Extended Higgs sector theory (mainly SUSY)

Georg Weiglein, DESY

Higgs Hunting 2014,
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Extended Higgs sectors: possible deviations from the Standard Model

SUSY as a test case: well motivated, theory predictions have been worked out to high level of sophistication

"Simplest" extension of the minimal Higgs sector:

Minimal Supersymmetric Standard Model (MSSM)

- 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 one: $\tan\beta \equiv \frac{v_u}{v_d}$, M_A (or $M_{H^\pm}$)

$\Rightarrow$ Upper bound on lightest Higgs mass, M_h:

Lowest order: $M_h \leq M_Z$

Including higher-order corrections: $M_h \lesssim 135\,\mathrm{GeV}$

Interpretation of the signal at 125 GeV within the MSSM?

Extended Higgs sectors, case I: 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: $M_A > 200 \text{ GeV}$

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

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} \simeq 1 - 0.3\% \left(\frac{200\ \rm GeV}{m_A}\right)^4$$

$$\frac{g_{htt}}{g_{h_{\rm SM}tt}} = \frac{g_{hcc}}{g_{h_{\rm SM}cc}} \simeq 1 - 1.7\% \left(\frac{200\ \rm GeV}{m_A}\right)^2$$

$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 40\% \left(\frac{200\ \rm GeV}{m_A}\right)^2 .$$

⇒ Need very high precision for the couplings

Possibility of a sizable deviation even if the couplings to gauge bosons and SM fermions are very close to the SM case

- 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

Simple example: common scale factor for all Higgs couplings, but no assumptions on undetectable / invisible decays

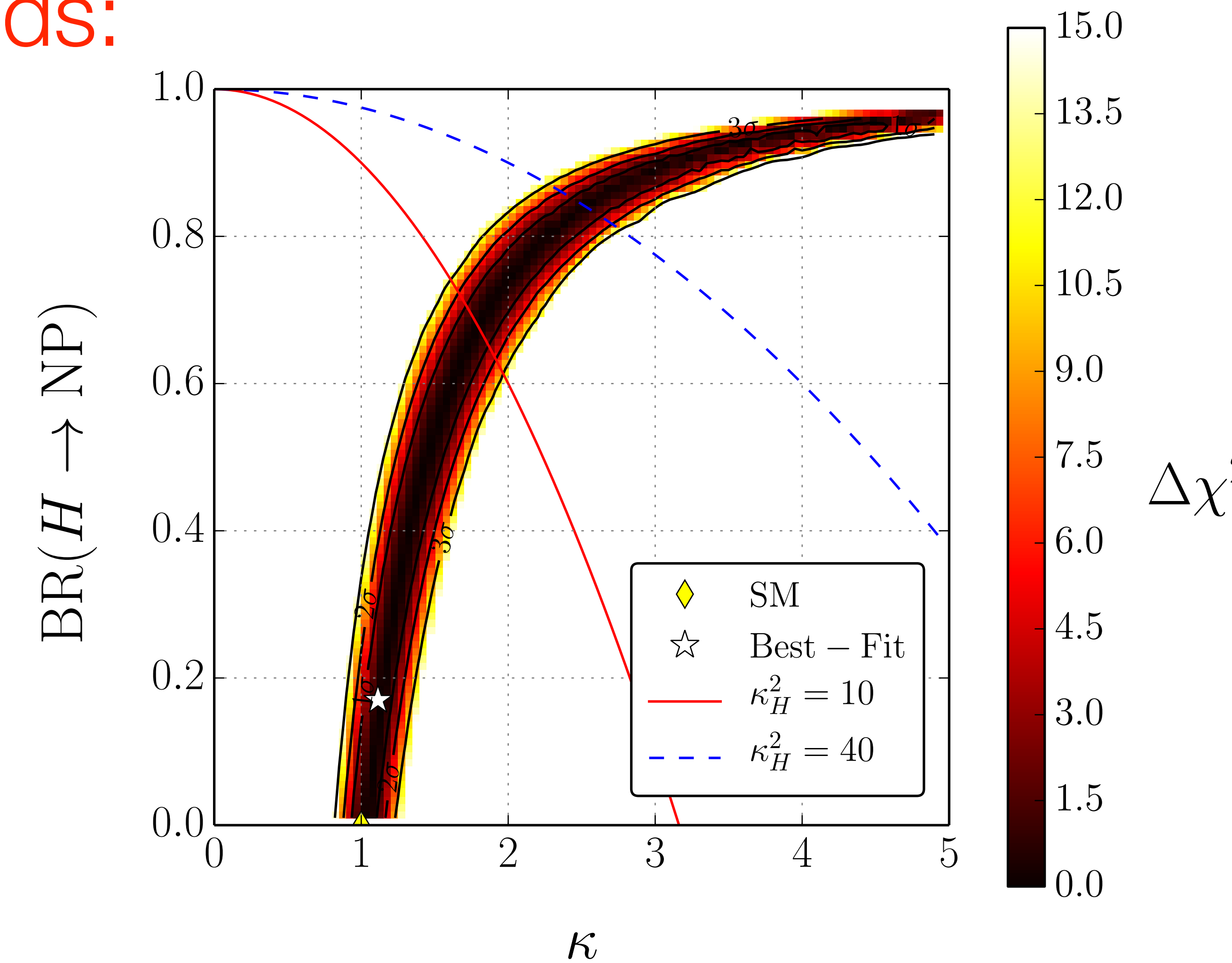
[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W. '14]

HiggsSignals

ATLAS + CMS bounds:

Common scale factor ϰ for all Higgs couplings

No assumptions on undetectable / invisible decays



⇒ • Large range possible for scale factor ϰ and branching ratio into new physics final states without additional theoretical assumptions

• Constraints on total width, $\varkappa_H$, are crucial!

