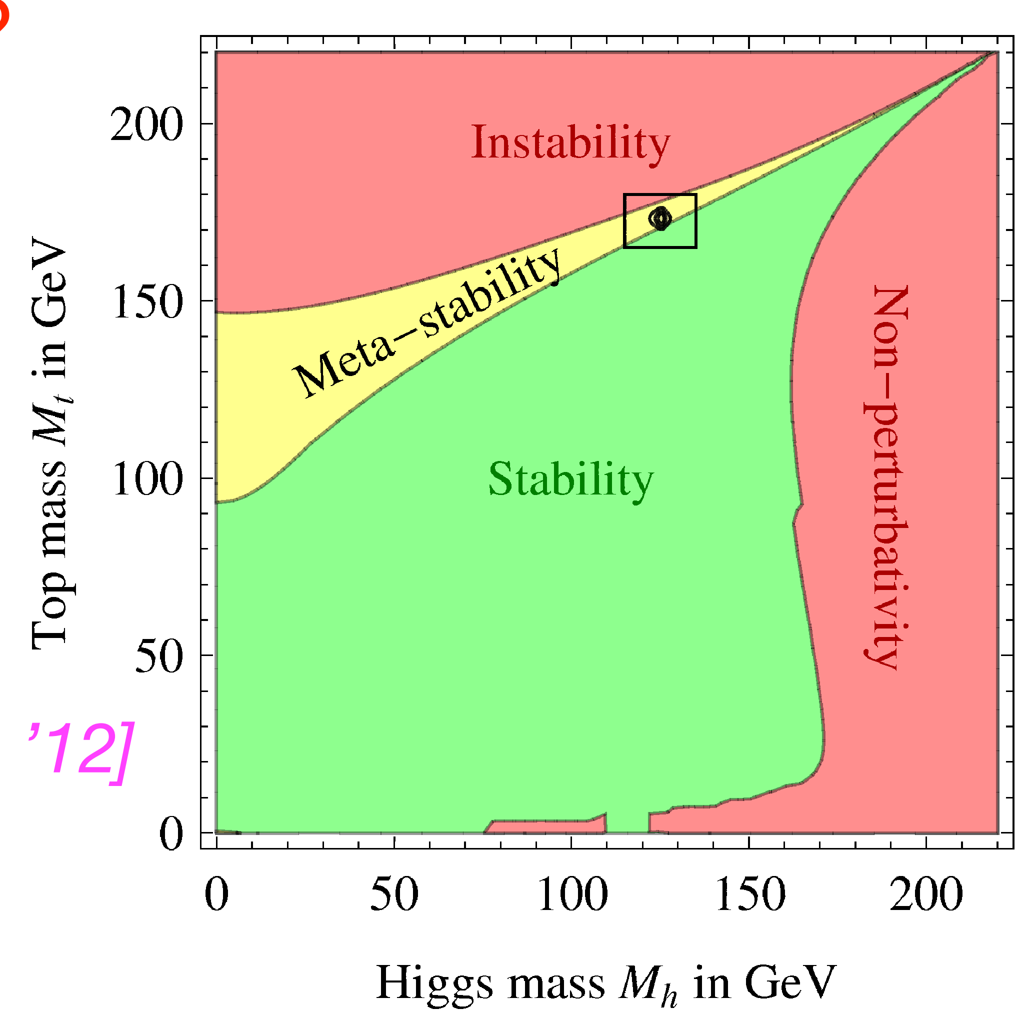
- Properties of the state at 125 GeV
- Impact on longitudinal vector boson scattering
- Search for additional states



Could there just be a single SM-like Higgs?

- Disregarding the hierarchy problem, could all the states of new physics sit at some very high scale?

- Vacuum stability in the SM: meta-stable vacuum?



[G. Degrassi et al. '12]

- Extended Higgs sector: contributions of additional Higgs states could stabilise the vacuum

- High-scale SUSY as the UV-completion of the SM?

Vacuum stability and high-scale SUSY

- SM cannot be matched to the MSSM if the scale of the MSSM particles is above about 10^{11} GeV *[G. Giudice, A. Strumia '12]*

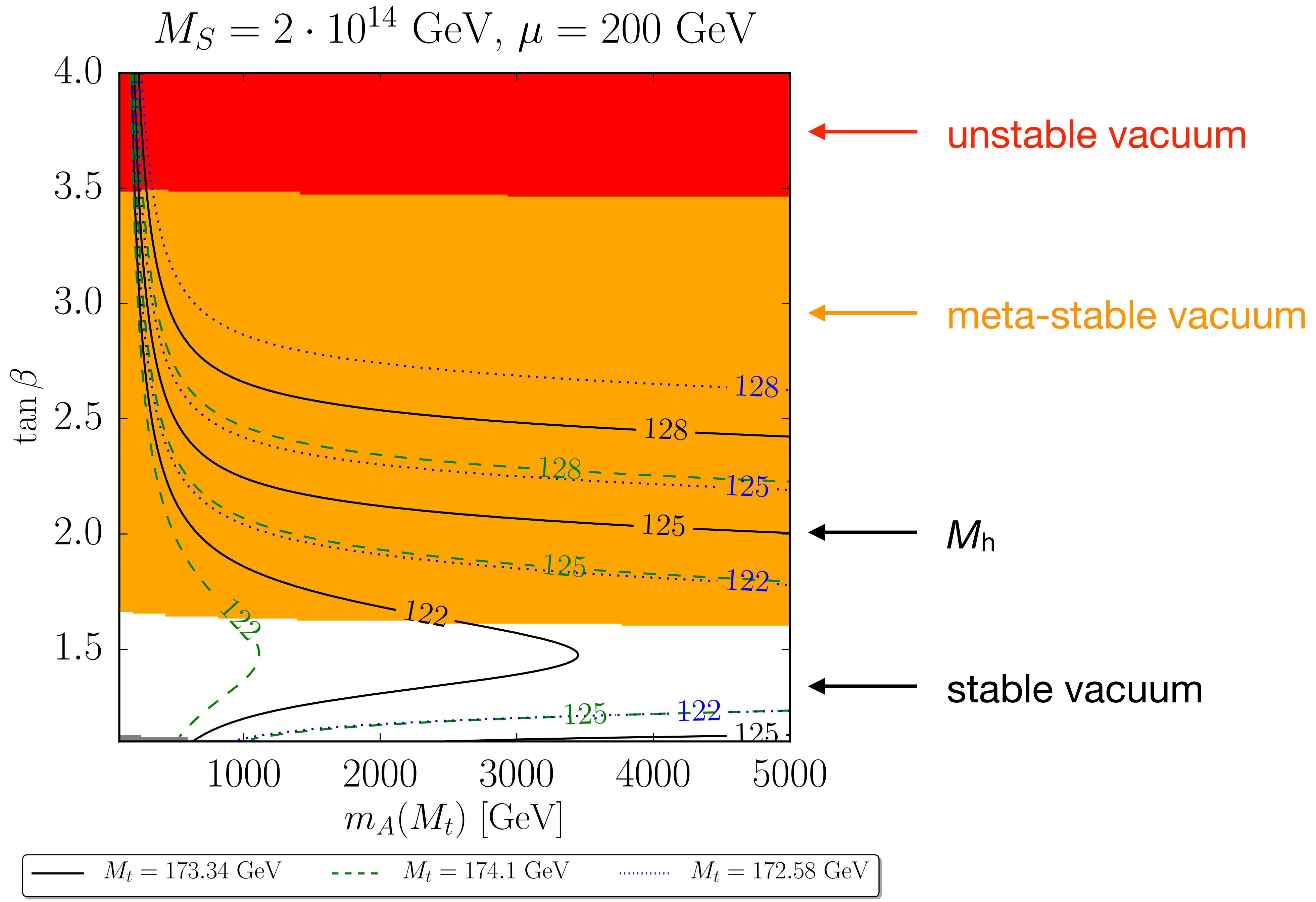
- 2HDM with and without light higgsinos / gauginos matched to the MSSM at high scale *[E. Bagnaschi, F. Brümmer, W. Buchmüller, A. Voigt, G. W. '15]*

⇒ Supersymmetric UV completion + stable vacuum + Higgs at 125 GeV works for 2HDM as low-scale model and for 2HDM + light higgsinos

Does not work for split SUSY case (light higgsinos and gauginos)

2HDM + light higgsinos at low scale, other MSSM states at high scale

[E. Bagnaschi, F. Brümmer, W. Buchmüller, A. Voigt, G. W. '15]



⇒Stable or meta-stable vacuum possible for low tanβ and large M_A

The Higgs-boson mass as a test for BSM physics (focus here on models with extended Higgs sectors)

Standard Model: a single parameter determines the whole Higgs phenomenology: M_{H}

In the SM the same Higgs doublet is used “twice” to give masses both to up-type and down-type fermions

$\Rightarrow$ extensions of the Higgs sector having (at least) two doublets are quite “natural”

$\Rightarrow$ Would result in several Higgs states

Many extended Higgs theories have over large part of their parameter space a lightest Higgs scalar with properties very similar to those of the SM Higgs boson

Example: SUSY in the “decoupling limit”

The minimal supersymmetric extension of the Standard Model (MSSM)

Superpartners for Standard Model particles:

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_L \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_L \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^\pm, H^\pm} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin } 1 \text{ / Spin } 0$$

$$\tilde{g} \qquad \tilde{\chi}^\pm_{1,2} \qquad \tilde{\chi}^0_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Two Higgs doublets, physical states: $h^0, H^0, A^0, H^\pm$

Exact SUSY $\Leftrightarrow m_{\mathrm{e}} = m_{\tilde{\mathrm{e}}}, \ldots$

$\Rightarrow$ SUSY can only be realised as a broken symmetry

MSSM: no particular SUSY breaking mechanism assumed, parameterisation of possible soft SUSY-breaking terms

The Higgs sector of the MSSM

Minimal Supersymmetric Standard Model (MSSM)

$\Rightarrow$ "Simplest" extension of the minimal Higgs sector:

- Two doublets to give masses to up-type and down-type fermions (extra symmetry forbids to use same doublet)

- SUSY imposes relations between the parameters

$\Rightarrow$ Two parameters instead of the one parameter (M_{H}) of the SM: $\tan\beta \equiv \frac{v_u}{v_d}$, M_{A} (or $M_{\mathrm{H}^\pm}$)

Higgs potential of the MSSM

MSSM Higgs potential contains two Higgs doublets:

$$V = \left(|\mu|^2 + m_{H_u}^2\right)\left(|h_u^0|^2 + |h_u^+|^2\right) + \left(|\mu|^2 + m_{H_d}^2\right)\left(|h_d^0|^2 + |h_d^-|^2\right)$$

$$+ \left[b\left(h_u^+ h_d^- - h_u^0 h_d^0\right) + \text{h.c.}\right]$$

$$+ \underbrace{\frac{g^2 + g'^2}{8}}\left(|h_u^0|^2 + |h_u^+|^2 - |h_d^0|^2 - |h_d^-|^2\right)^2 + \underbrace{\frac{g'^2}{2}}\left|h_u^+ h_d^{0*} + h_u^0 h_d^{-*}\right|^2$$

gauge couplings, in contrast to the SM

Five physical states: $h^0, H^0, A^0, H^\pm$

Parameters (besides g, g'):

μ: mixing term of the two Higgs doublets in superpotential, $\mu H_d H_u$

m_{H_u}, m_{H_d}, b: soft SUSY-breaking parameters

The "µ problem"

MSSM contains term $\mu H_d H_u$ in superpotential

μ: dimensionful parameter

For EW symmetry breaking required: $\mu \sim$ electroweak scale

But: no a priori reason for $\mu \neq 0$, $\mu \ll M_{\rm Pl}$

Possible solution: μ related to v.e.v. of additional field

$\Rightarrow$ Introduction of extra singlet field S, v.e.v. $s \Rightarrow$ "NMSSM"

Superpotential: $\mathcal{V} = \lambda H_d H_u S + \frac{1}{3}\kappa S^3 + \ldots$

Physical states in NMSSM Higgs-sector:

S_1, S_2, S_3 (CP-even), P_1, P_2 (CP-odd), $H^\pm$

Higgs mass bound in the MSSM

Prediction for $M_{\rm h}$, $M_{\rm H}$, . . .

Tree-level result for $M_{\rm h}$, $M_{\rm H}$:

$$M^2_{\rm H,h} = \frac{1}{2}\left[M_{\rm A}^2 + M_{\rm Z}^2 \pm \sqrt{(M_{\rm A}^2 + M_{\rm Z}^2)^2 - 4M_{\rm Z}^2 M_{\rm A}^2 \cos^2 2\beta}\right]$$

$\Rightarrow M_{\rm h} \leq M_{\rm Z}$ at tree level

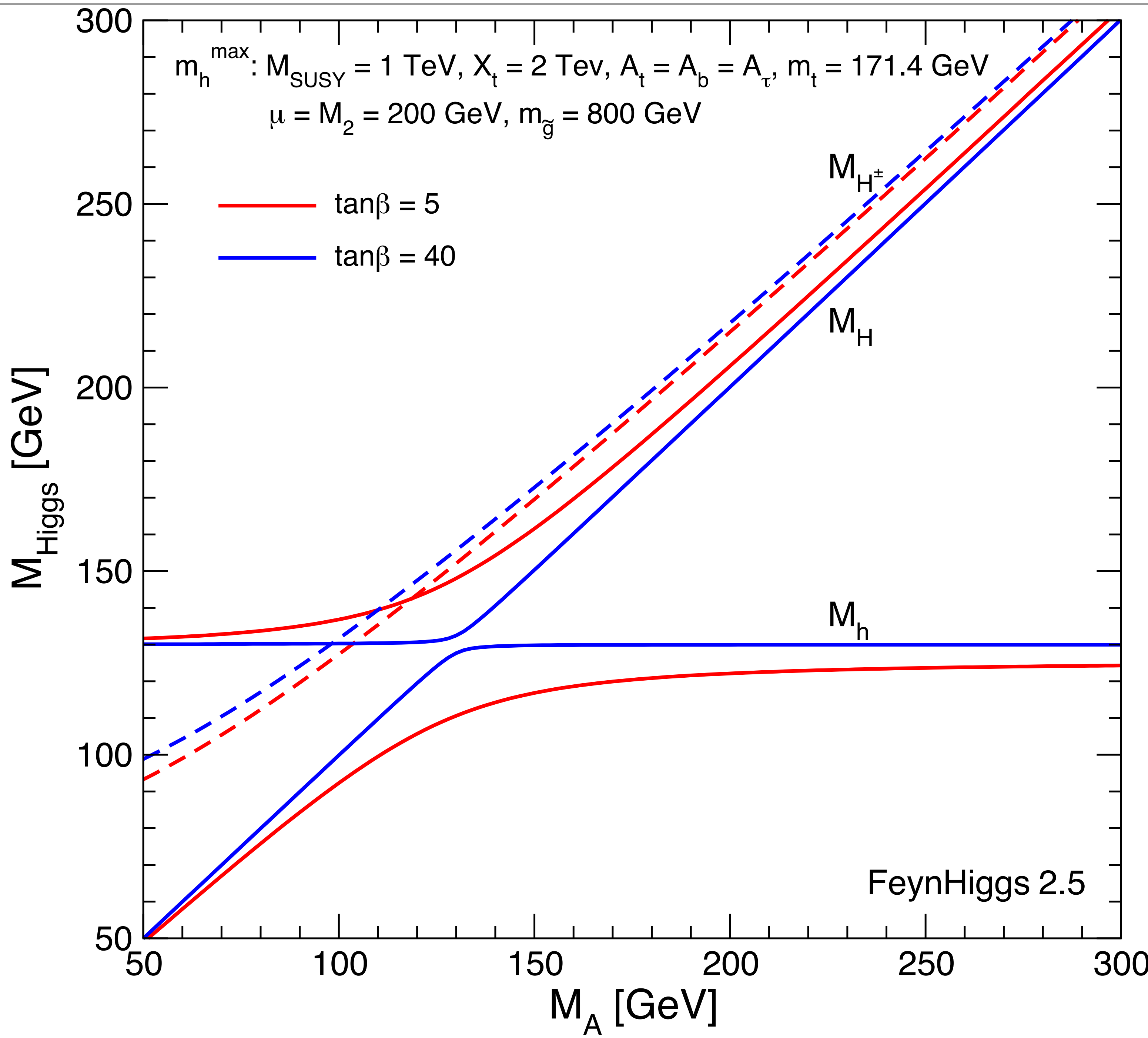
MSSM tree-level bound (gauge sector): excluded by LEP!

Large radiative corrections (Yukawa sector, . . .):

Yukawa couplings: $\frac{{\rm e}\, m_{\rm t}}{2M_{\rm W} s_{\rm W}}, \frac{{\rm e}\, m_{\rm t}^2}{M_{\rm W} s_{\rm W}}, \ldots$

$\Rightarrow$ Dominant one-loop corrections: $G_\mu m_{\rm t}^4 \ln\left(\frac{m_{\tilde{\rm t}_1} m_{\tilde{\rm t}_2}}{m_{\rm t}^2}\right)$, $\quad \mathcal{O}(100\%)$!

Higgs mass predictions in the MSSM: important test of the model



⇒ Upper bound on M_h; for $M_A \gg M_Z$: ``decoupling region'' with SM-like light Higgs and all other Higgses heavy

Predictions for Higgs mass and potential in SUSY: full model (MSSM) vs. effective field theory (EFT)

Full model (MSSM, NMSSM, ...):

- Contributions of all particles in the loop: $\tilde{t}, \tilde{b}, \tilde{q}, \tilde{l}, \tilde{\chi}^{\pm}, \ldots$
  contributions from all sectors of the model

- Diagrammatic / effective potential methods

- Mass effects of all particles taken into account: every possible mass pattern can be considered

$$\Delta m_{\mathrm{h}}^2 \sim m_{\mathrm{t}}^4 G_{\mathrm{F}} \log\left(\frac{m_{\tilde{\mathrm{t}}}^2}{m_{\mathrm{t}}^2}\right) + \ldots$$

- Very large higher-order corrections:
  tree-level upper bound: 91 GeV $\xrightarrow[\text{radiative corrections}]{}$ observed value: 125 GeV

⇒ Relative effect of higher-order corrections in M_{h}^2: ≳90%

Full model (MSSM), continued

- Roughly: 1 GeV change in (effective value of) $m_t \Rightarrow$ 1 GeV change in m_h

- *FeynHiggs* (fixed order contribution): Two-loop result in on-shell scheme
  \+ (optional) reparametrisation in terms of $m_t(m_t)$ + (see below)
  TeV scale: both log terms and non-log terms are numerically important!

- Estimate of remaining theoretical uncertainties from unknown higher-order corrections: ~ 3 GeV uncertainty, depending on the parameter region (uncertainties are relatively large in region of large stop mixing)

- Full model (MSSM): preferred method for relatively light SUSY

- Improvement: need 3-loop, … contributions; all contributions of $O(\alpha_t^i \alpha_s^j)$ needed; compensations between different contributions expected
  Partial 3-loop results available *[S. Martin '07] [R. Harlander, P. Kant, L. Mihaila, M. Steinhauser '08]*

Effective field theory (EFT) approach

What if the SUSY particles (or part of the spectrum) sit at very high scales (10^{14} GeV, M_{Pl}, …)? High-scale SUSY, split SUSY, …
⇒ very large logs, log terms dominate, need to be resummed ⇒ EFT

Heavy SUSY particles integrated out
Low-scale model is just the SM (1 Higgs doublet), or split-SUSY type scenario with 1 doublet, or 2HDM, …
Large mass gap between different scales required!