CP properties

While the current measurements disfavour a pure CP-odd state compared to a pure CP-even state, the bounds on a CP-mixed state are still very weak

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 SUSY models (and many other BSM models) a_3 is loop-induced and heavily suppressed

CP properties

⇒ Even a rather large CP-admixture would not lead to detectable effects in the angular distributions of $H \to ZZ^{*} \to 4\,l$, etc. because of the smallness of a_3

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

Global analyses of the properties of h(125)

- Since the mass of the light Higgs state h is a crucial prediction of SUSY models, this observable plays an important role for constraining the parameter space when confronting theory and experiment

- Strong ongoing efforts to improve Higgs-mass predictions in the MSSM and beyond: new higher-order corrections, improved precision for the NMSSM, ..., improved predictions in the multi-TeV region of the stop masses, ...

- SUSY Higgs production: recent update of estimate of remaining theoretical uncertainties *[E. Bagnaschi, R. Harlander, S. Liebler, H. Mantler, P. Slavich '14]*

- Constraints from Higgs search limits and properties of the signal at 125 GeV

Improved prediction for the mass of the light Higgs h of the MSSM for large stop masses

- Combination of fixed-order Feynman-diagrammatic result up to two-loop order with all-order resummation of leading and sub-leading logarithmic contributions from top / stop sector (from two-loop RGEs for λ, h_t, g_s)

- Requires consistent merging of diagrammatic results in the on-shell scheme with leading logarithmic contributions in the MSbar scheme:

$$\Delta M_h^2 = (\Delta M_h^2)^{\rm RGE}(X_t^{\overline{\rm MS}}) - (\Delta M_h^2)^{\rm FD,LL1,LL2}(X_t^{\rm OS}) \ ,$$

$$M_h^2 = (M_h^2)^{\rm FD} + \Delta M_h^2 \ .$$

$$X_t^{\overline{\rm MS}} = X_t^{\rm OS}\left[1 + 2L\left(\frac{\alpha_s}{\pi} - \frac{3\,\alpha_t}{16\,\pi}\right)\right] \qquad L \equiv \ln\left(\frac{M_S}{m_t}\right)$$

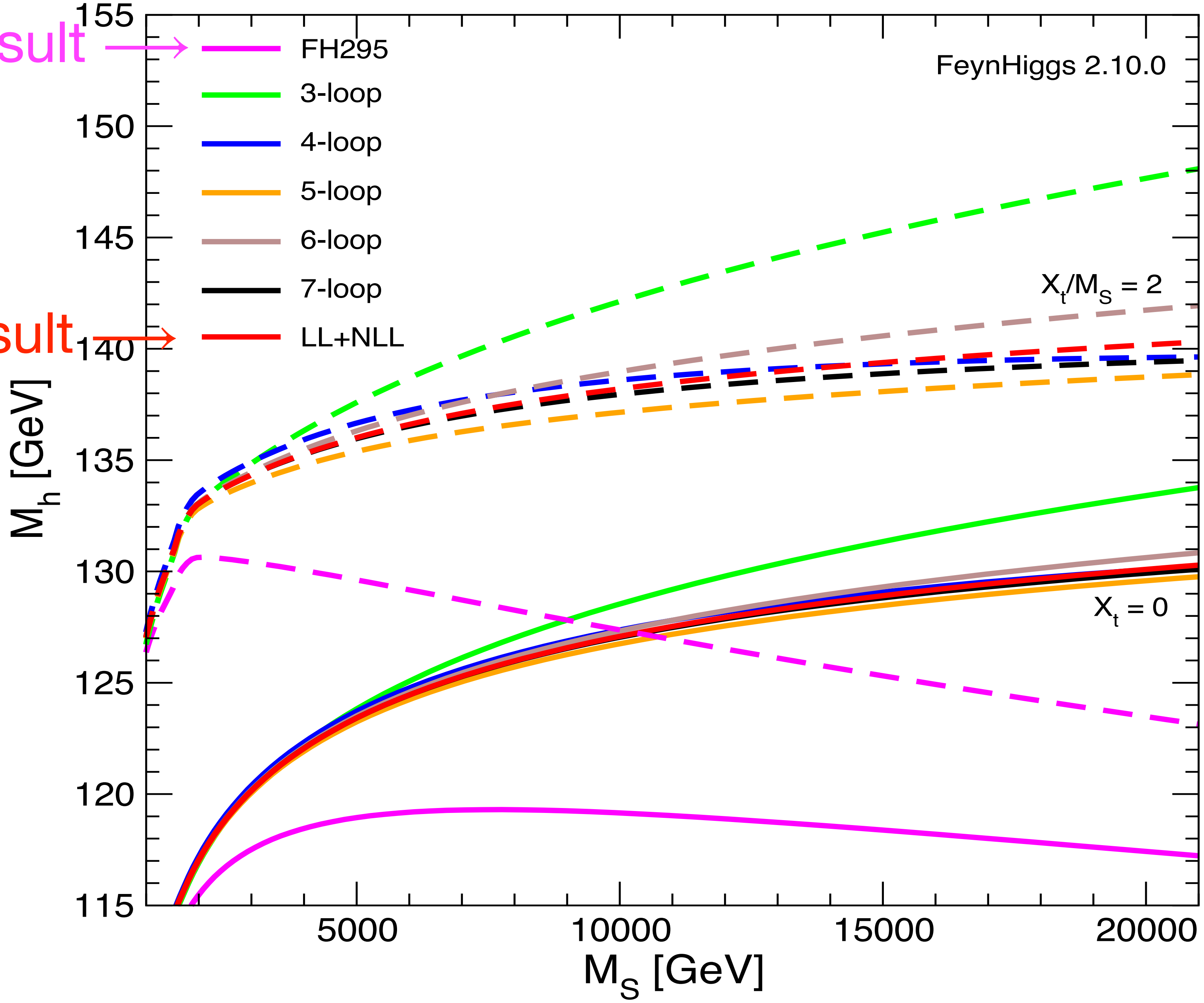
- Results are implemented in the public code *FeynHiggs*
[T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. W. '14]