Impact of heavy particles only via boundary conditions + threshold corrections at high scale
High-scale SUSY: renormalisation-group (RG) running + Higgs-mass computation involve only SM contributions
SUSYHD *[J. Pardo Vega, G. Villadoro ’15]*, *FlexibleSUSY* *[P. Athron, J.-h. Park, D. Stöckinger, A. Voigt ’14]*, *MhEFT* *[G. Lee, C. Wagner ’16]*, …

In case of several thresholds: need to integrate out part of the spectrum

Hybrid approach: leading log improvement of fixed-order result for heavy SUSY particles

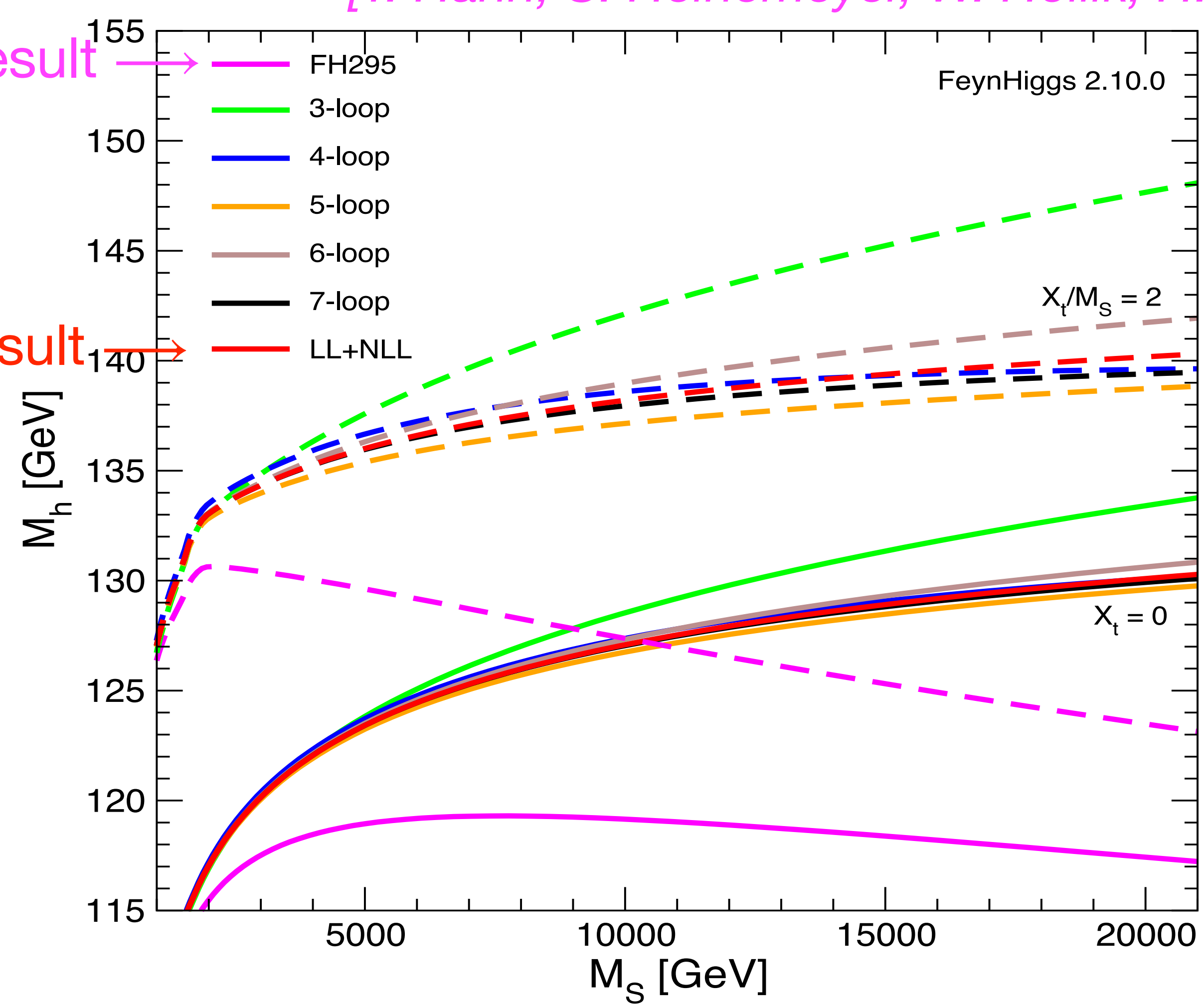
If some SUSY particles are much heavier than O(1 TeV): larger log contributions ⇒ improvement with resummation of leading logs

⇒ First step: diagrammatic fixed-order contributions up to two-loop order + resummation of leading and next-to-leading logs

[T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. W. '14]

Fixed-order result

Full result



⇒ Leading log resummation relevant for $M_S \gtrsim 2$ TeV

Current status of hybrid approach predictions

FeynHiggs:
[H. Bahl, T. Hahn, S. Heinemeyer, W. Hollik, S. Paßehr, H. Rzehak, G. W. '16, 17']
Combination of fixed-order result up to the two-loop level in the on-shell scheme with a log resummation in the MSbar/DRbar scheme
Resummation of full LL, NLL + NNLL at $O(\alpha_t\alpha_s, \alpha_t^2)$
Logs already contained in the fixed-order result are consistently subtracted

Pure EFT result agrees very well ($\Delta M_h \lesssim 0.1$ GeV) with *SUSYHD* for high-scale SUSY scenario, if NNLO top Yukawa coupling is used in *SUSYHD* (shift by ≈ 0.5 GeV for NNNLO top Yukawa coupling)

Recent implementations of hybrid approach also for *FlexibleSUSY* *[P. Athron, J.-h. Park, T. Steudtner, D. Stöckinger, A. Voigt '16]* and *SPheno* *[F. Staub, W. Porod '17]*

Comparison: hybrid and EFT approach

Numerical comparison below is done for simplest case of high-scale SUSY model: $M_{\mathrm{soft}} = \mu = M_A \equiv M_{\mathrm{SUSY}}$ (single-scale scenario)

In realistic cases the task is to provide the most accurate prediction for the Higgs masses, decay and production processes for a given SUSY spectrum (appropriate combination of fixed-order result and log resummation) together with a reliable estimate of the remaining theoretical uncertainties

Significant progress during the last years: ``KUTS” Workshop series (Workshops on precision SUSY Higgs Mass calculations, 7th meeting: Karlsruhe, July 2017)

Comparison: hybrid and EFT approach

In decoupling limit, $M_{\rm soft} = \mu = M_A \equiv M_{\rm SUSY} \gg M_Z$, imaginary parts neglected:

EFT result:

$$
\begin{aligned}
(M_h^2)_{\rm EFT} = {} & 2v^2_{\overline{\rm MS}}\lambda(M_t) + \frac{1}{\sqrt{2}v_{\overline{\rm MS}}} T_h^{\rm SM}\Big|_{\rm fin} - \tilde{\Sigma}_{hh}^{\rm SM}(m_h^2) \\
& - \tilde{\Sigma}_{hh}^{\rm SM\prime}(m_h^2) \cdot \left[2v^2_{\overline{\rm MS}}\lambda(M_t) + \frac{1}{\sqrt{2}v_{\overline{\rm MS}}} T_h^{\rm SM}\Big|_{\rm fin} - \tilde{\Sigma}_{hh}^{\rm SM}(m_h^2) - m_h^2 \right] + \ldots
\end{aligned}
$$

Result of hybrid approach:

$$
\begin{aligned}
(M_h^2)_{\rm FH} = {} & m_h^2 - \hat{\Sigma}_{hh}^{\rm MSSM}(M_h^2) + \left[2v^2_{\overline{\rm MS}}\lambda(M_t)\right]_{\rm logs} + \left[\hat{\Sigma}_{hh}^{\rm MSSM}(m_h^2)\right]_{\rm logs} = \\
= {} & m_h^2 + \left[2v^2_{\overline{\rm MS}}\lambda(M_t)\right]_{\rm logs} - \left[\hat{\Sigma}_{hh}^{\rm MSSM}(m_h^2)\right]_{\rm nolog} \\
& - \hat{\Sigma}_{hh}^{\rm MSSM\prime}(m_h^2)\left(\left[2v^2_{\overline{\rm MS}}\lambda(M_t)\right]_{\rm logs} - \left[\hat{\Sigma}_{hh}^{\rm MSSM}(m_h^2)\right]_{\rm nolog}\right) + \ldots
\end{aligned}
$$

Comparison: hybrid and EFT approach

- Hybrid approach contains non-logarithmic terms of O(v/M_{SUSY}) that correspond to higher-dimensional operators in the EFT approach

- Differences in the parametrisation of the non-logarithmic contributions (on-shell/MSbar parameters, …)

- Higher-order terms arising from the determination of the propagator pole: differences in non-SM contributions cancel out in the limit of a heavy SUSY scale if all relevant terms at a given order are included (cancellation with subloop renormalisation)

- Parameter conversion DRbar ↔ on-shell

Obstacle for detailed comparison: parameter conversion

- Comparison of fixed-order results in different schemes:
  Parameter conversion, e.g. $p^{\mathrm{OS}} = p^{\overline{\mathrm{DR}}} + \Delta p$

⇒ Differences at higher orders, indication for possible size of unknown higher-order corrections

- For results containing series of (resummed) higher-order logs: correct form of higher-order logs needs to be maintained, would be affected by parameter conversion as above

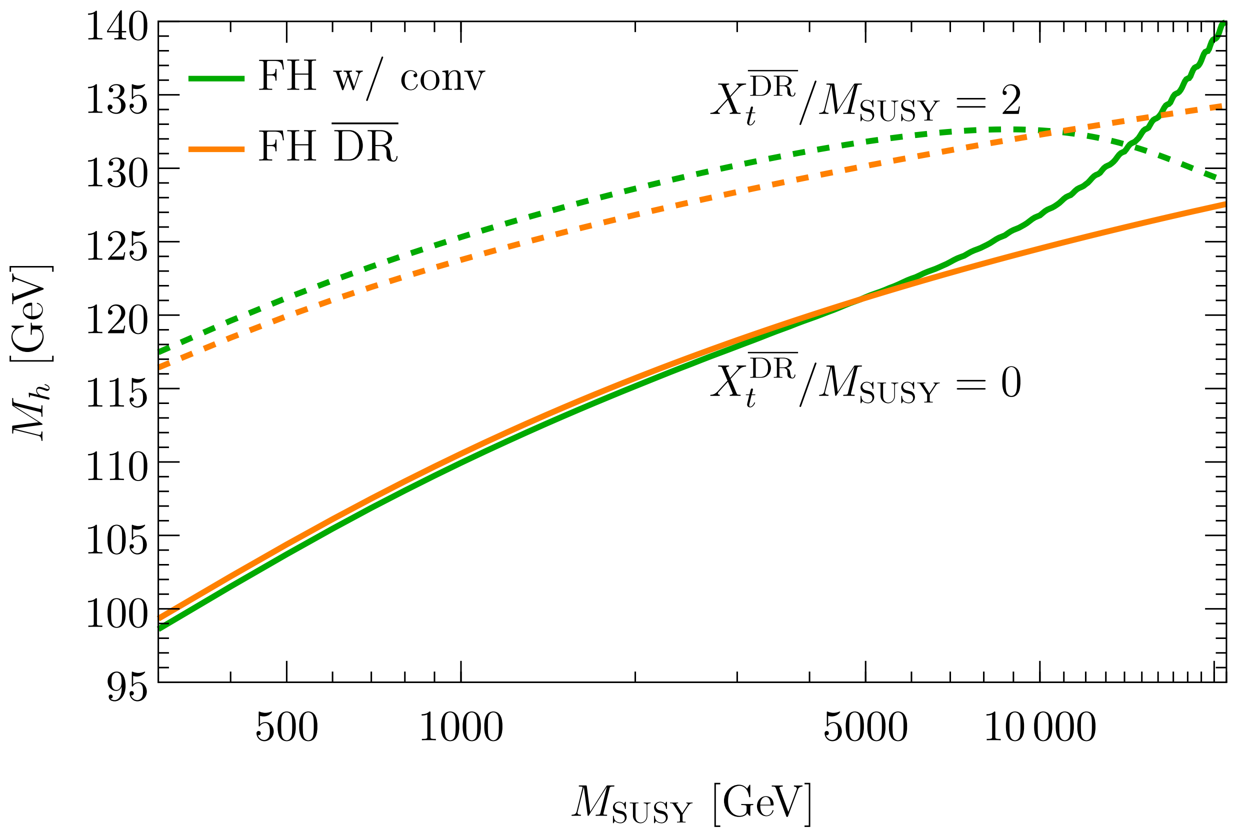
⇒ Perform parameter conversion in fixed-order result rather than in infinite series of higher-order logs

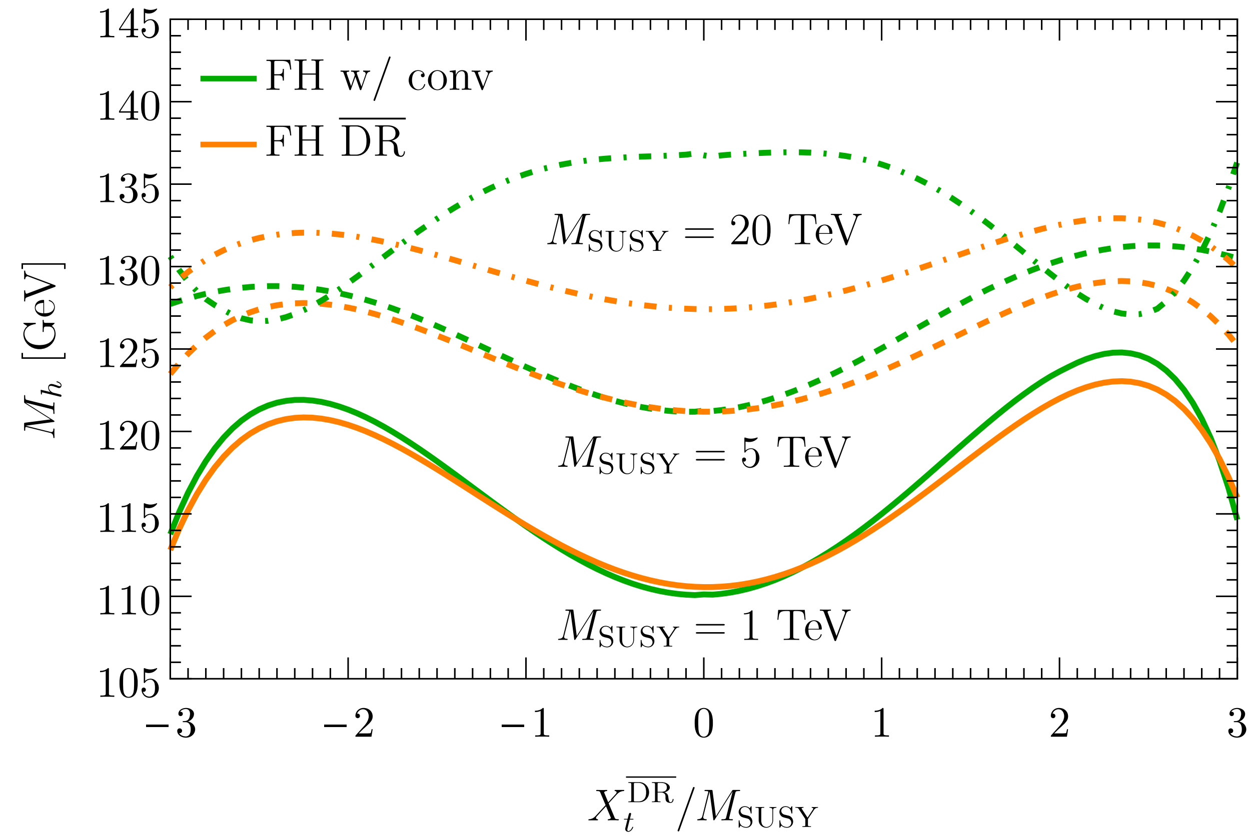
⇒ Fixed-order result in *FeynHiggs* for DRbar parameters in the stop sector
For on-shell input parameters: only logarithmic terms included in conversion

$$X_t^{\overline{\mathrm{DR}},\mathrm{EFT}} = X_t^{\mathrm{OS}} \left[1 + \left(\frac{\alpha_s}{\pi} - \frac{3\alpha_t}{16\pi} (1 - X_t^2/M_S^2) \right) \ln \frac{M_S^2}{M_t^2} \right]$$

Effect of parameter conversion on higher-order logarithmic contributions within *FeynHiggs*

[H. Bahl, S. Heinemeyer, W. Hollik, G. W.'17]



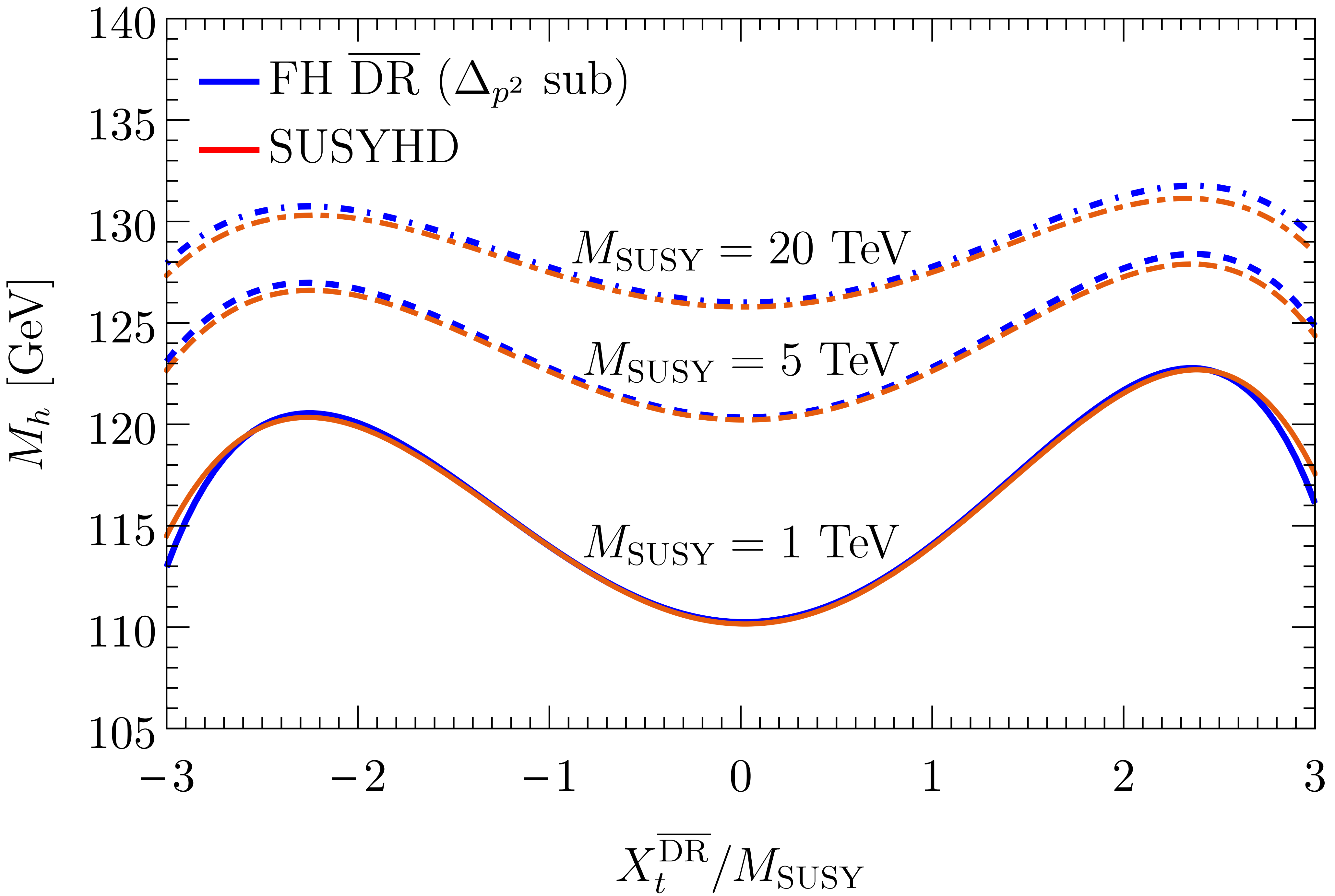


⇒ If parameter conversion is done as for a fixed-order result: Generation of logarithmic higher-order effects which are numerically large for high SUSY scales

FeynHiggs result with DRbar stop-sector parameters is numerically stable for large SUSY scales

Comparison of *FeynHiggs* results with *SUSYHD*

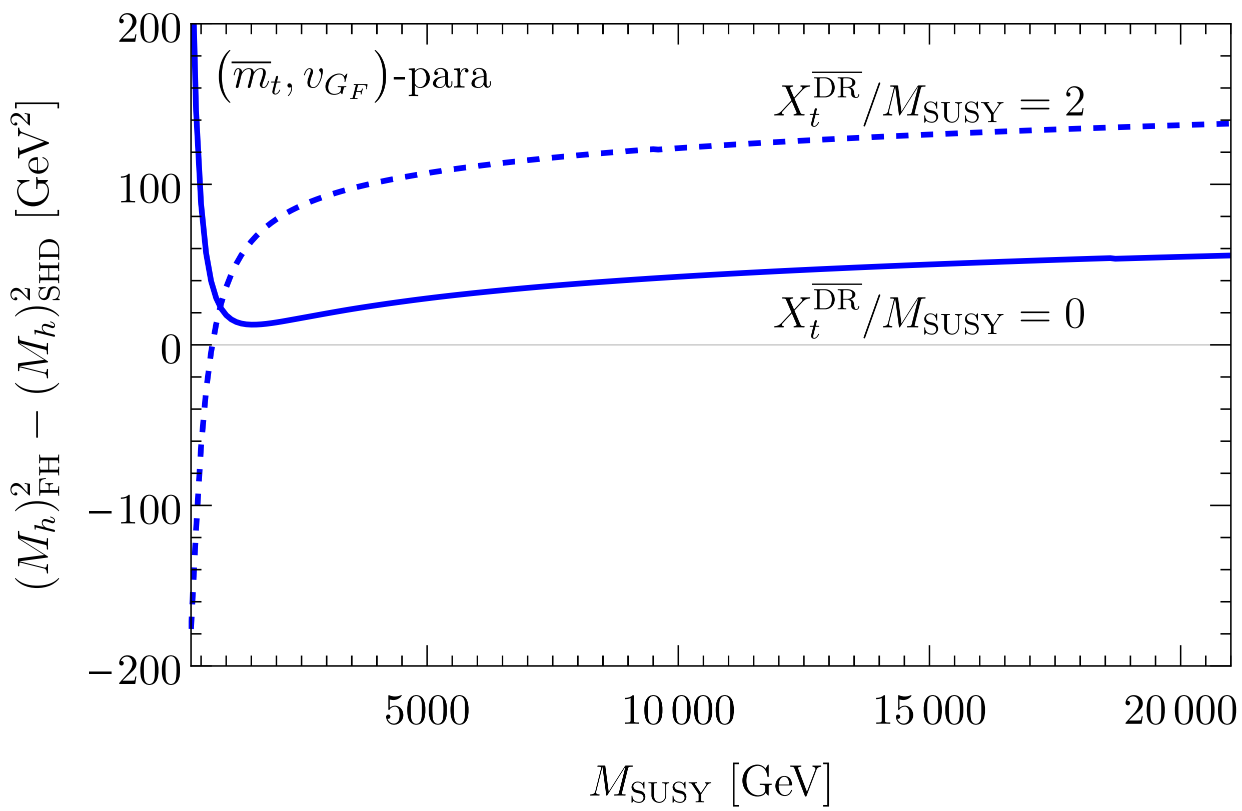
[H. Bahl, S. Heinemeyer, W. Hollik, G. W.'17]

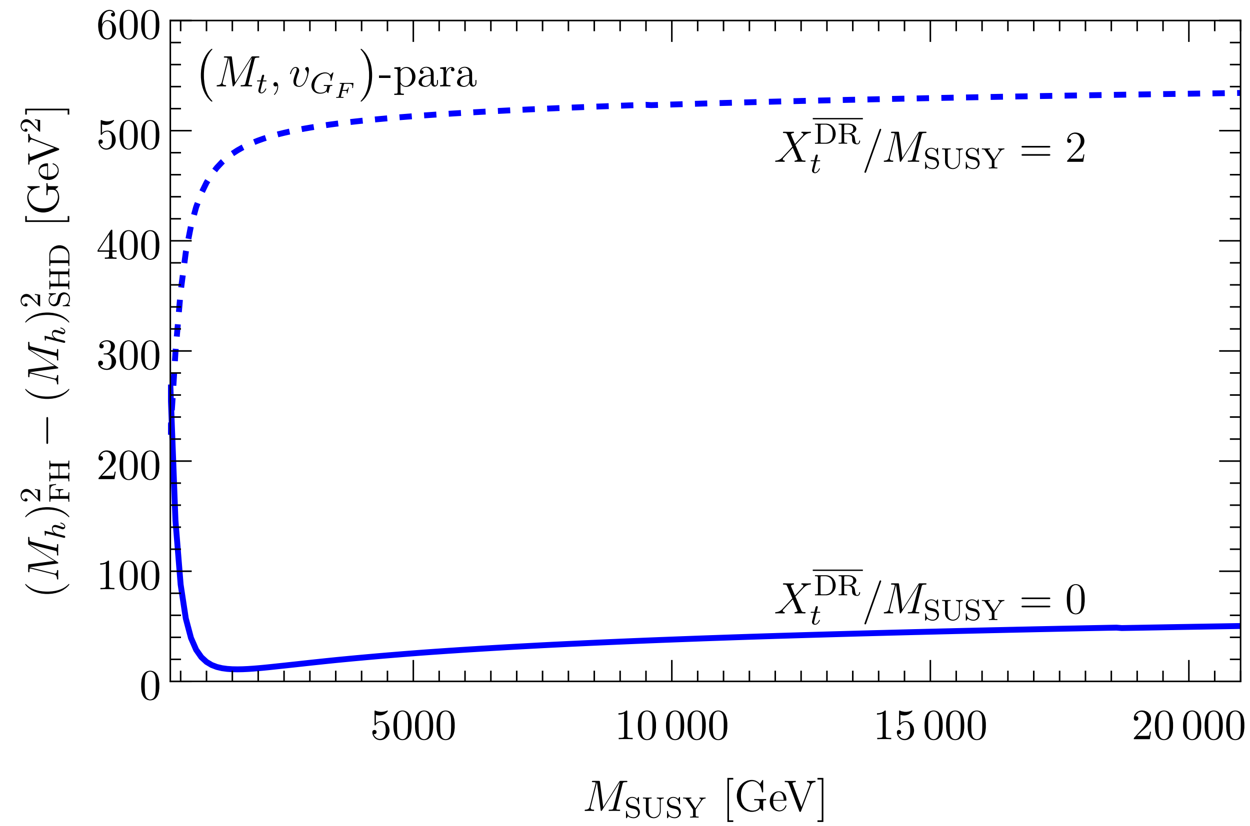


⇒ Good agreement for M_h within ≈ 1 GeV

Impact of different parametrisations of non-logarithmic contributions

[H. Bahl, S. Heinemeyer, W. Hollik, G. W.'17]



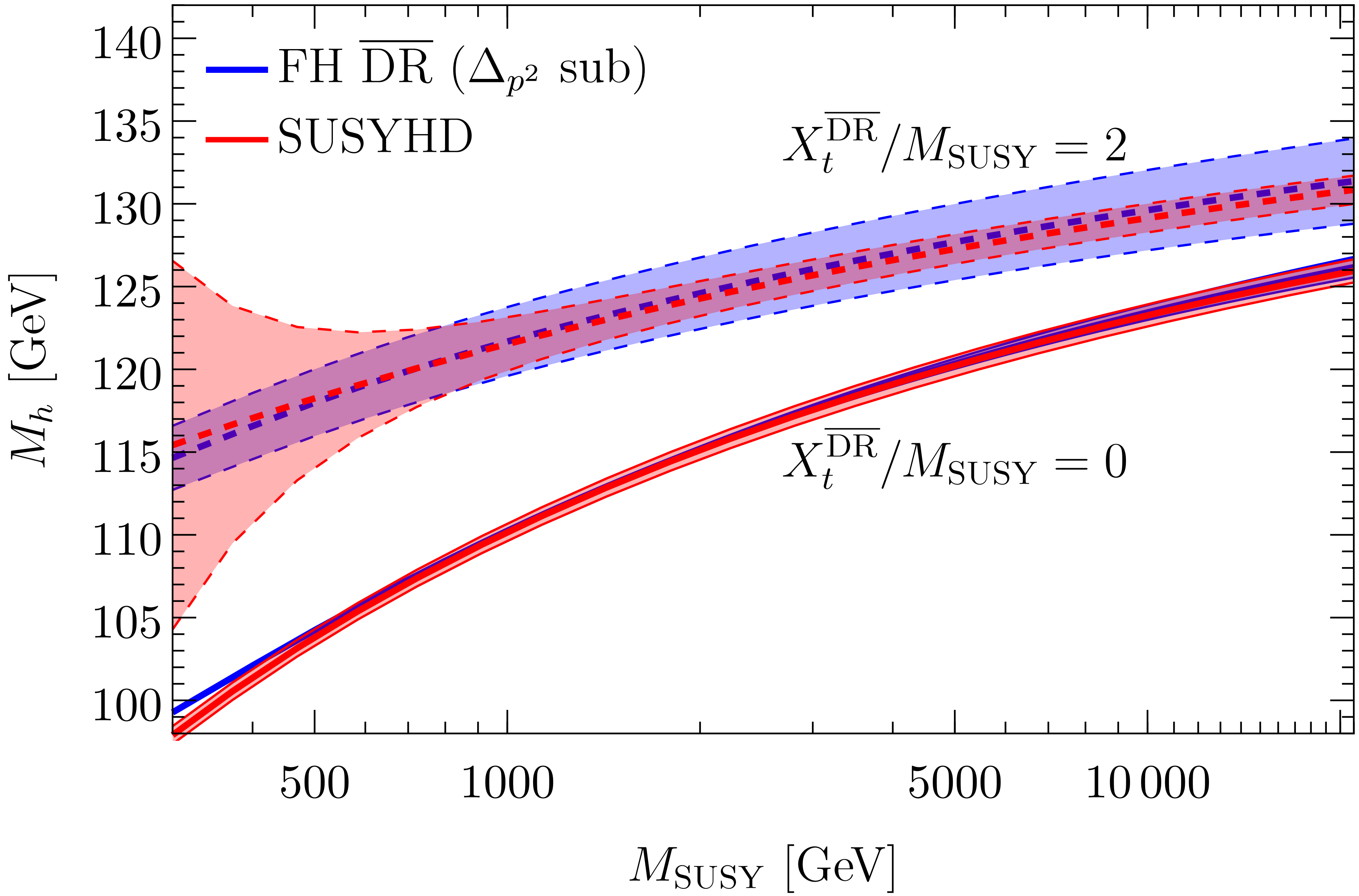


⇒ Nearly constant shifts for large M_{SUSY}

Larger deviations for small SUSY scales

Uncertainty estimates of *FeynHiggs* and *SUSYHD*

[H. Bahl, S. Heinemeyer, W. Hollik, G. W.'17]



Different sources of higher-order uncertainties considered
Work in progress towards improved parameter-space dependent estimate of remaining theoretical uncertainties

Higgs phenomenology in extended Higgs sectors

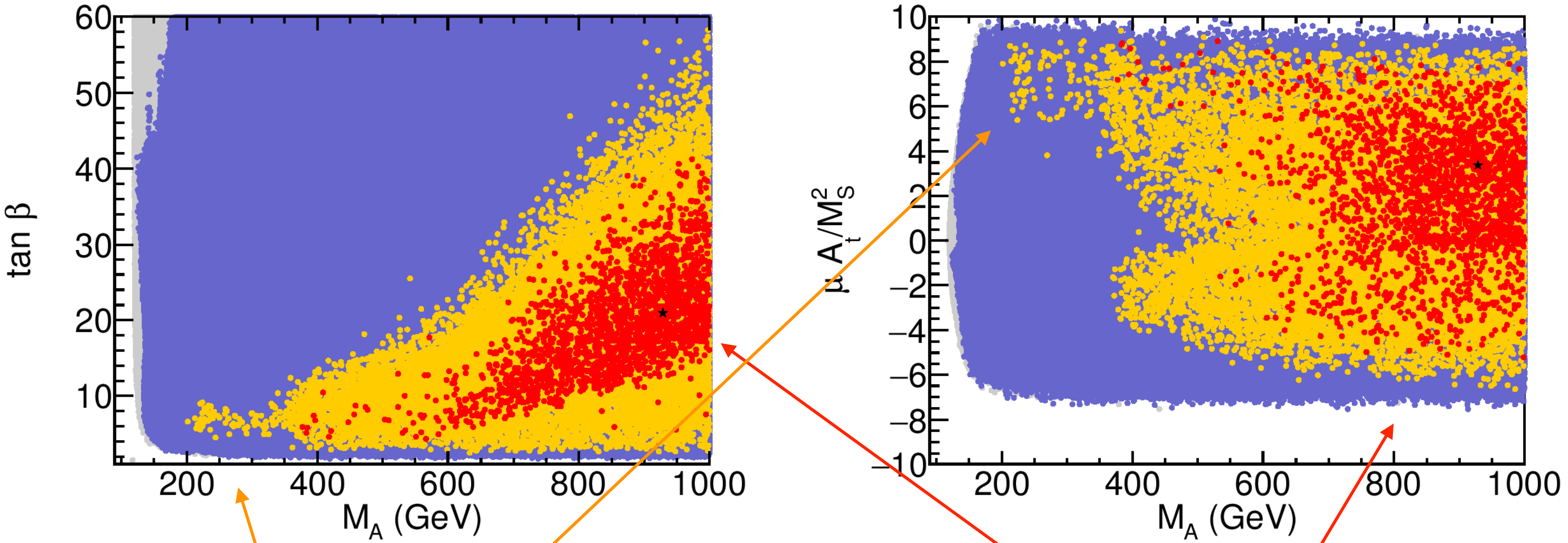
SM-like Higgs in extended Higgs sector: one of the neutral Higgs mass eigenstates has to be approximately aligned with the direction of the Higgs v.e.v. in field space
Limit of a SM Higgs: ``alignment limit"

Alignment limit in an extended Higgs sector is realised if all additional Higgs states are heavy: ``decoupling limit"

Other possibility: ``alignment without decoupling"
Occurs generically in 2HDMs, requires for h as SM-like state a cancellation between tree-level and loop-contributions in MSSM

Global fit in the MSSM, h125 as light MSSM Higgs

[P. Bechtle, H. Haber, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '16]



``Alignment without decoupling region'', allowed at 95% CL level, all other Higgses can be light

Best-fit point: ``decoupling region'', other Higgses are heavy

Extended Higgs sectors with heavy new states

Most obvious possibility: state at 125 GeV corresponds to the lightest state of an extended Higgs sector

Heavy additional Higgs states ⇒ decoupling behaviour

Interference effects can be important for heavy Higgs phenomenology

Examples:

- Interference effects of the heavy Higgs signal with the background and with the state at 125 GeV
- MSSM with CP-violation: h_2, h_3 are typically nearly mass-degenerate, have a large mixing

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”:

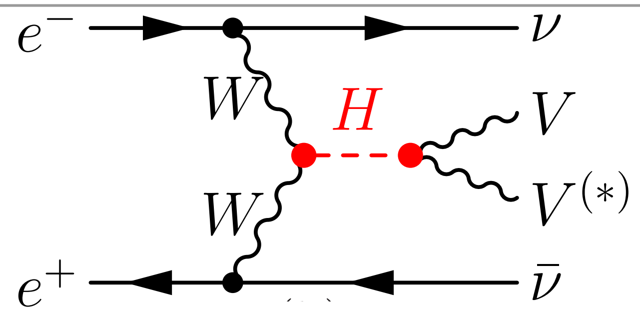
$$\sum_i g^2_{H_i VV} = \left(g^{\mathrm{SM}}_{HVV}\right)^2$$

⇒ •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

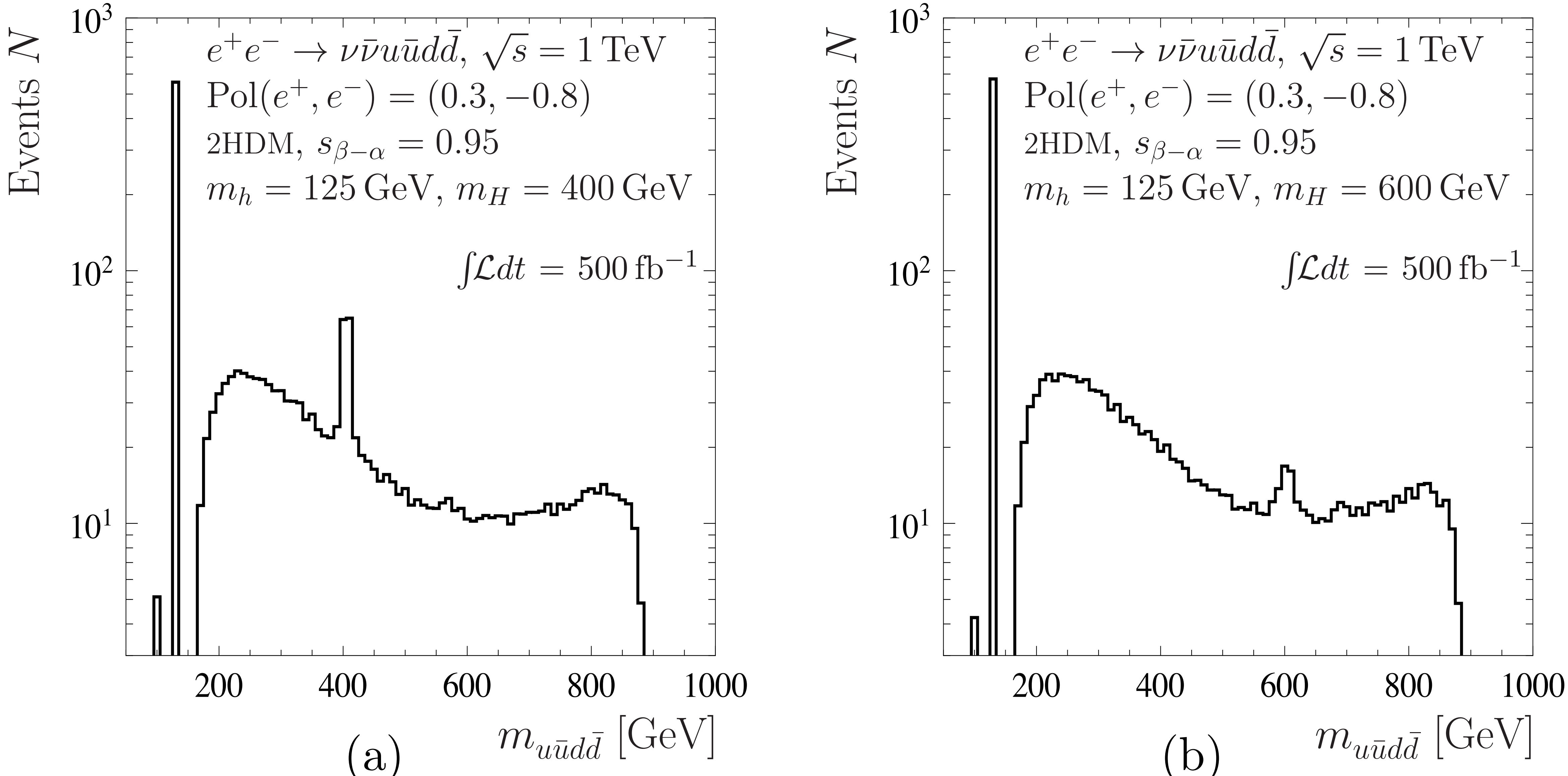
• Searches for additional Higgs bosons need to test compatibility with the observed signal at 125 GeV!

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]

$$g_{\rm hVV} = \sin(\beta-\alpha)\, g^{\rm SM}_{\rm HVV}, \quad g_{\rm HVV} = \cos(\beta-\alpha)\, g^{\rm SM}_{\rm HVV}, \quad V = W^\pm, Z$$



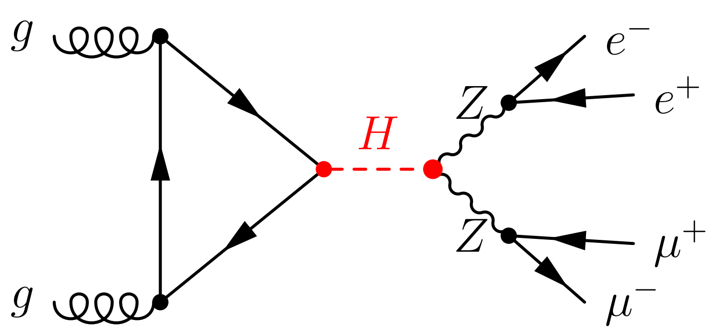
$\Rightarrow$ ILC: Potential sensitivity beyond the kinematic reach of Higgs pair production

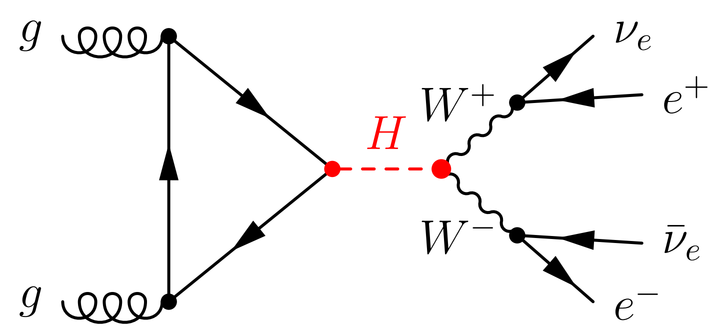
LHC: sensitivity to an additional heavy Higgs boson of a Two-Higgs-Doublet model (2HDM)

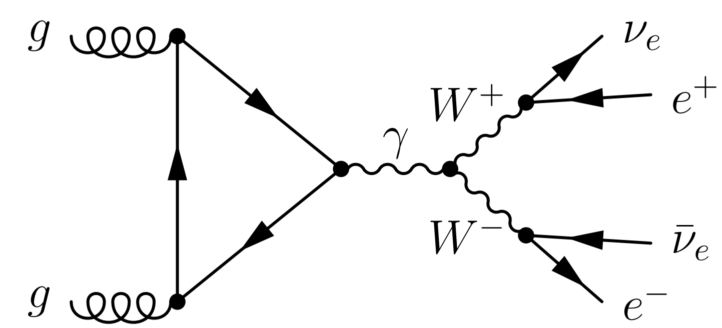
Analysis of gg → $e^+e^-\mu^+\mu^-$ and gg → $ll\nu\nu$ including signal, background and H-h, H-background interference:

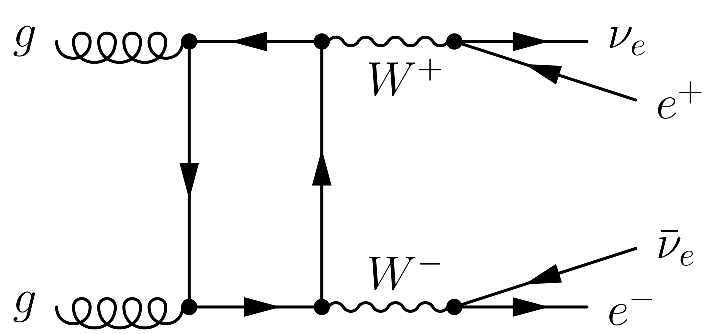
[N. Greiner, S. Liebler, G. W. ’15]

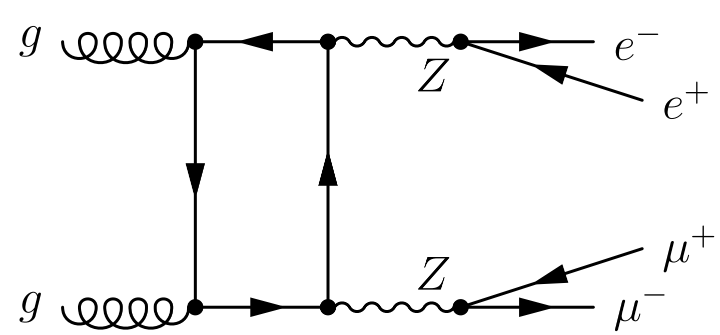
Double-resonant W and Z contributions:



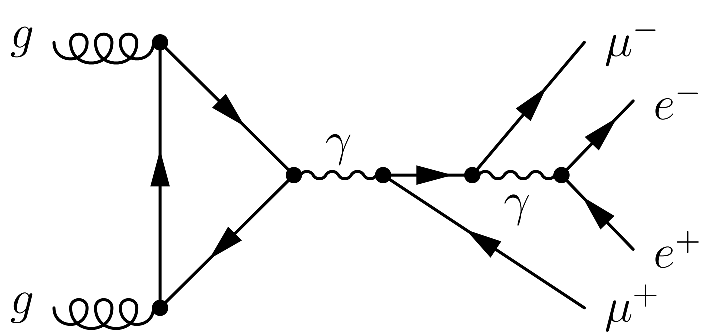


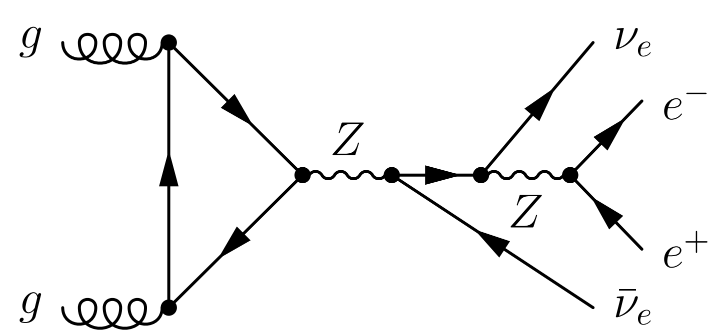


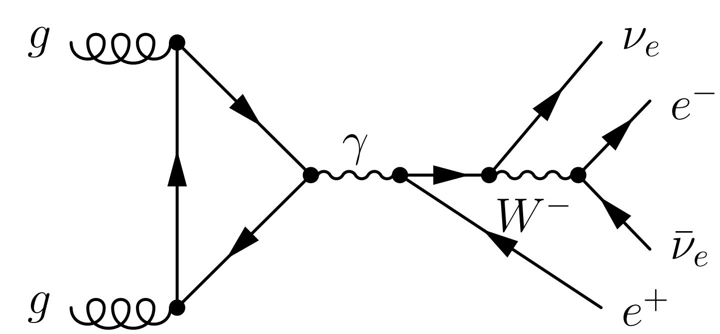




Single- and non-resonant W and Z contributions:



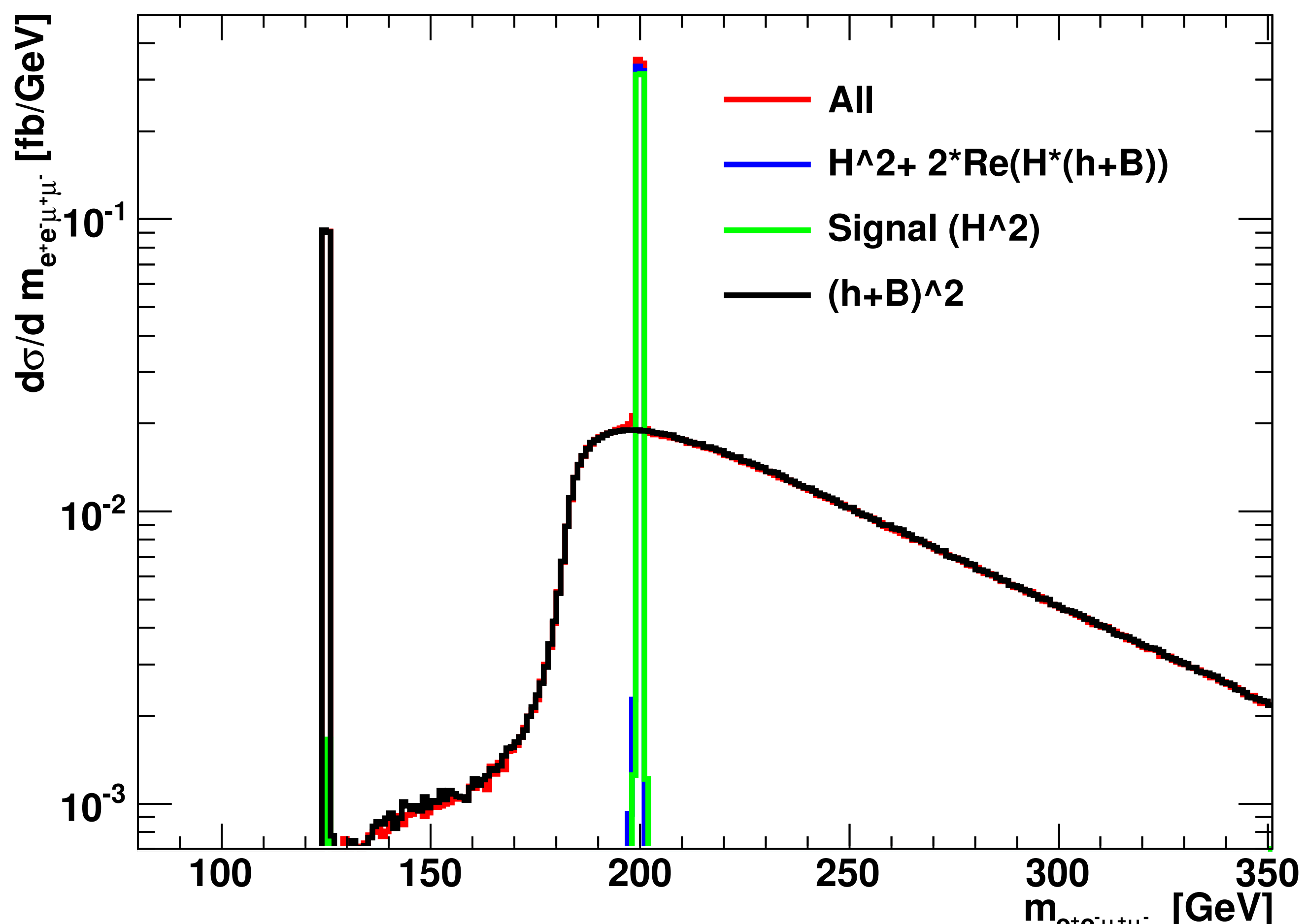




gg → $e^+e^-\mu^+\mu^-$, invariant mass distribution

[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

Small interference effects in the sample scenario chosen by ATLAS

Larger interference effects possible for higher values of tanβ

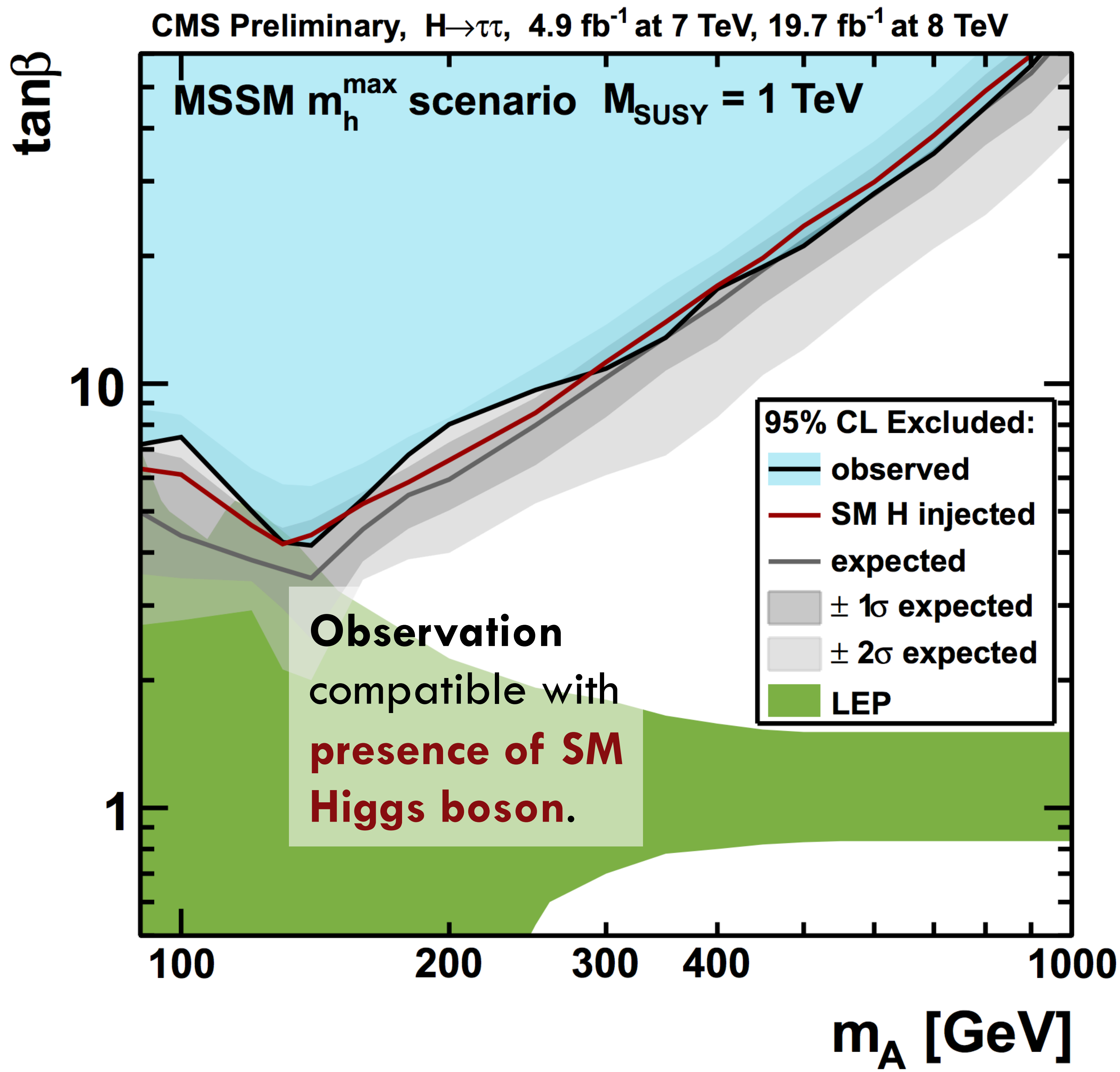
Interference effects can be important (enhanced sensitivity for heavy Higgs H!) for searches with more statistics

CMS results for h, H, A → ττ search

[CMS Collaboration ’14]

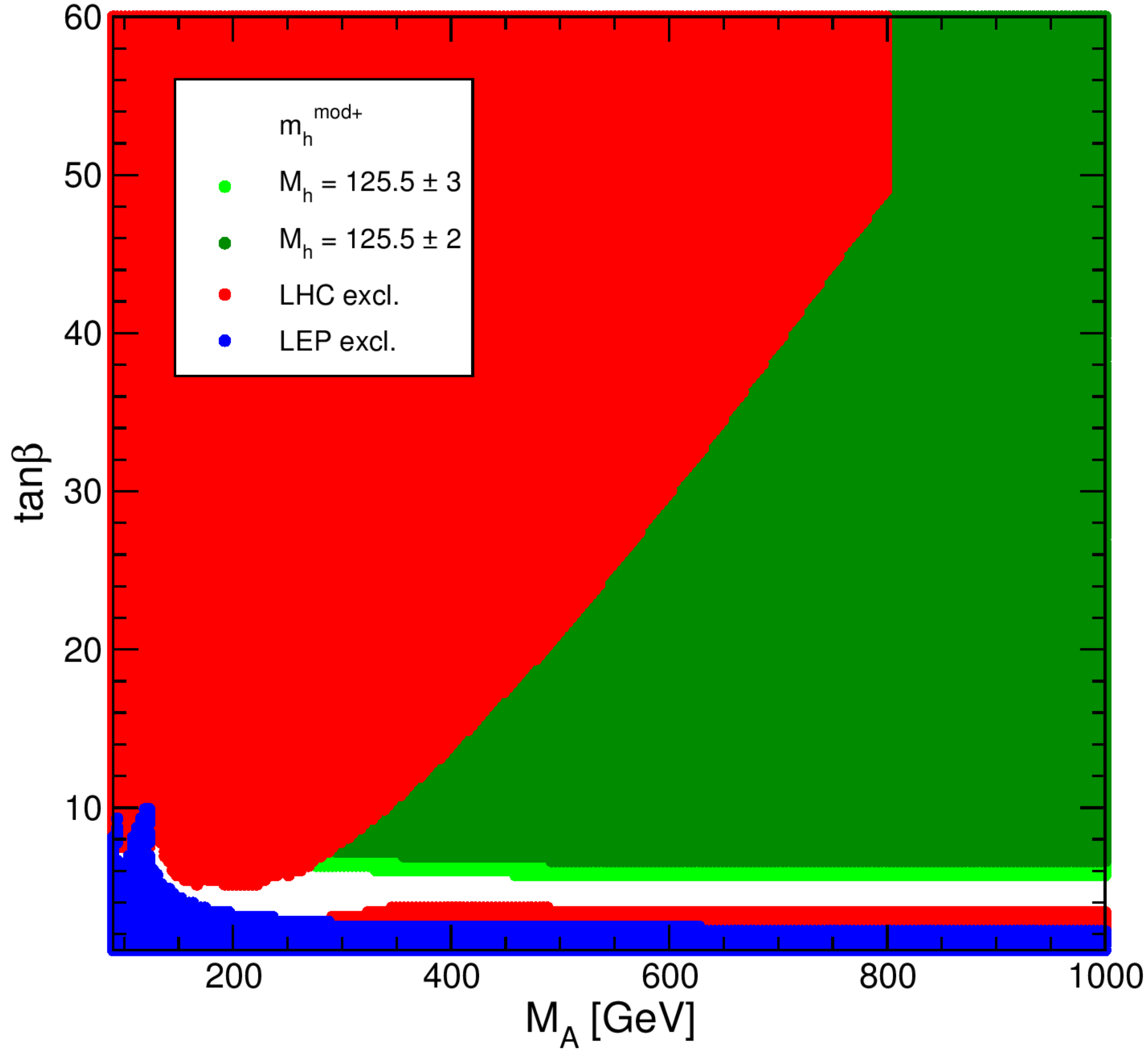
Analysis has started to become sensitive to the presence of the signal at 125 GeV

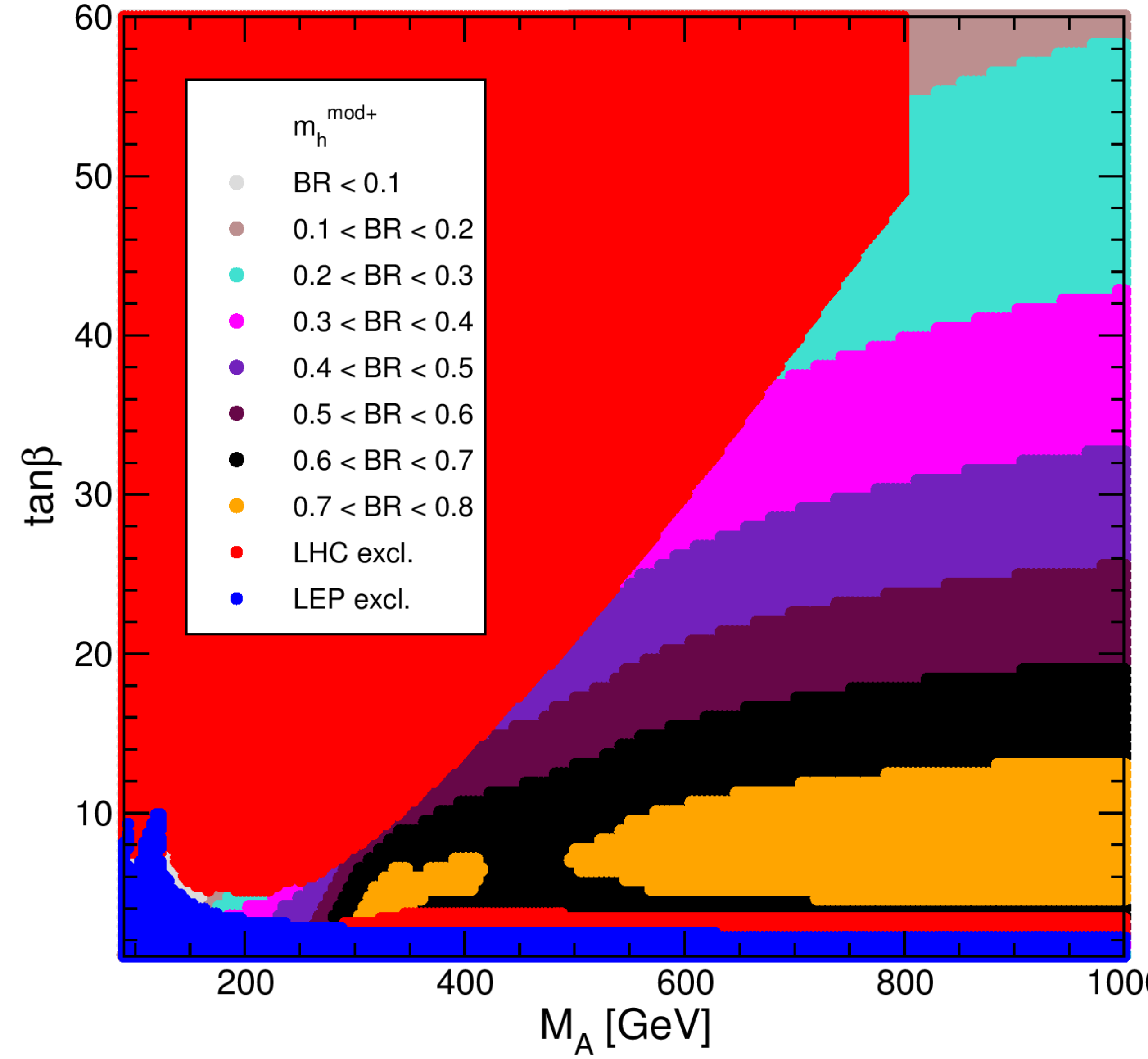
⇒ Searches for Higgs bosons of an extended Higgs sector need to test compatibility with the signal at 125 GeV (→ appropriate benchmark scenarios) and search for additional states



m_h^{mod} benchmark scenario

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





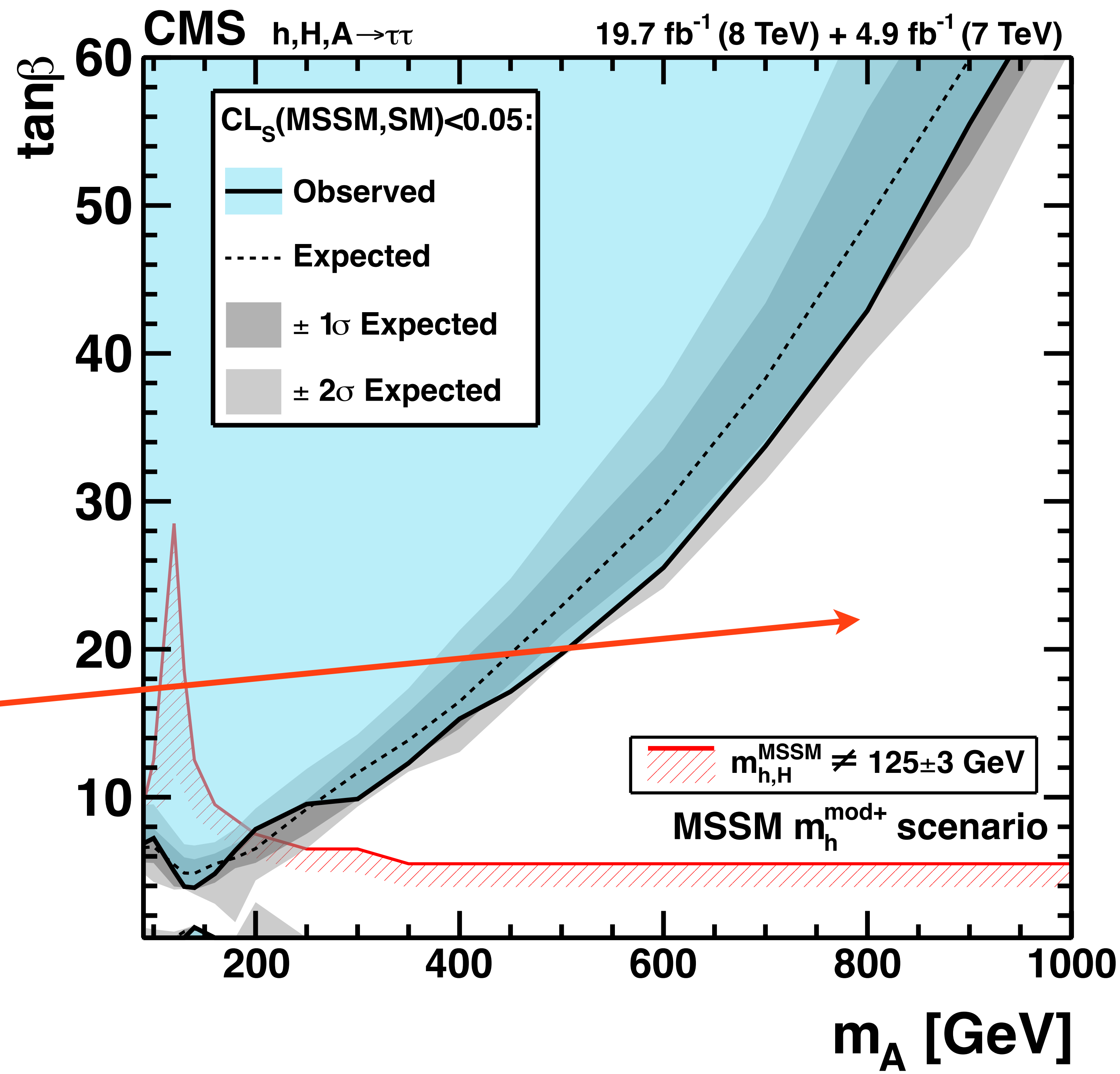
Small modification of well-known m_h^{max} scenario where the light Higgs h can be interpreted as the signal at 125 GeV over a wide range of the parameter space