Numerical impact of new contributions

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

Fixed-order result →

Full result →



⇒ Sizable upward shift for $m_{\tilde{t}} \gtrsim 2$ TeV

[O. Buchmueller et al '14]

Large impact for confronting CMSSM, etc. with signal at 126 GeV

Work in progress

Comparison of recent results in the literature, improved estimate of remaining theoretical uncertainties from unknown higher-order corrections
[P. Draper, G. Lee, C. Wagner ’14], [S. Borowka, T. Hahn, S. Heinemeyer, G. Heinrich, W. Hollik ’14], [E. Bagnaschi, G. Giudice, P. Slavich, A. Strumia ’14], ...

Dedicated effort for Higgs mass prediction in the MSSM: KUTS Workshop series, second meeting: DESY, October 20-22, 2014, just before Hamburg Higgs workshop

Katharsis of Ultimate Theory Standards >

workshop-2014-10

KUTS workshop (II)

DESY Hamburg, 20.-22.10.2014

Preliminary program:
20.10. morning: arrival
afternoon: review/overview about goals, status, calculations
21.10. morning: progress overview calculations
afternoon: progress overview codes
evening: workshop dinner
22.10. morning: identification of how to proceed
afternoon: departure/DESY Higgs WS

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

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]*

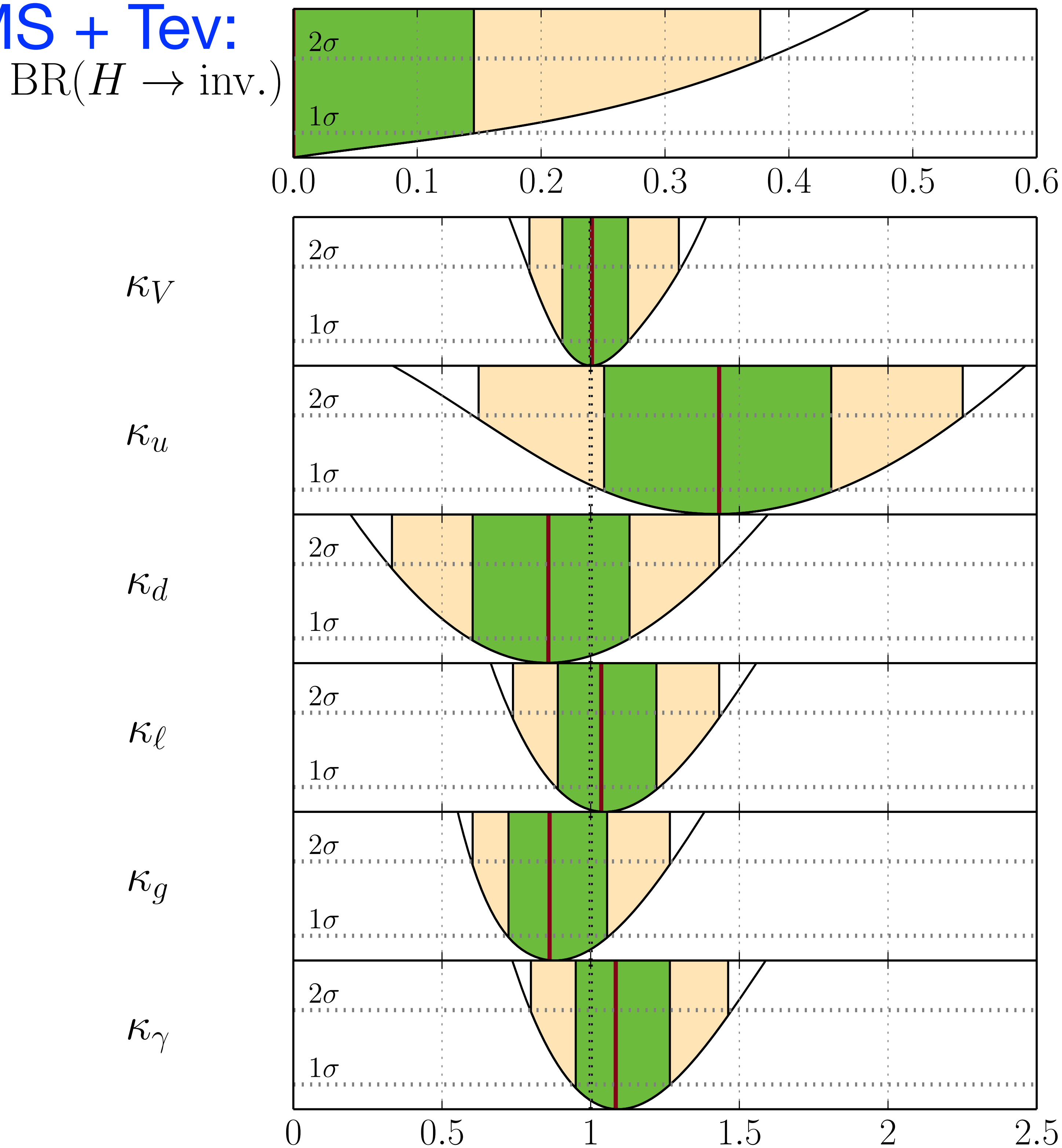
- *HiggsSignals:* *[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein '13]*

  - 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

Constraints on coupling scale factors from ATLAS + CMS + Tevatron data

ATLAS + CMS + Tev:



Seven fit parameters

HiggsSignals

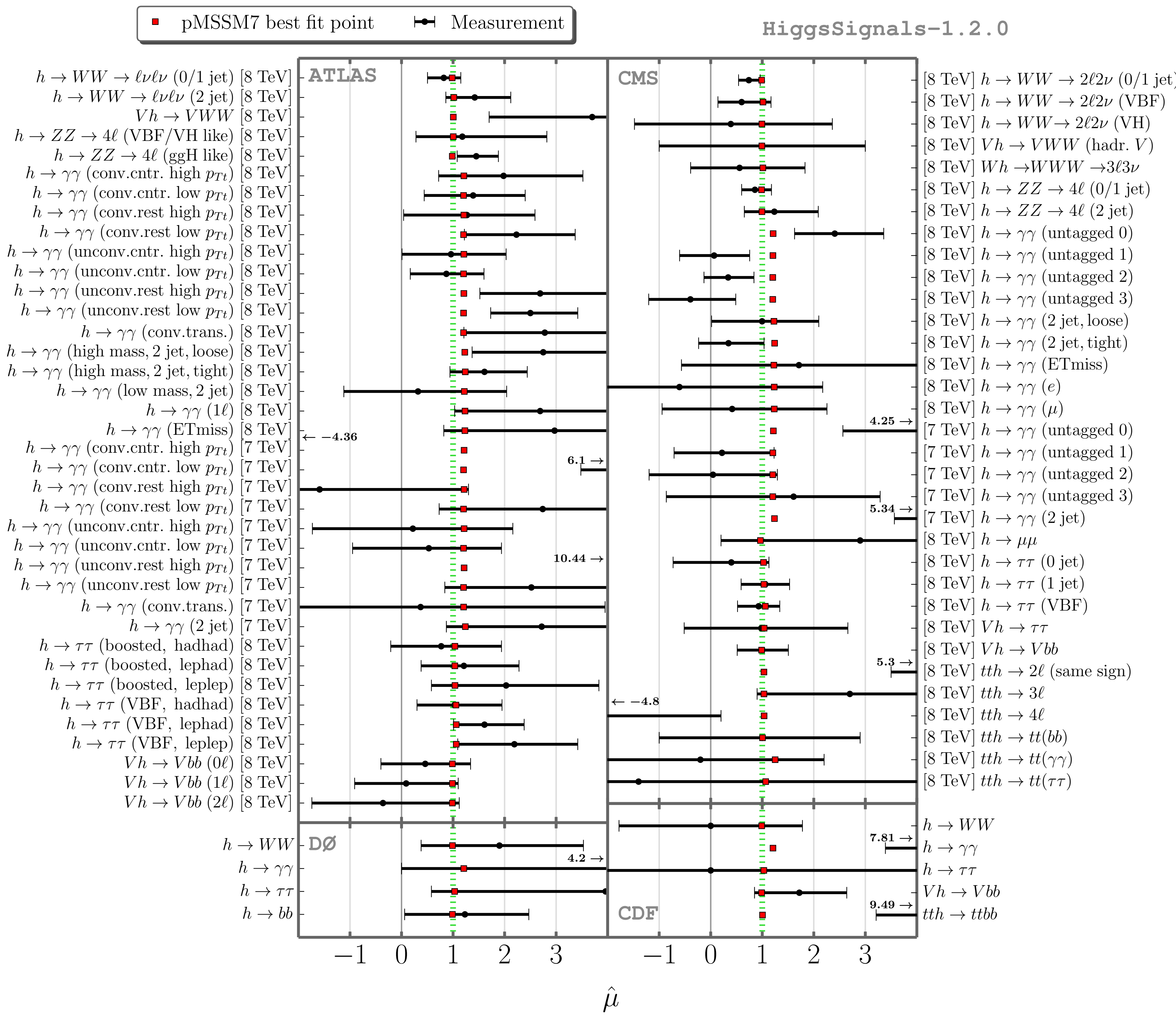
[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W. '14]

⇒ Significantly improved precision compared to ATLAS or CMS results alone

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:



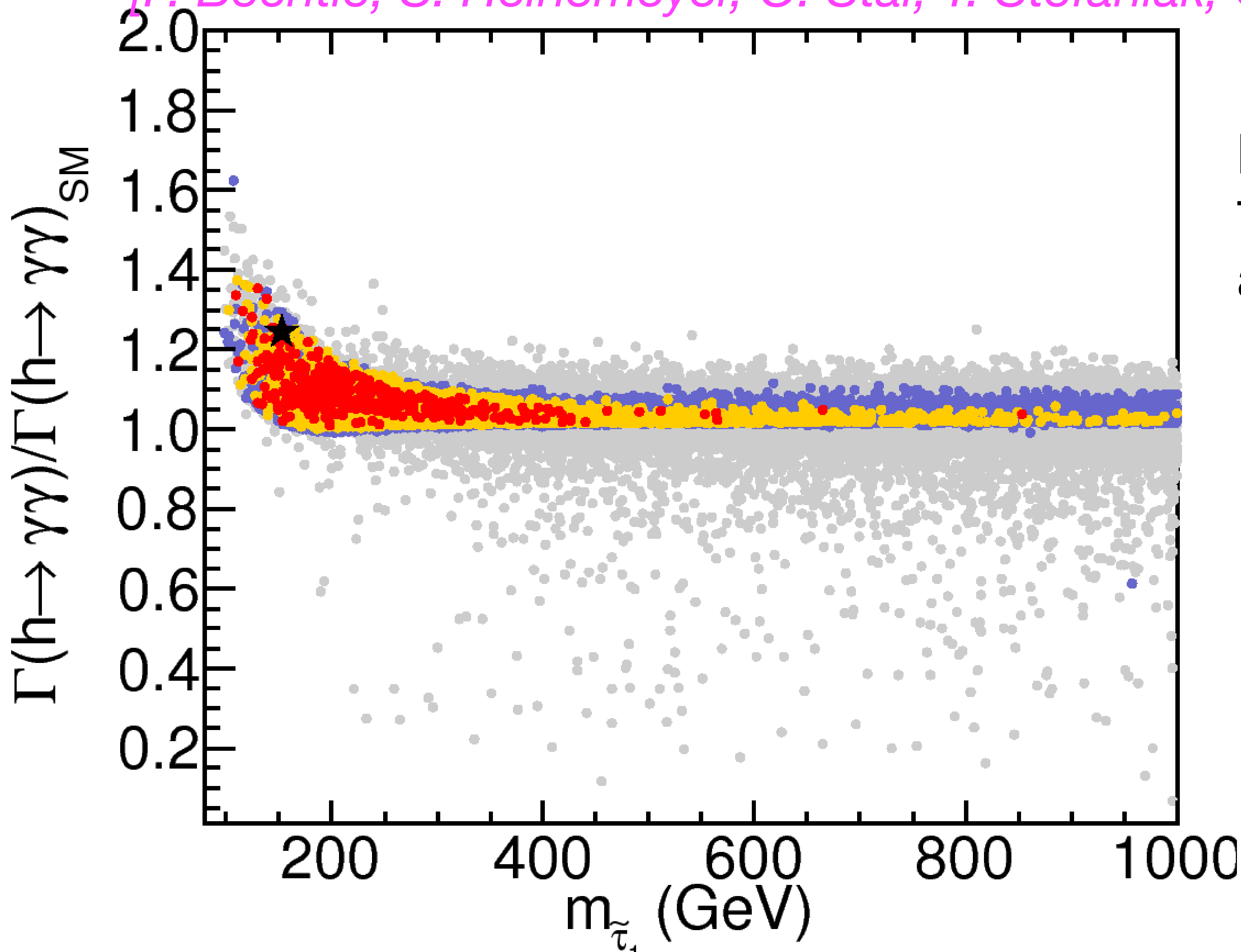
HiggsSignals

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

⇒ 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

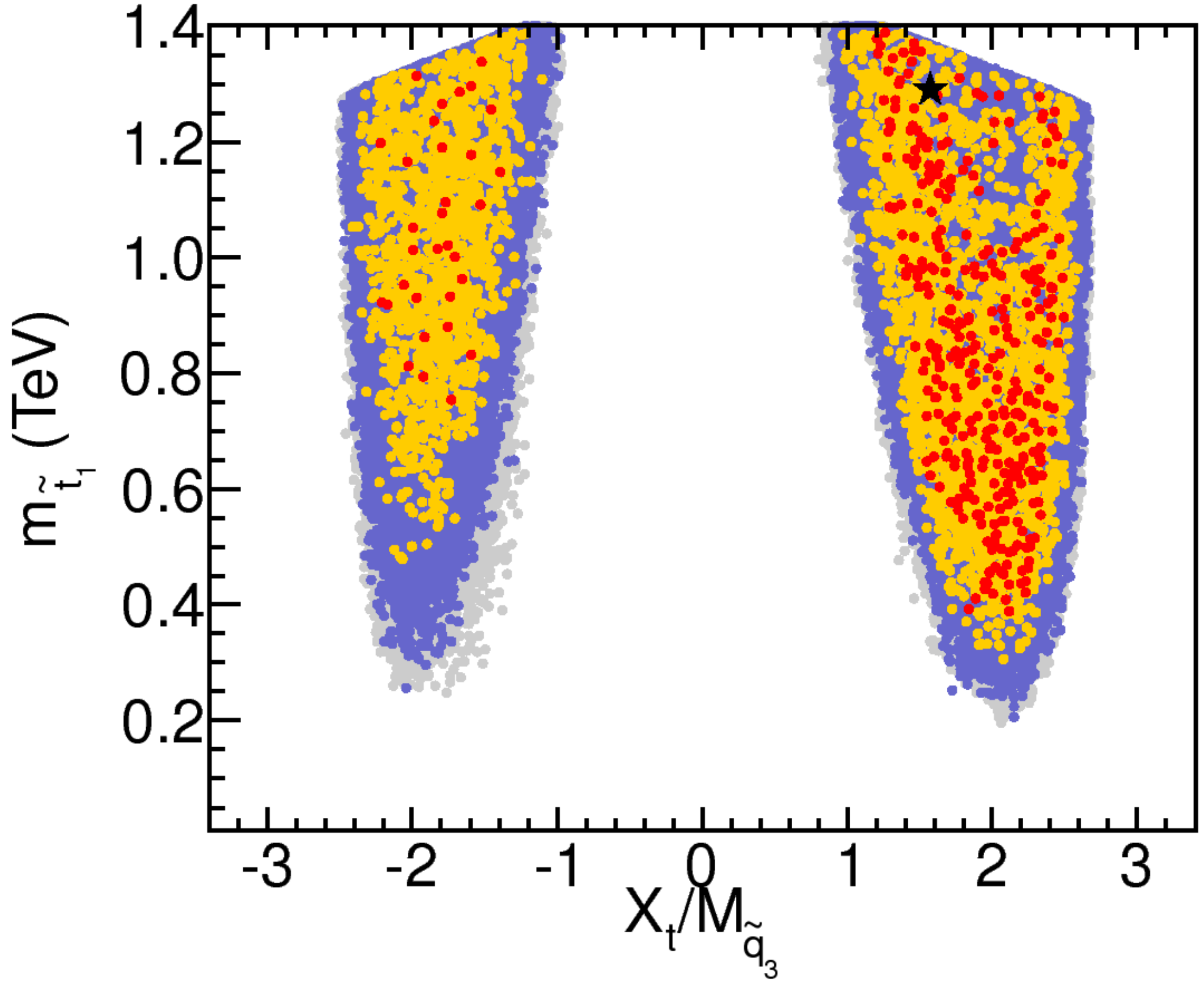
Fit assumes slepton mass universality: $M_{\tilde{E}_{1,2}} = M_{\tilde{L}_{1,2}} = M_{\tilde{l}_3}$