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

CMS results 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

"Wedge region", where only h(125) can be detected; difficult to cover in $\tau\tau$ channel also with more luminosity

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

Higgs mixing: possible interference effects

Total cross section:

$$\sigma_{\rm tot} = \sigma(b\bar{b}H) + \sigma(b\bar{b}A) \text{ (incoherent sum)}$$

holds only in the $\mathcal{CP}$-conserving case

But: in reality we don’t know whether $\mathcal{CP}$ in the Higgs sector is conserved or not

In the general case:

Complex parameters $\Rightarrow$ loop corrections induce $\mathcal{CP}$-violation

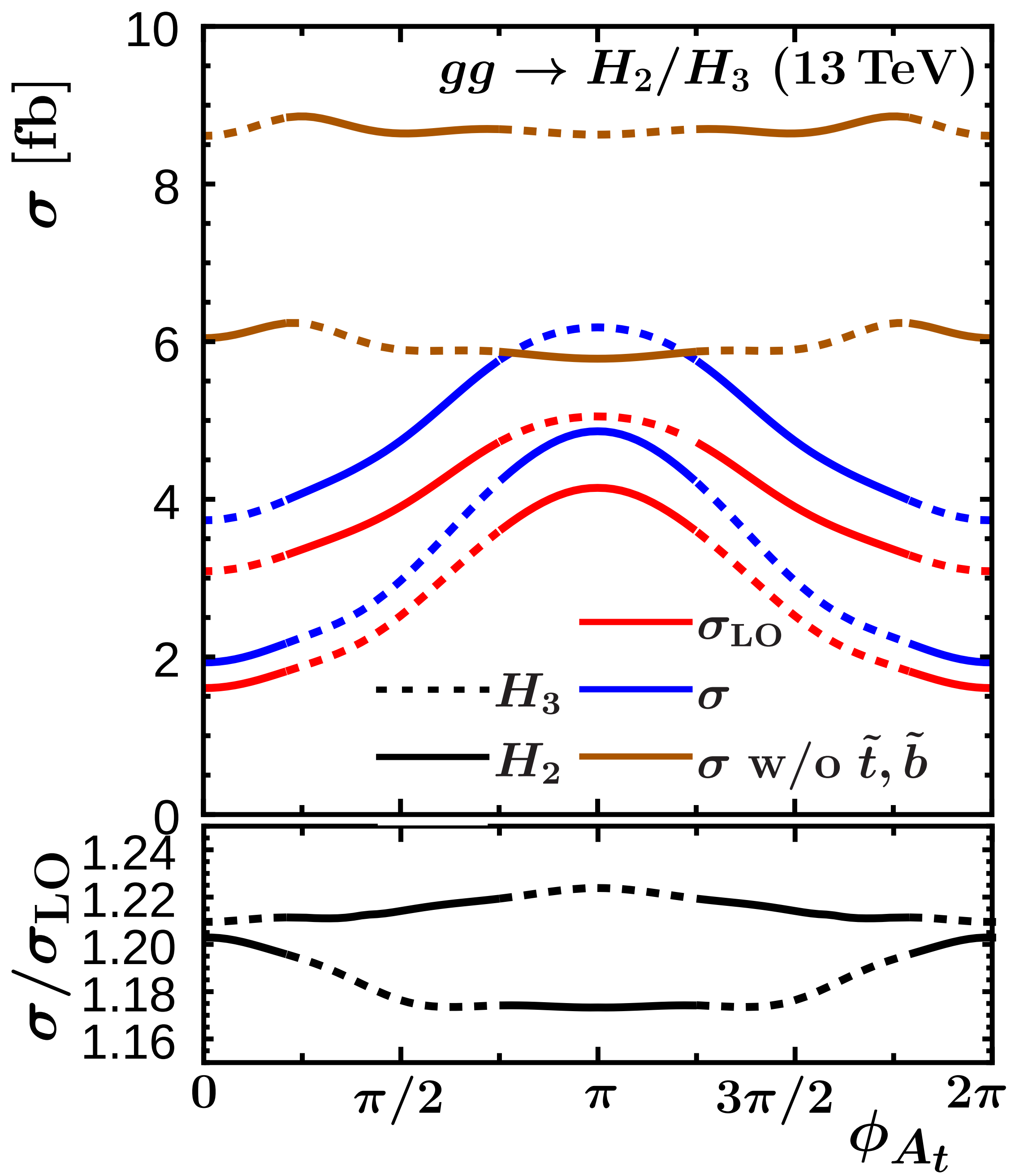
Two Higgs states, nearly mass degenerate, large mixing

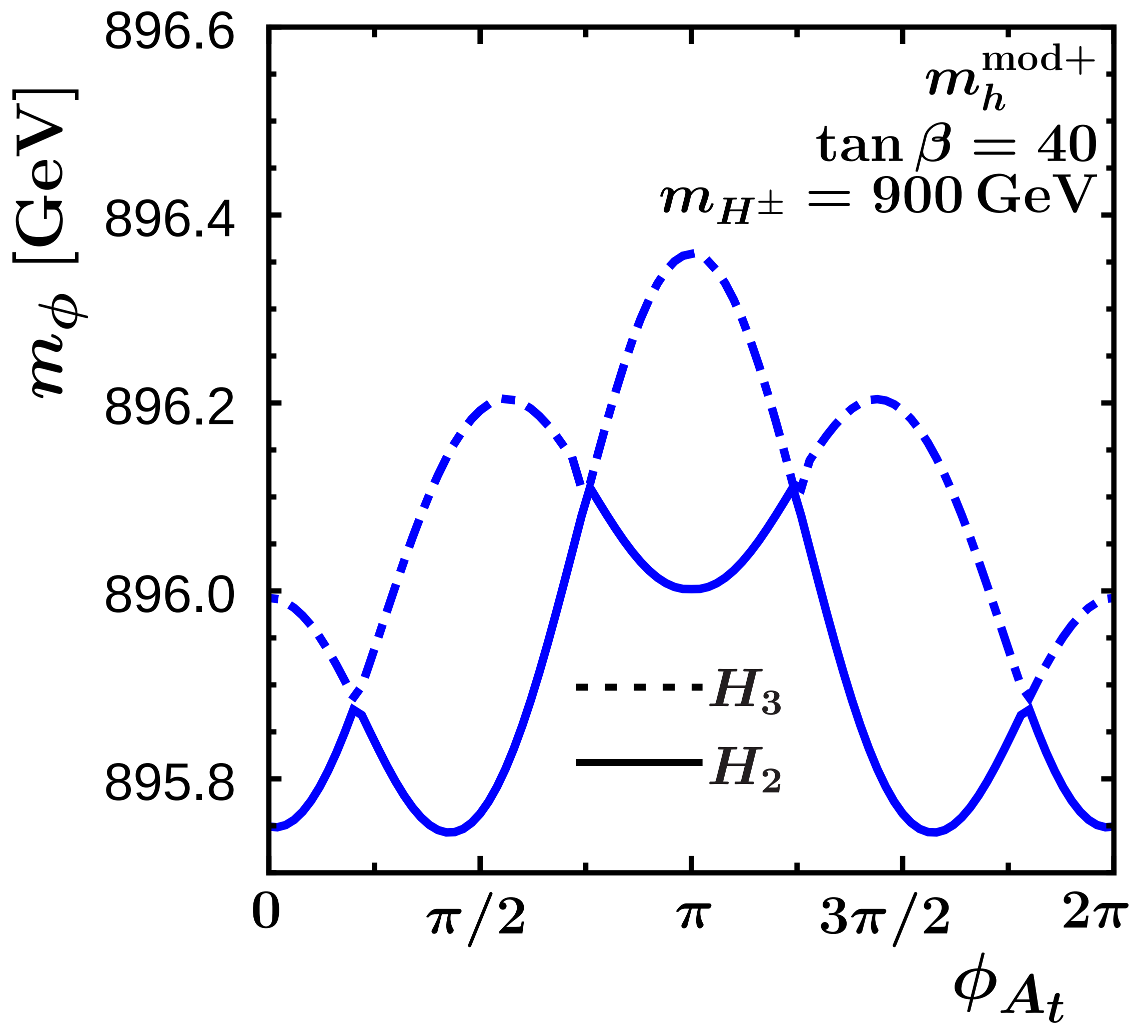
$\Rightarrow$ Large (destructive) interference possible

Higgs production via gluon fusion in the MSSM with CP-violation: extension of the *SusHi* code

[S. Liebler, S. Patel, G. W. '16]

gg → h_2h_3, dependence on phase ϕ_{At}:





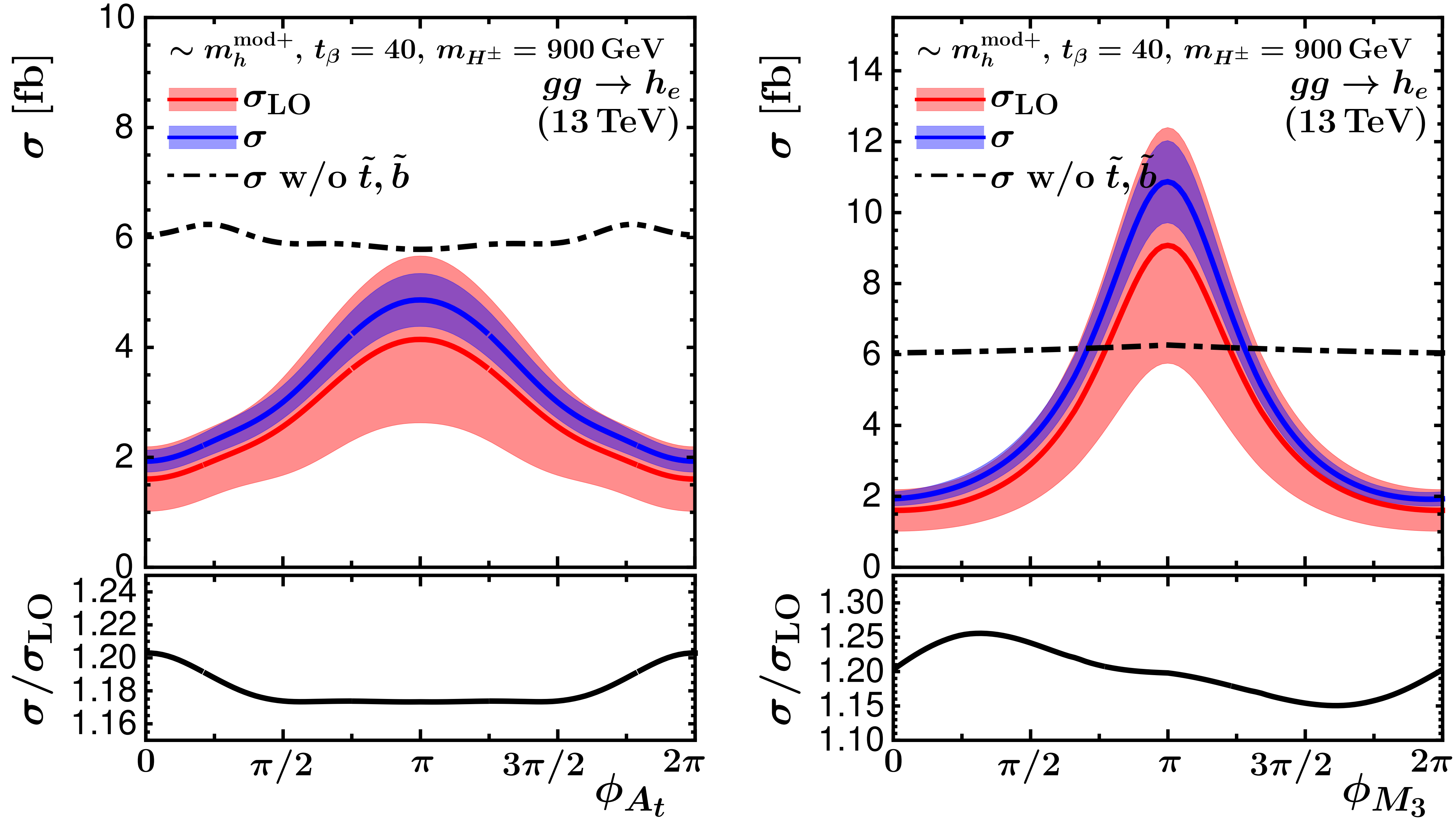
Only production process shown here

⇒ Full result for σ x BR needs to incorporate interference contribution

Higgs production via gluon fusion in the MSSM with CP-violation: extension of the *SusHi* code

[S. Liebler, S. Patel, G. W. '16]

Phase dependence for dominantly CP-even state "h_e":



⇒ Significant reduction of theoretical uncertainty w.r.t. LO result

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

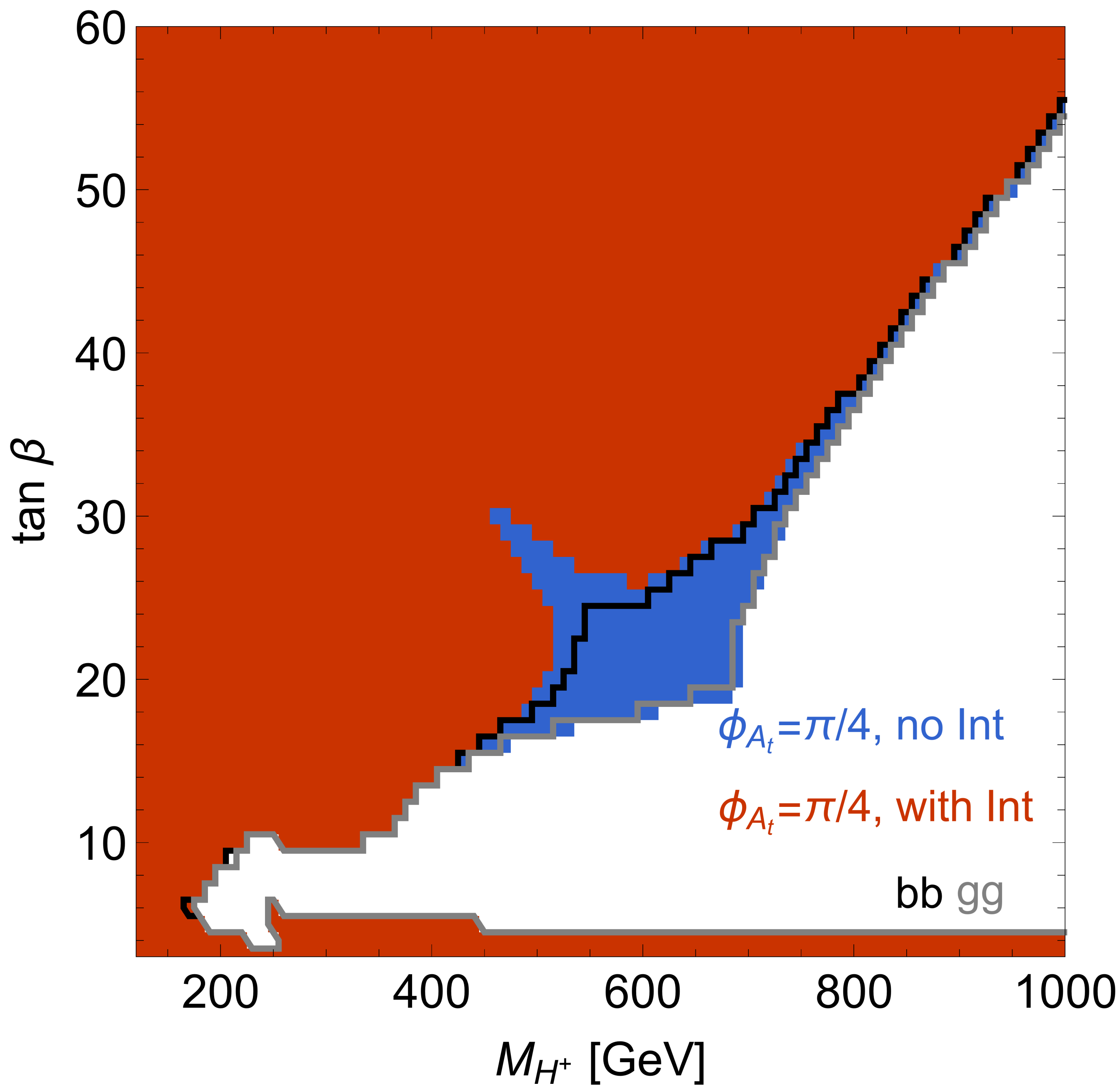
[E. Fuchs, G. W. '17]

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

CP-violating case, $\phi_{A_t} = \pi / 4$

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 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

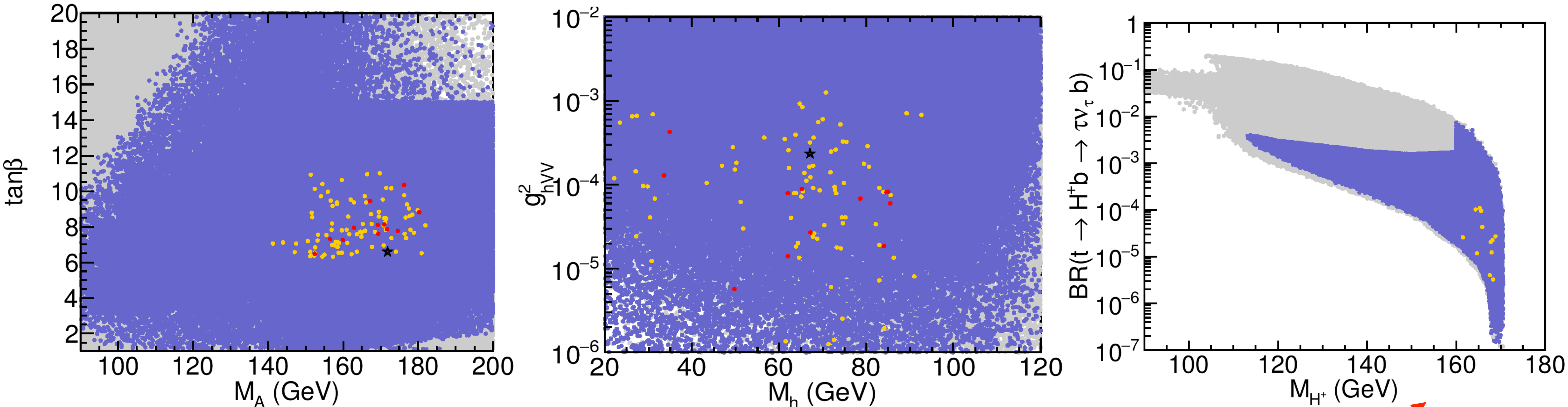
⇒ Lightest neutral Higgs with heavily suppressed couplings to gauge bosons, may have a mass below the LEP limit of 114.4 GeV for a SM-like Higgs (in agreement with LEP bounds)

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.