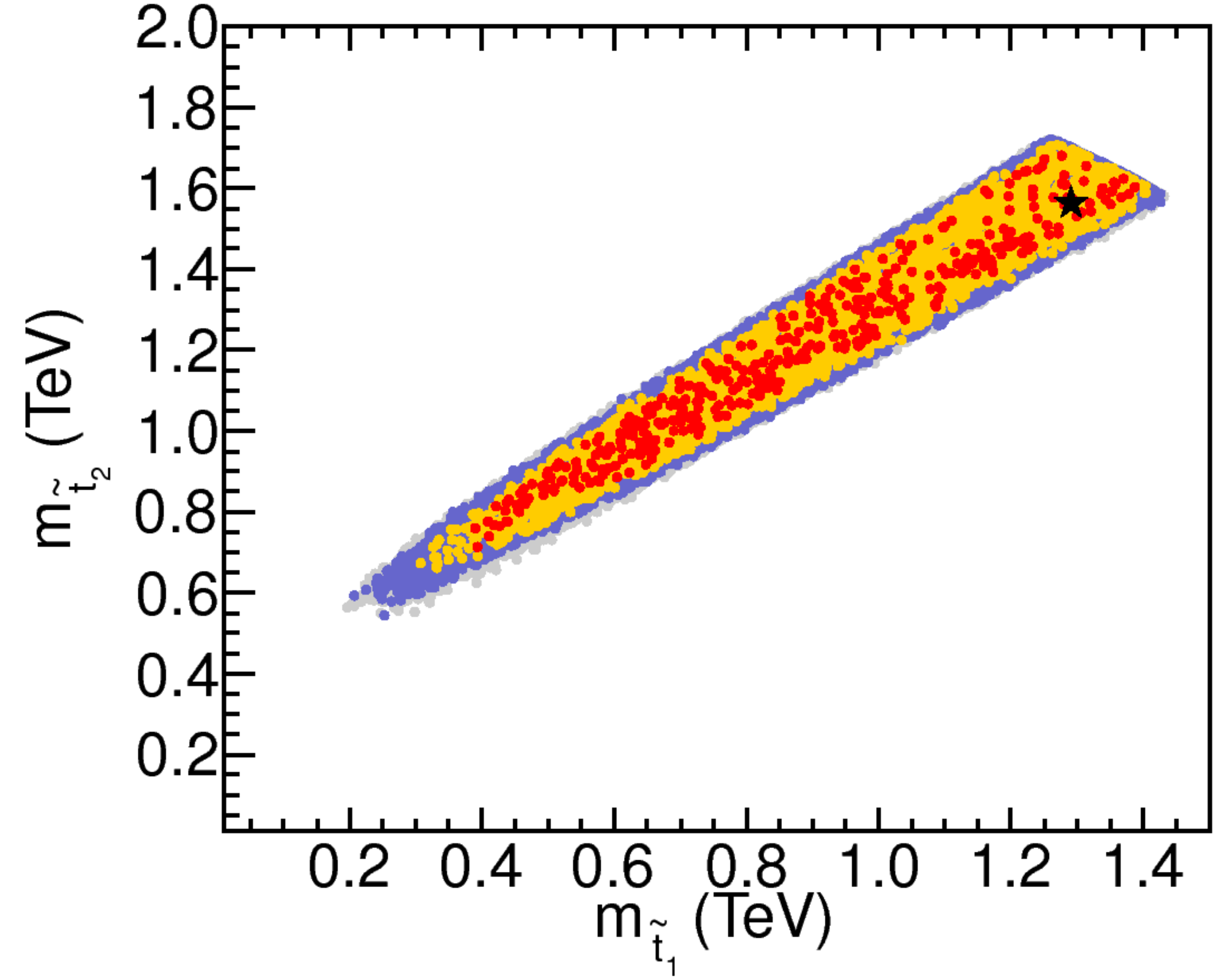
⇔ Also impact from g_μ - 2

Interpretation of the signal at 126 GeV in terms of the light Higgs h of the MSSM

MSSM fit, preferred values for the stop masses:

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





⇒ Large stop mixing required

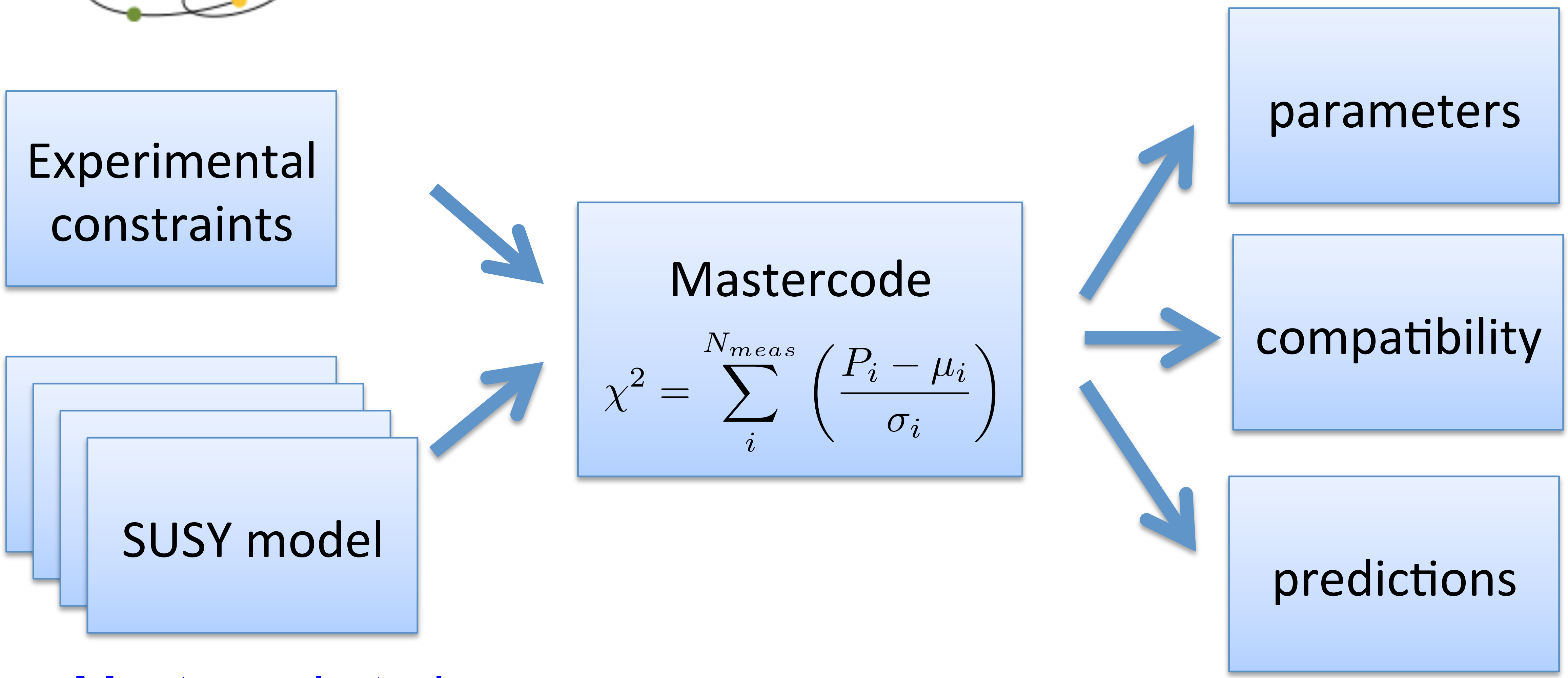
Best fit prefers heavy stops beyond 1 TeV

But good fit also for light stop down to ≈300 GeV

MasterCode, global SUSY fits: CMSSM, NUHM1, NUHM2, pMSSM10

[O. Buchmueller et al '14]

Global fit of SUSY



- Mastercode today
  - **supergravity:** CMSSM, NUHM1, NUHM2 NEW

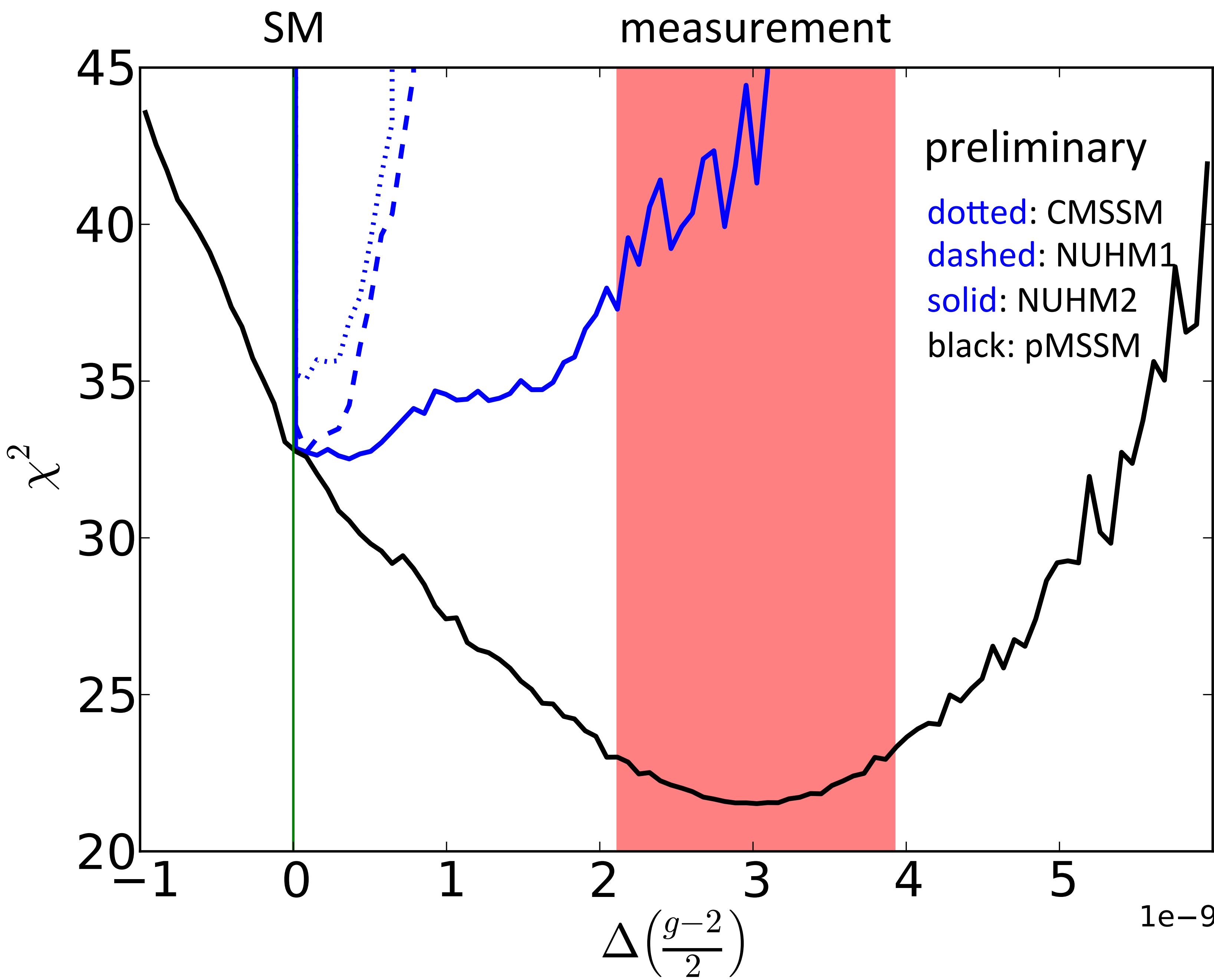
    $$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ (m^2_{H_u},\ m^2_{H_d})$$