Global fit in the MSSM, h125 as heavy MSSM Higgs

[P. Bechtle, H. Haber, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune ’16]

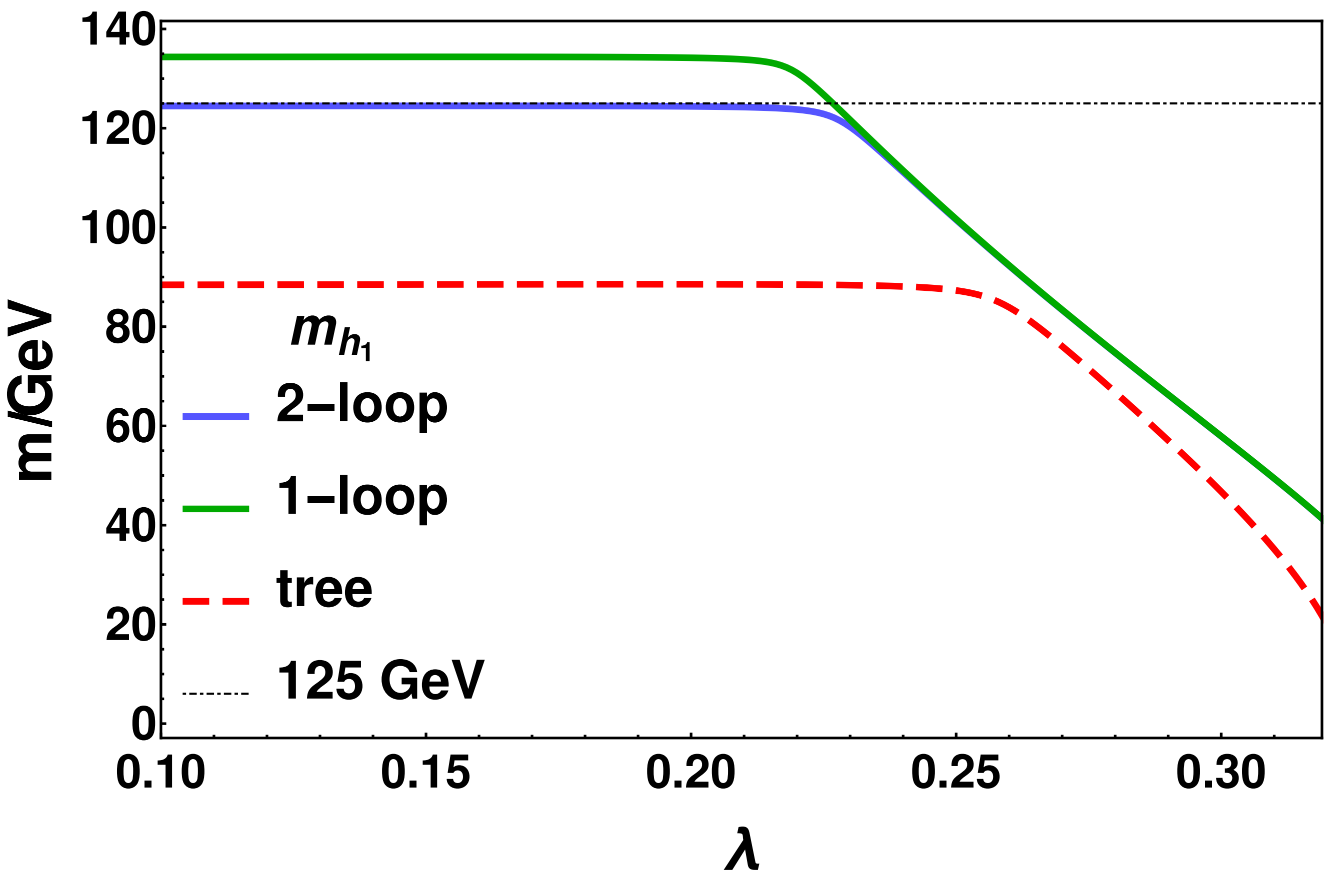


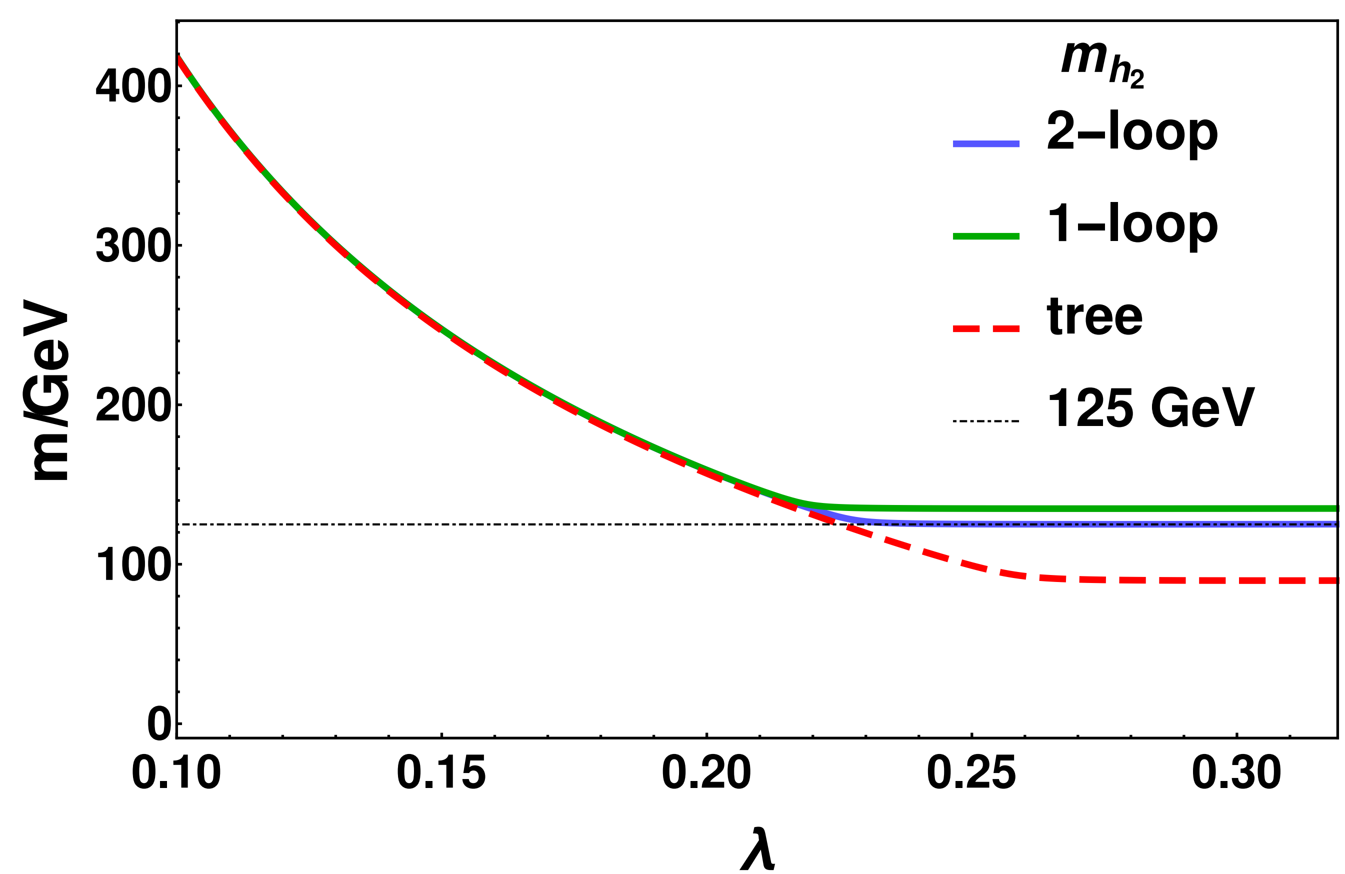
⇒Very light Higgs h is compatible with the experimental results
Tight constraints in the MSSM from charged Higgs searches

The NMSSM: two Higgs doublets and a singlet

Mass of the lightest and next-to-lightest Higgs in the NMSSM:
NMSSM version of *FeynHiggs*

[P. Drechsel, L. Galeta, S. Heinemeyer, G. W. '16]





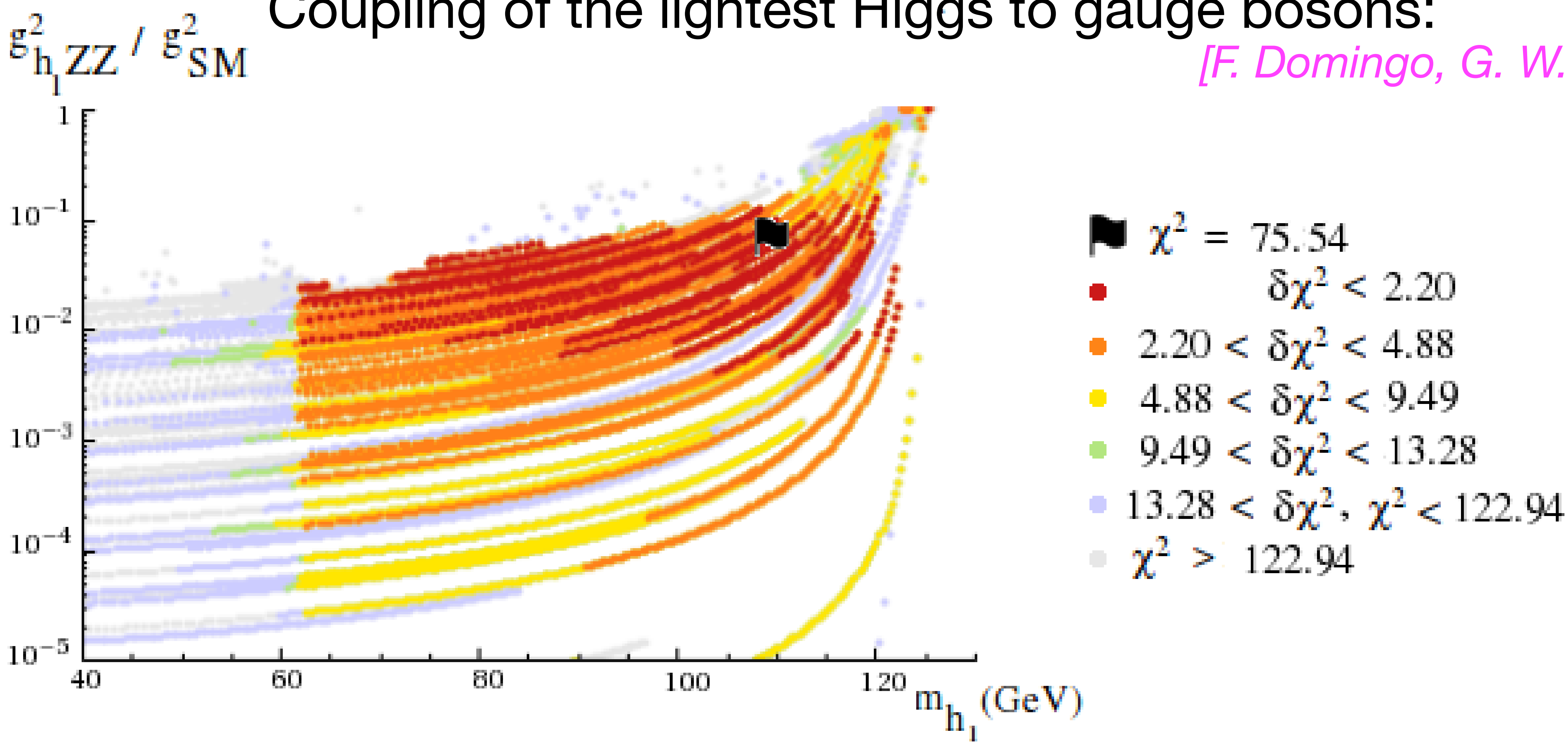
⇒ Variation of λ leads to cross-over behaviour between doublet-like and singlet-like state

⇒ The case where the signal at 125 GeV is not the lightest Higgs arises generically in the NMSSM

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

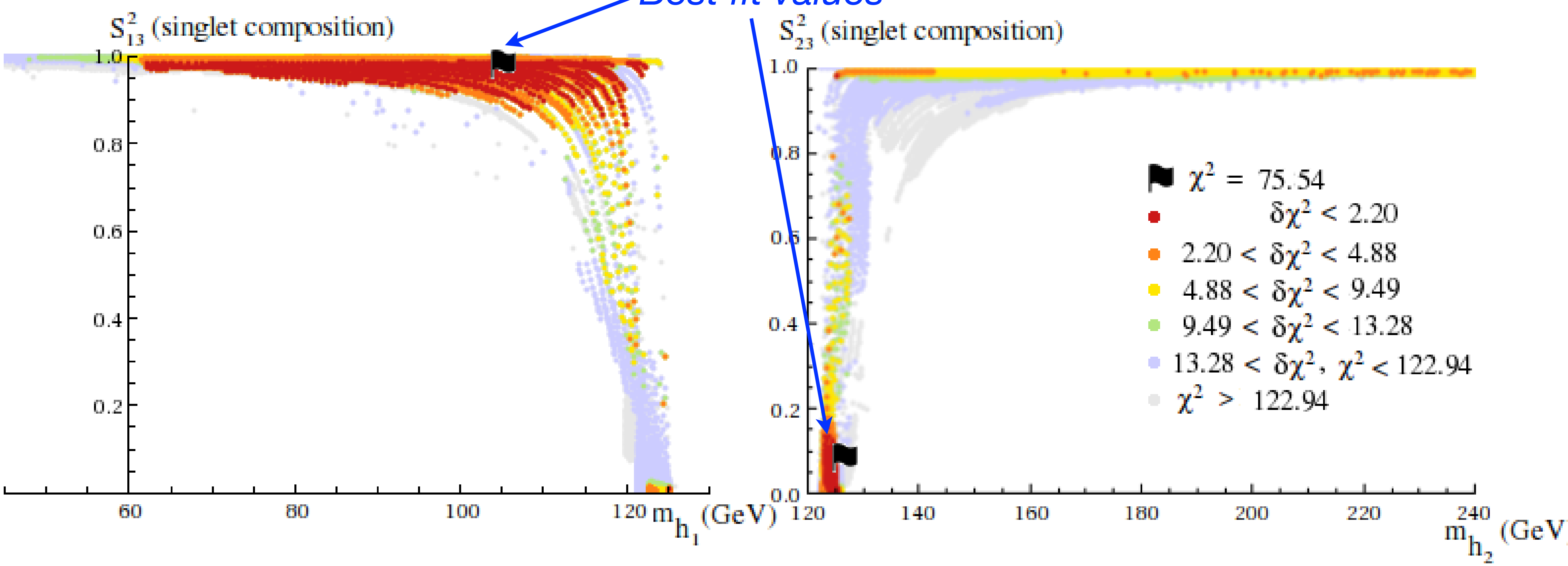
⇒ Strong suppression of the coupling to gauge bosons

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]

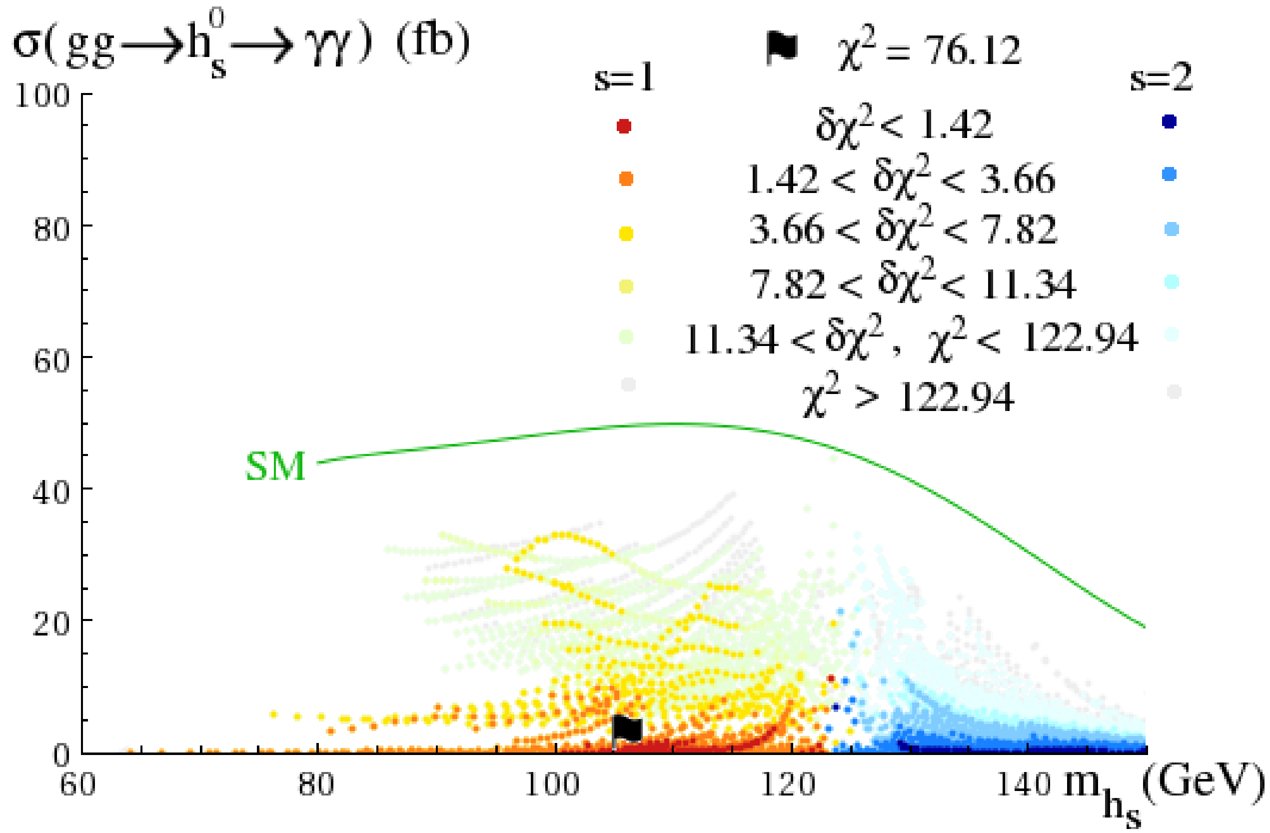
Best fit values

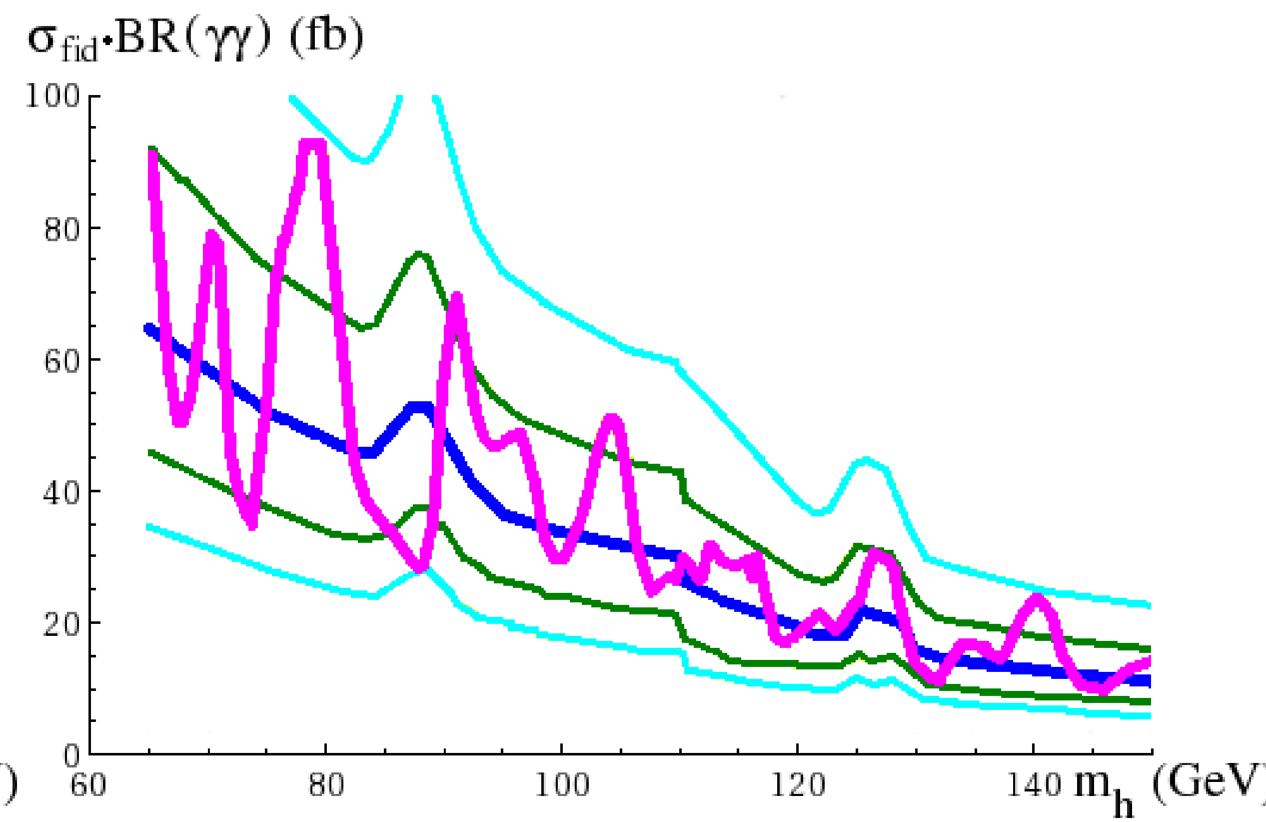


⇒ Additional light Higgs with suppressed couplings to gauge bosons, in agreement with all existing constraints

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]*

What next?

Studying the properties of the detected particle with high precision will help us to better understand the mechanism of electroweak symmetry breaking

Higgs self-coupling: the ``holy grail” of Higgs physics, provides access to the Higgs potential and the structure of the vacuum
HHH: very difficult even at HL-LHC, ILC, …
HHHH: seems out of reach in foreseeable future

Higgs physics as a window to new physics
Example: Higgs → dark matter decays

Higgs decays to dark matter particles

- If dark matter consists of one or more particles with a mass below about 63 GeV, then the decay of the state at 125 GeV into a pair of dark matter particles is kinematically open

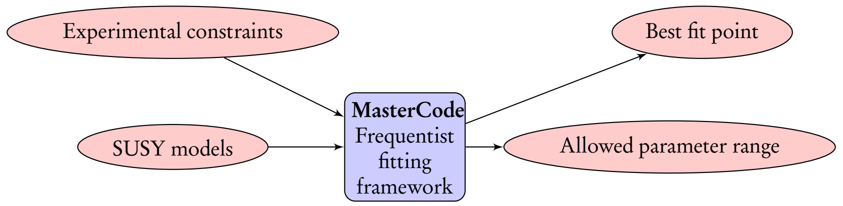
- The detection of an invisible decay mode of the state at 125 GeV could be a manifestation of BSM physics
  - Direct search for $H \to$ invisible
  - Suppression of all other branching ratios

$\Rightarrow$ Sizeable deviations possible even if the couplings to gauge bosons and SM fermions are very close to the SM case

- Note: invisible decays $\neq$ undetectable decays (decay products that are buried under the QCD background, e.g. non-b jets, gg, ...)

Where are the additional Higgses and other BSM states?

Example: SUSY global fit for SUSY GUT models or pMSSM10



Observables / constraints:

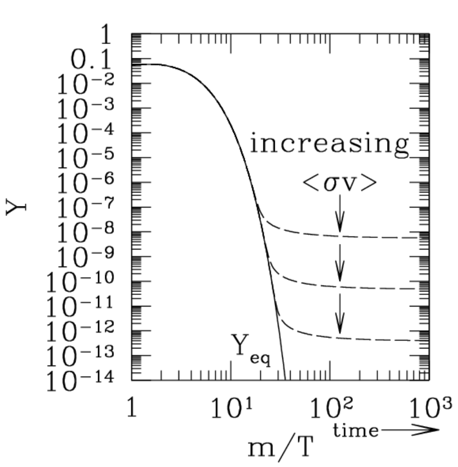
Higgs sector: signal strengths of observed signal + search limits

Indirect measurements

- $(g-2)_\mu$. 3.4σ discrepancy may be explained with $\mathcal{O}(100)$ GeV smuons.
- M_W, M_Z, M_h and EWPO.
- Flavor observables ($B_s \to \mu\mu$, $b \to s\gamma$).

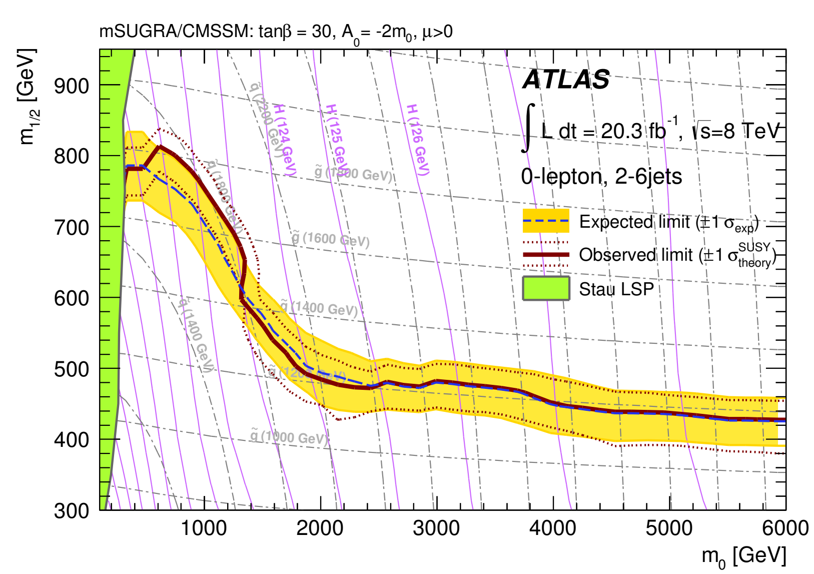
Dark matter

- Relic density and direct detection.



Collider – GUT models

- Limits are independent of $A_0, \tan\beta, m^2_{H_u}$ and $m^2_{H_d}$.
- Due to unification, limits on squarks and gluinos are relevant also for sleptons and electroweakinos.



SUSY search limits for pMSSM10

Three classes of constraints

Colored sparticle production

We have combined the following CMS searches:

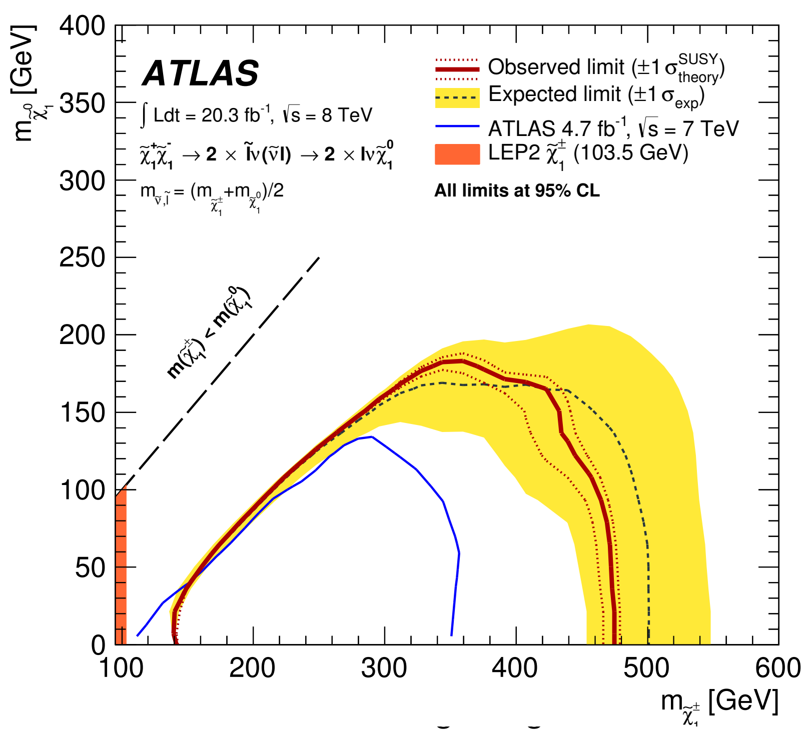
- 0-lepton M_{T2}
- 1-lepton M_{T2}^{W}
- 2-lepton OS/SS
- ≥ 3 leptons.

Compressed stop scenarios

This scenario is separately in a way similar to the EWK SMS. The stop cross-section is set to zero.

Electroweakinos production

- Simplified ModelS (SMS) approach. Limited mass hierarchies.
- Slepton production.
- $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$ via sleptons.
- $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$ via WZ.

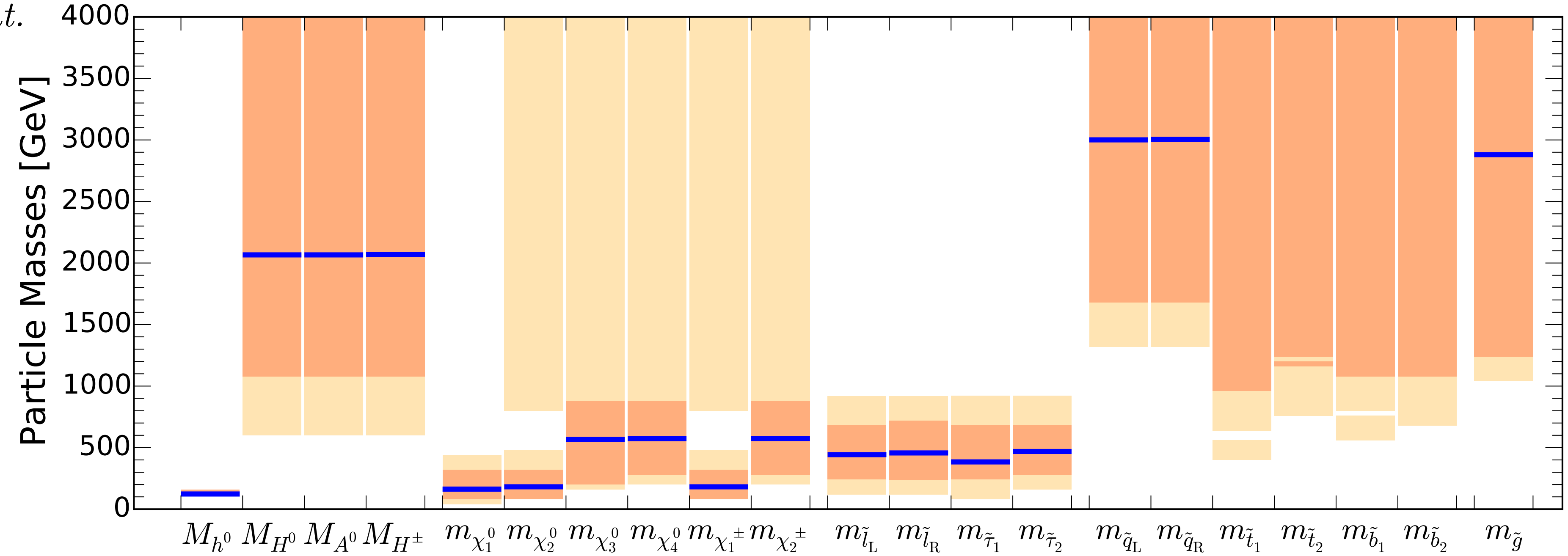


Prospects for SUSY searches after Run 1 of the LHC

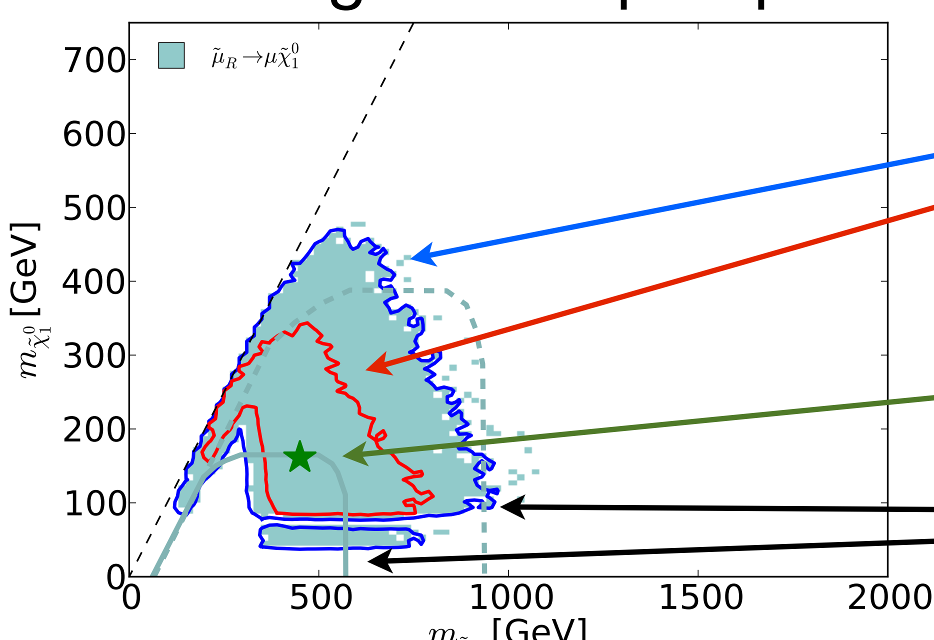
MasterCode: Global fit in the MSSM with 10 parameters

[K. de Vries et al '15]

Summary of mass ranges predicted in the pMSSM10. The light (darker) peach shaded bars indicate the 95% (68%) CL intervals, whereas the blue horizontal lines mark the values of the masses at the best-fit point.



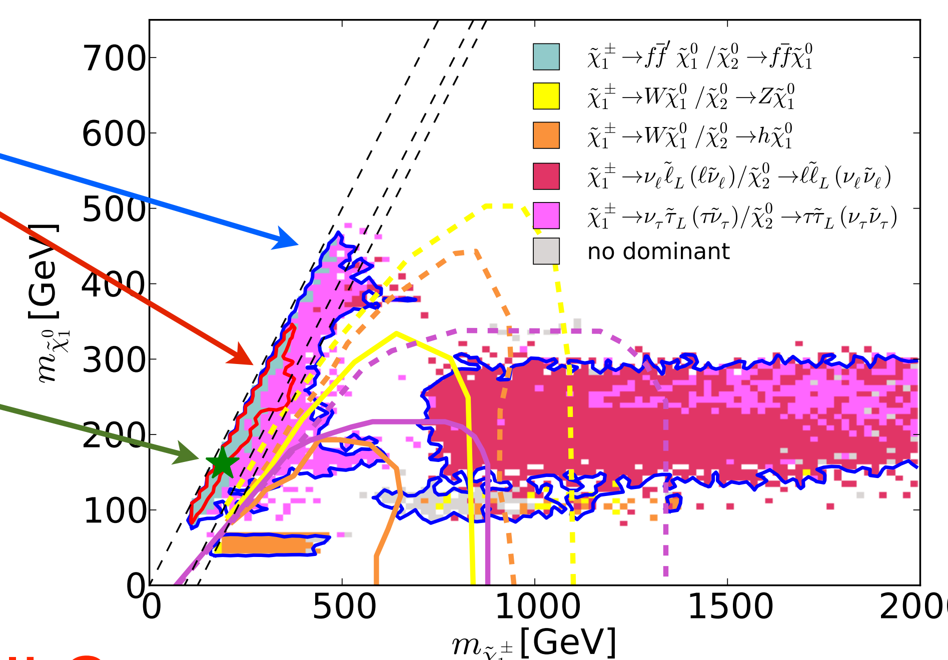
Best fit region and prospects at the LHC with 300 / 3000 fb^{-1}:



68% / 95%
C.L. contours

Best fit points

300 / 3000 fb^{-1}



⇒ Good prospects for Run 2 of the LHC and the ILC

Conclusions

The discovery of a Higgs boson at the LHC has provided us with a window to the mechanism of electroweak symmetry breaking and the structure of the vacuum

⇒ We will learn a lot from the further exploration of the properties of the new particle!

The discovered particle looks SM-like so far, but it could be part of an extended Higgs sector or even a composite state

⇒ The underlying physics could be very different without spoiling the present compatibility with the experimental data

Test of BSM models requires precise prediction for the mass of the SM-like Higgs to determine available parameter space

If some of the BSM particles are heavy:

⇒ Combination of fixed-order and EFT approach

Conclusions

Higgs phenomenology in extended Higgs sectors:
Interference effects can be important for phenomenology of heavy Higgs bosons
Additional Higgs bosons need not be heavy, can also be below 125 GeV!
Case of a light non-SM like Higgs happens generically in singlet extensions

Global SUSY fits:
Preference for scenarios where at least a part of the colour-neutral spectrum is relatively light

⇒ Rich physics programme at LHC, HL-LHC and future e^+e^- collider(s)

Backup

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 $\Gamma/\Gamma_{\mathrm{SM}} < 5.4$ at 95% C.L., where 8.0 was expected, ATLAS: $\Gamma/\Gamma_{\mathrm{SM}} < 5.7$ 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

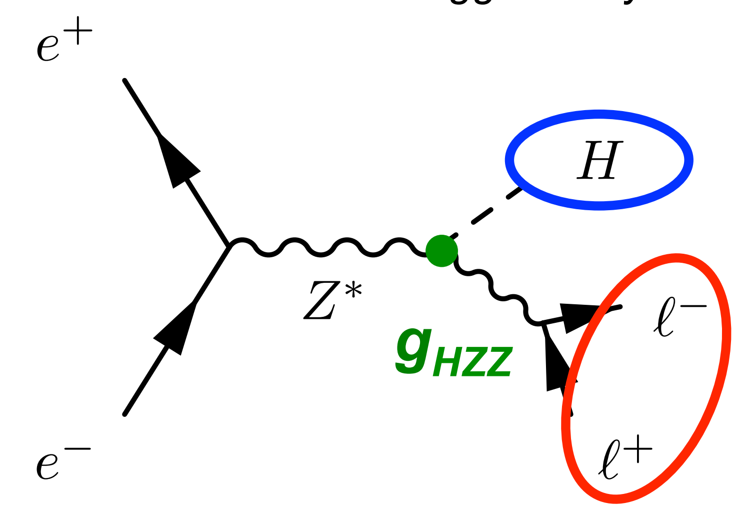
Destructive interference between Higgs- and gauge-boson contributions (unitarity cancellations) ⇒ difficult to reach $\Gamma/\Gamma_{\mathrm{SM}} \approx 1$ even for high statistics

Standard method at a Linear Collider for the model-independent determination of the total width

Linear Collider (LC): absolute measurements of *ZH* cross section and Higgs branching ratios possible

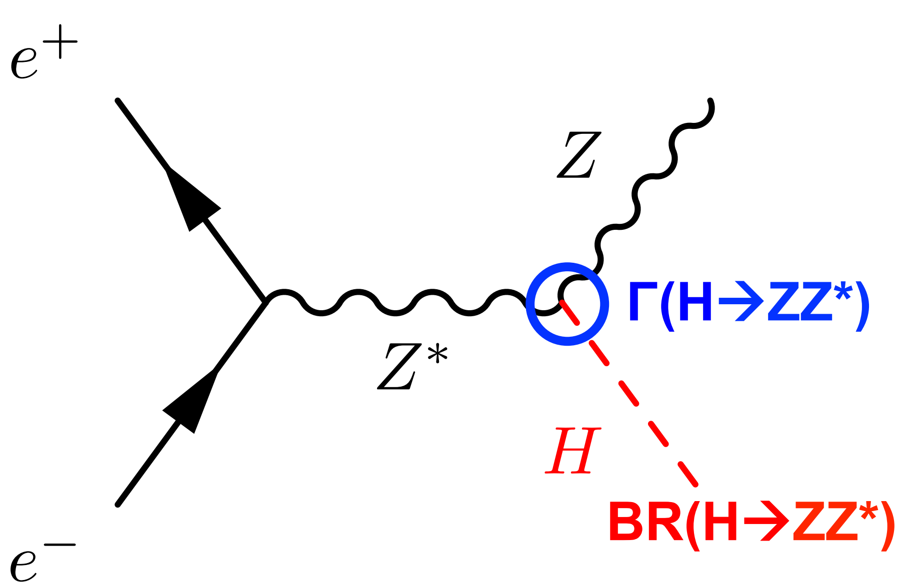
$\Rightarrow$ Model-independent determination of the total Higgs width

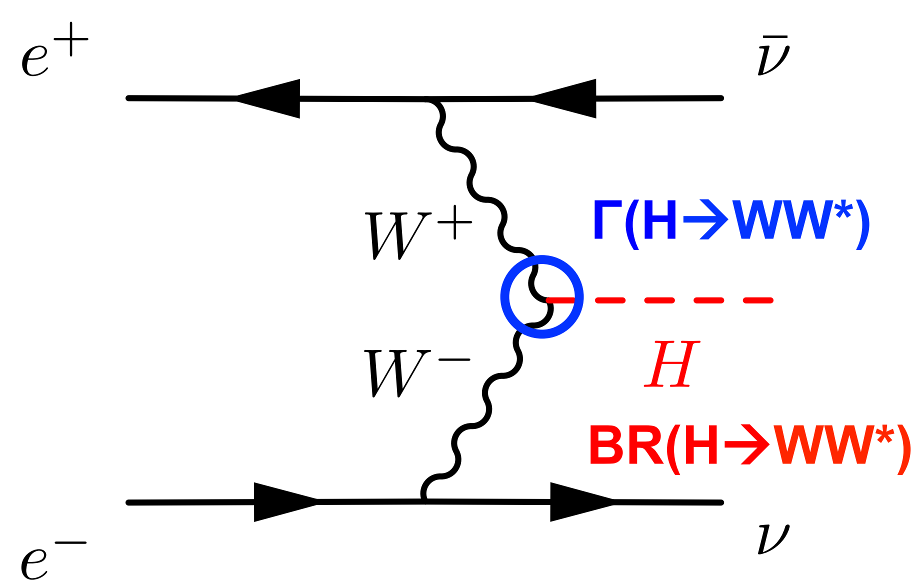
Reconstruct $Z \to l^+ l^-$
independent of Higgs decay
sensitive to invisible Higgs decays



$$m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

$$\Gamma_H = \Gamma(H \to XX)/\mathrm{BR}(H \to XX)$$





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

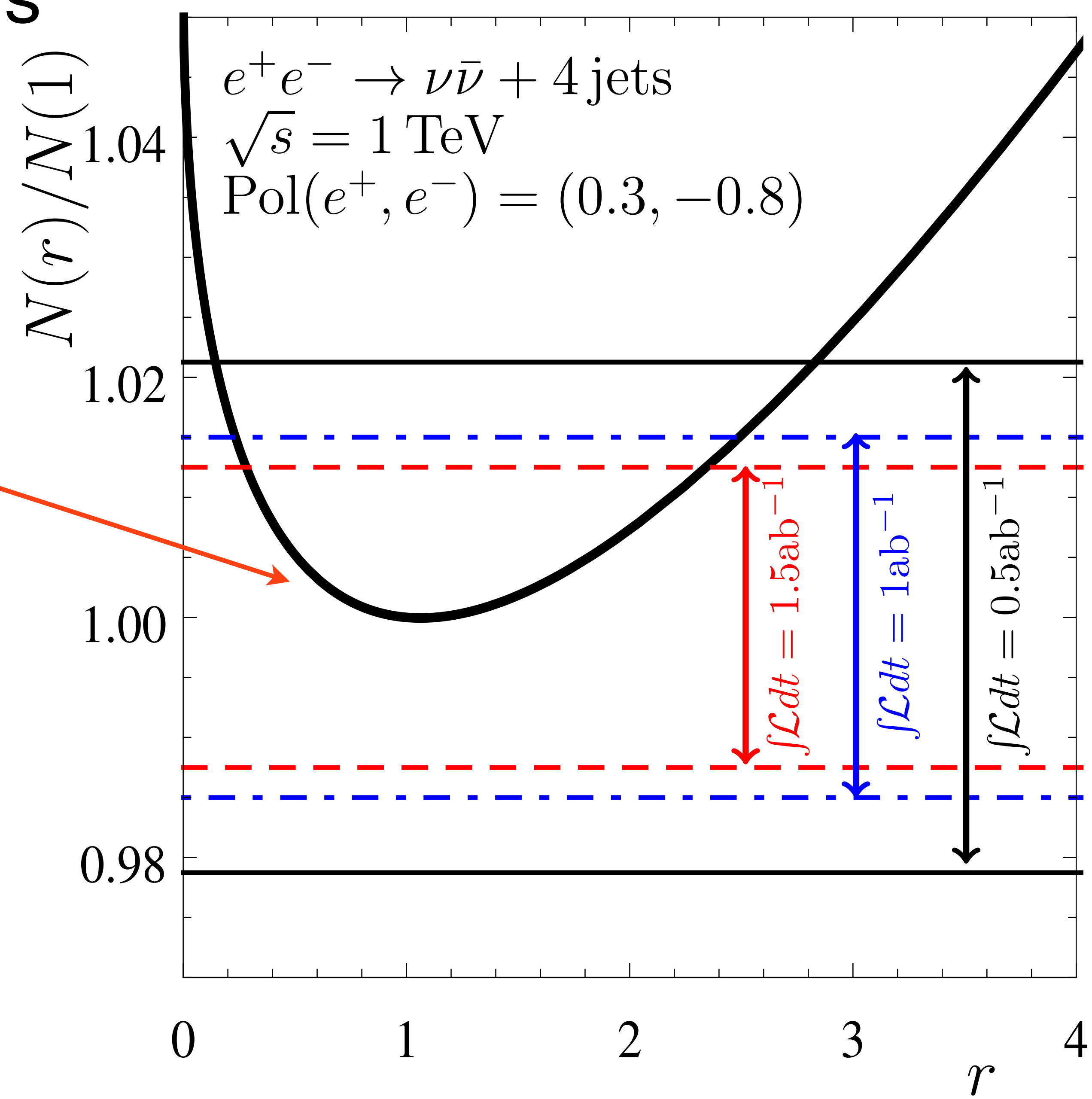
[S. Liebler, G. Moortgat-Pick, G. Weiglein '15]

Same theoretical assumptions as in LHC analyses

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

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

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



⇒ Limited sensitivity even with high integrated luminosity

Qualitative behaviour at the LHC is the same!

CP properties

$\mathcal{CP}$ properties: more difficult than spin, observed state can be any admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd components

Observables mainly used for investigaton of $\mathcal{CP}$-properties ($H \to ZZ^*, WW^*$ and H production in weak boson fusion) involve HVV coupling

General structure of HVV coupling (from Lorentz invariance):

$$a_1(q_1, q_2)g^{\mu\nu} + a_2(q_1, q_2) \left[(q_1 q_2)\, g^{\mu\nu} - q_1^\mu q_2^\nu\right] + a_3(q_1, q_2)\epsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$$

SM, pure $\mathcal{CP}$-even state: $a_1 = 1, a_2 = 0, a_3 = 0$,

Pure $\mathcal{CP}$-odd state: $a_1 = 0, a_2 = 0, a_3 = 1$

However: in many models (example: SUSY, 2HDM, ...) a_3 is loop-induced and heavily suppressed

CP properties

⇒ Observables involving the *HVV* coupling provide only limited sensitivity to effects of a CP-odd component, even a rather large CP-admixture would not lead to detectable effects in the angular distributions of H → ZZ^* → 4 l, etc. because of the smallness of a_3

Hypothesis of a pure CP-odd state is experimentally disfavoured

However, there are only very weak bounds so far on an admixture of CP-even and CP-odd components

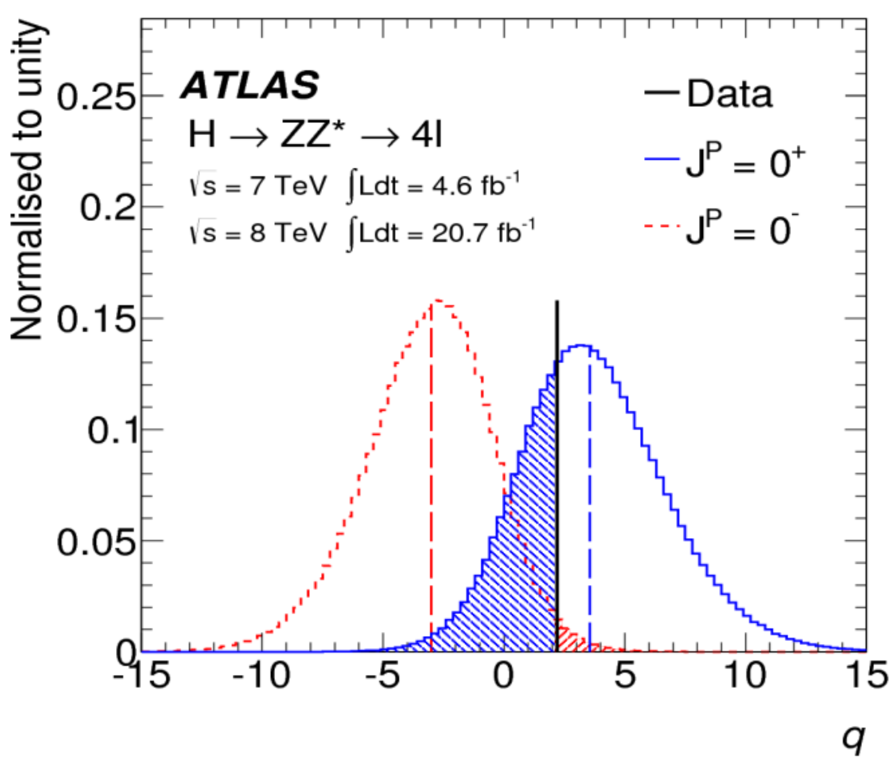
Channels involving only Higgs couplings to fermions could provide much higher sensitivity

Test of spin and CP hypotheses

[ATLAS Collaboration '13]

The SM 0^+ has been tested against different J^P hypotheses using the three ATLAS discovery channels

0^+ against 0^-



Channel	0^- assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 0^-)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 0^-)$	$\mathrm{CL_s}(J^P = 0^-)$
$H \to ZZ^*$	$1.5 \cdot 10^{-3}$	$3.7 \cdot 10^{-3}$	0.31	0.015	0.022

<u>H→ZZ</u> analysis excludes the 0^- hypothesis at 97.8% CLs

0^+ against $1^{+/-}$

Combined <u>H→ZZ and H→WW</u> analysis excludes those hypotheses up to 99.7%

Channel	1^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^+)$	$\mathrm{CL_s}(J^P = 1^+)$
$H \to ZZ^*$	$4.6 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	0.55	$1.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$
$H \to WW^*$	0.11	0.08	0.70	0.02	0.08
Combination	$2.7 \cdot 10^{-3}$	$4.7 \cdot 10^{-4}$	0.62	$1.2 \cdot 10^{-4}$	$\boxed{3.0 \cdot 10^{-4}}$

➢ **1^+ hypothesis has been excluded at 99.97%**

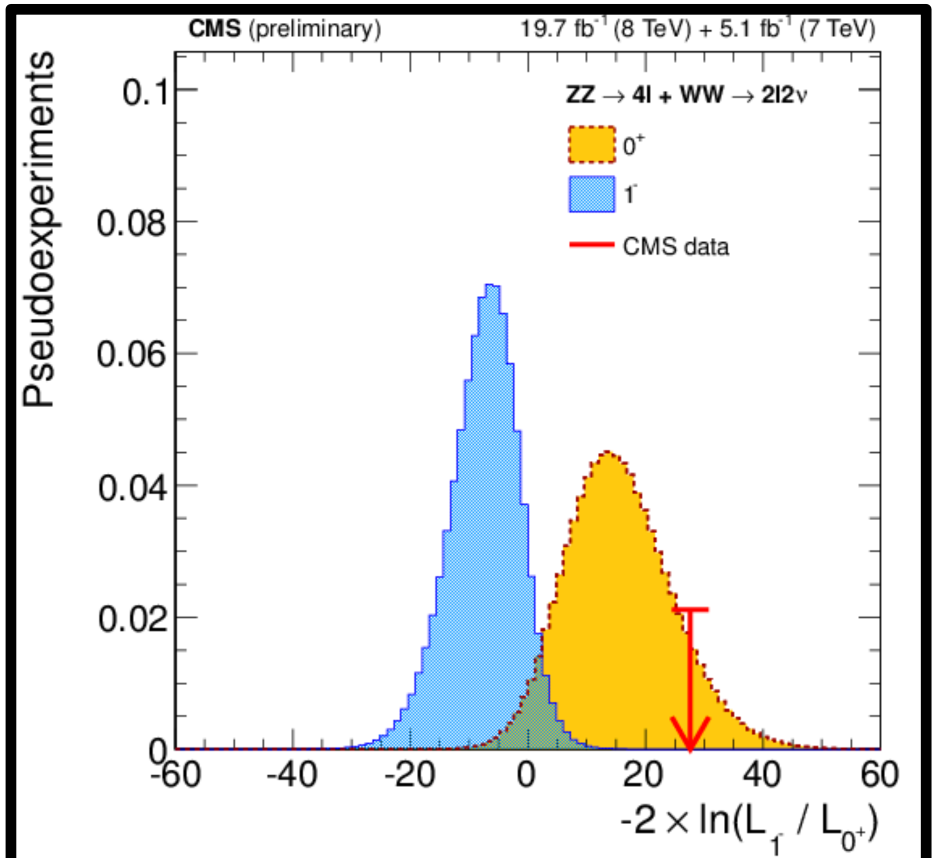
Channel	1^- assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^-)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^-)$	$\mathrm{CL_s}(J^P = 1^-)$
$H \to ZZ^*$	$0.9 \cdot 10^{-3}$	$3.8 \cdot 10^{-3}$	0.15	0.051	0.060
$H \to WW^*$	0.06	0.02	0.66	0.006	0.017
Combination	$1.4 \cdot 10^{-3}$	$3.6 \cdot 10^{-4}$	0.33	$1.8 \cdot 10^{-3}$	$\boxed{2.7 \cdot 10^{-3}}$

➢ **1^- hypothesis has been excluded at 99.7%**

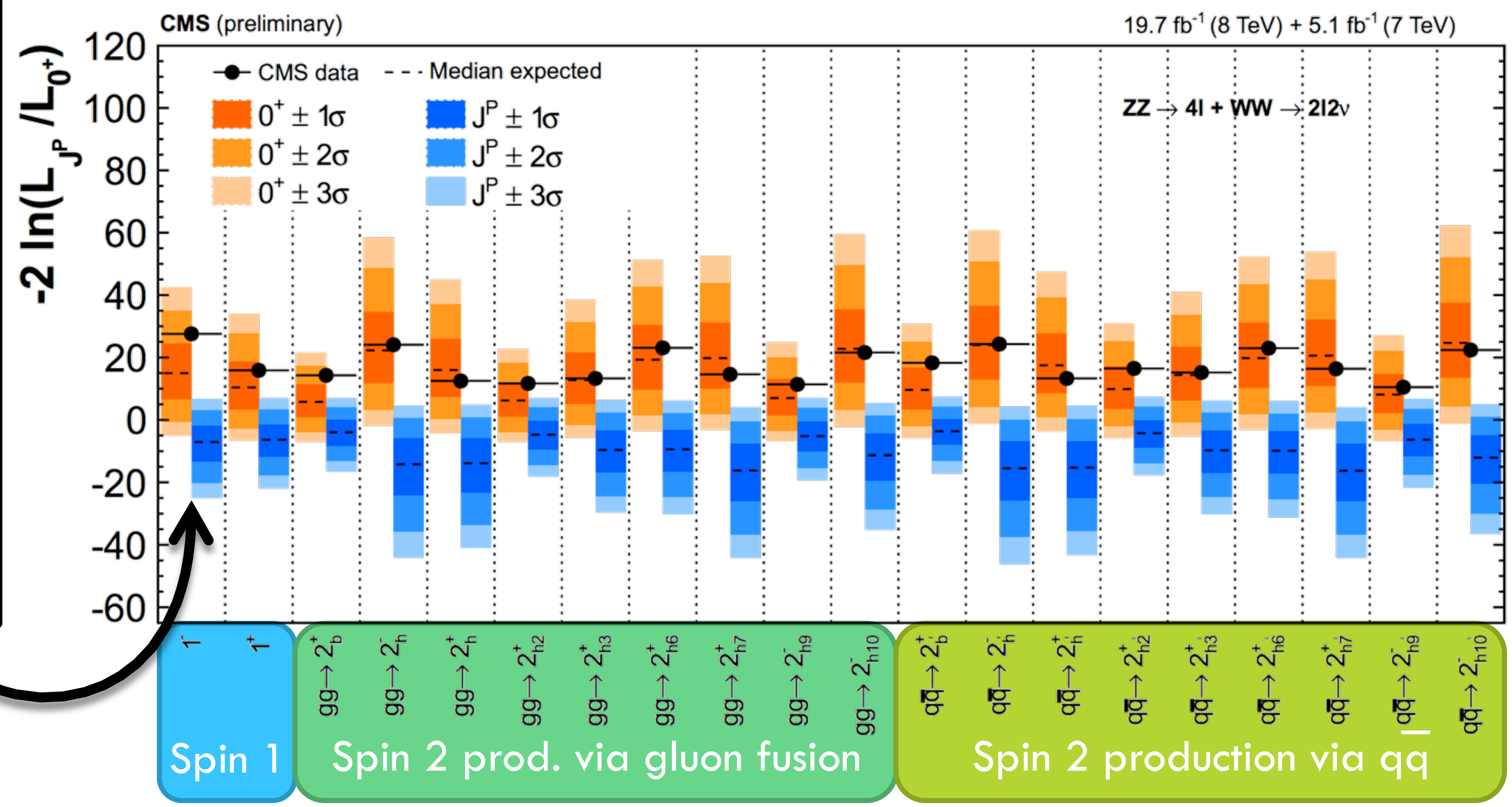
Test of spin and CP hypotheses

[CMS Collaboration ’14]

- Combination of H→WW→2ℓ2ν and H→ZZ→4ℓ.
- All tested hypotheses excluded at more than 99.9% CL_S.



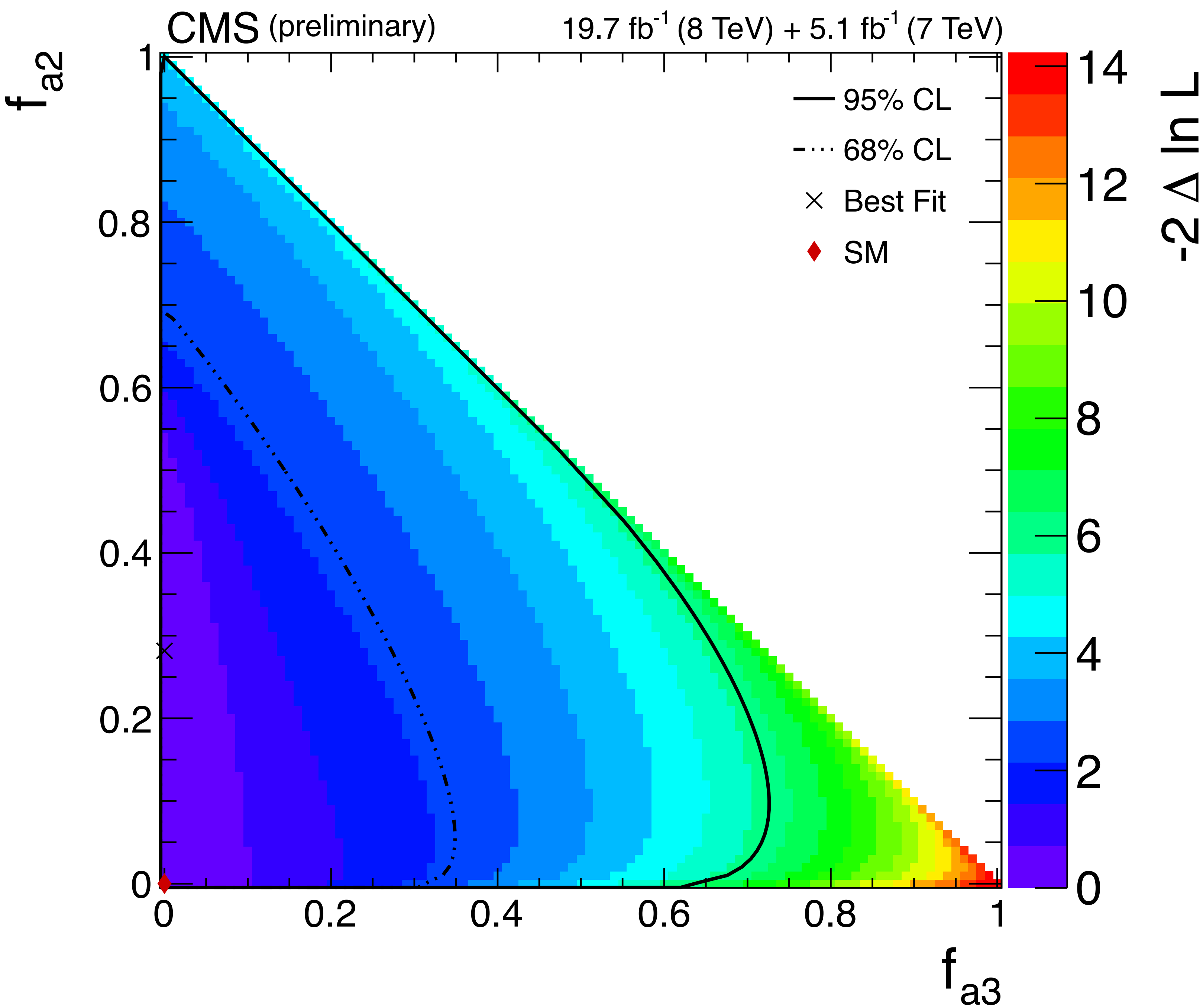
Hypothesis test for 0⁺ vs. 1⁻



Experimental analyses beyond the hypotheses of pure CP-even / CP-odd states

[CMS Collaboration '14]

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3}$$



Experimental analyses beyond the hypotheses of pure CP-even / CP-odd states

Loop suppression of a_3 in many BSM models

⇒ Even a rather large CP-admixture would result in only a very small effect in f_{a3}!

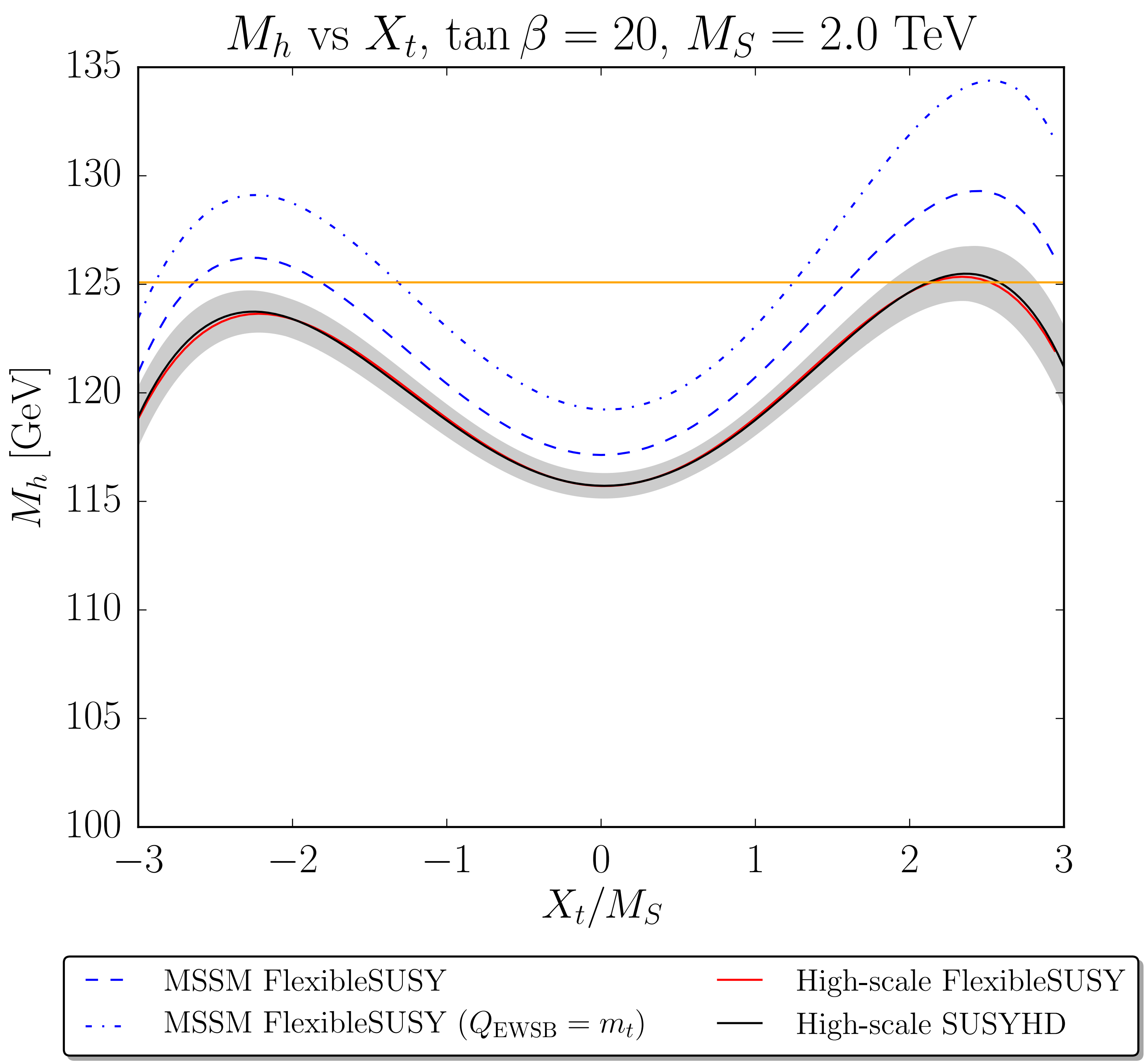
⇒ Extremely high precision in f_{a3} needed to probe possible deviations from the SM

The Snowmass report sets as a target that should be achieved for f_{a3} an accuracy of better than 10^{-5}!

Note: large effects also occur within the DRbar scheme
Different options for doing the full model calculation

Option 1: Higgs mass computation at scale $Q = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$

Option 2: First run parameters down to scale Q = m_t, compute Higgs mass there



FlexibleSUSY

[E. Bagnaschi, A. Voigt, G. W. '15]

⇒ Differences are of higher order, much larger than uncertainty estimated in *SUSYHD*

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: $M_A > 200 \text{ GeV}$

- $\Rightarrow M_A \gg M_Z$: ``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

The quest for identifying the underlying physics

In general 2HDM-type models one expects % level deviations from the SM couplings for BSM particles in the TeV range, e.g.

$$
\begin{aligned}
\frac{g_{hVV}}{g_{h_{\rm SM}VV}} &\simeq 1 - 0.3\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^4 \\
\frac{g_{htt}}{g_{h_{\rm SM}tt}} = \frac{g_{hcc}}{g_{h_{\rm SM}cc}} &\simeq 1 - 1.7\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2 \\
\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} &\simeq 1 + 40\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2 .
\end{aligned}
$$

⇒ Need very high precision for the couplings