  - **phenomenological:** pMSSM10 NEW

    $$m_{\tilde{q}_{12}},\ m_{\tilde{q}_3},\ m_{\tilde{l}},\ M_1,\ M_2,\ M_3,\ A,\ M_A,\ \tan\beta,\ \mu$$

pMSSM fit: signal at 125 GeV interpreted as light Higgs h

[O. Buchmueller et al '14]



	χ^2/n_{dof}	p-value
CMSSM	35.1/23	5.1 %
NUHM1	32.7/22	6.6 %
NUHM2	32.5/21	5.2 %
pMSSM10	21.1/17	22 %

pMSSM10 resolves the **tension** between (g-2) and LHC constraints. This **significantly improves** the **fit**.

Search for non-standard heavy Higgses

"Typical" features of extended Higgs sectors:

- A light Higgs with SM-like properties, couples with about SM-strength to gauge bosons
- Heavy Higgs states that decouple from the gauge bosons

⇒ • A signal could show up in H → ZZ → 4 l as a small bump, very far below the expectation for a SM-like Higgs (and with a much smaller width)

• Particularly important search channel: H, A → $\tau\tau$

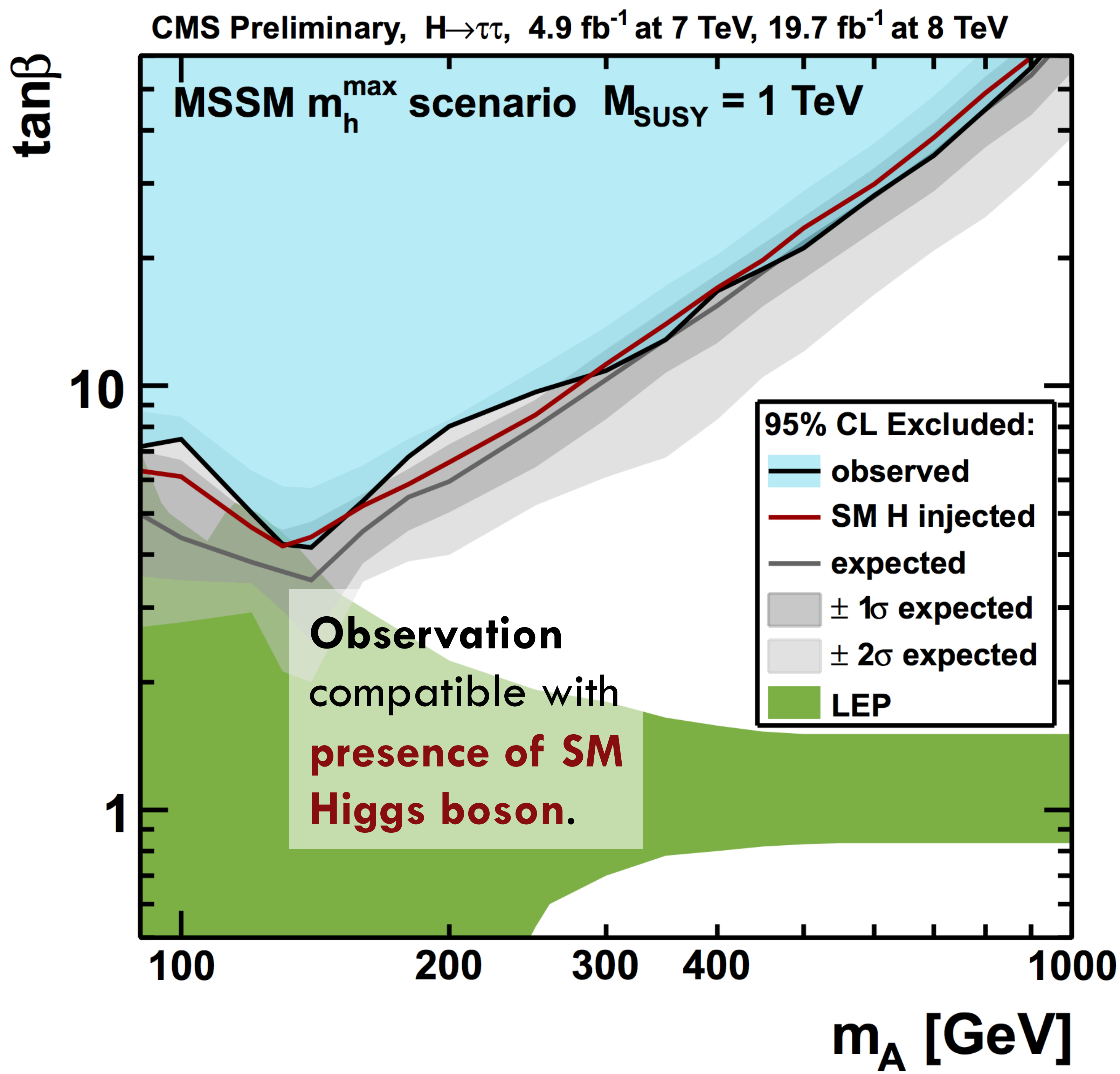
• Non-standard search channels can play an important role: H → hh, H, A → $\chi\chi$, ...

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

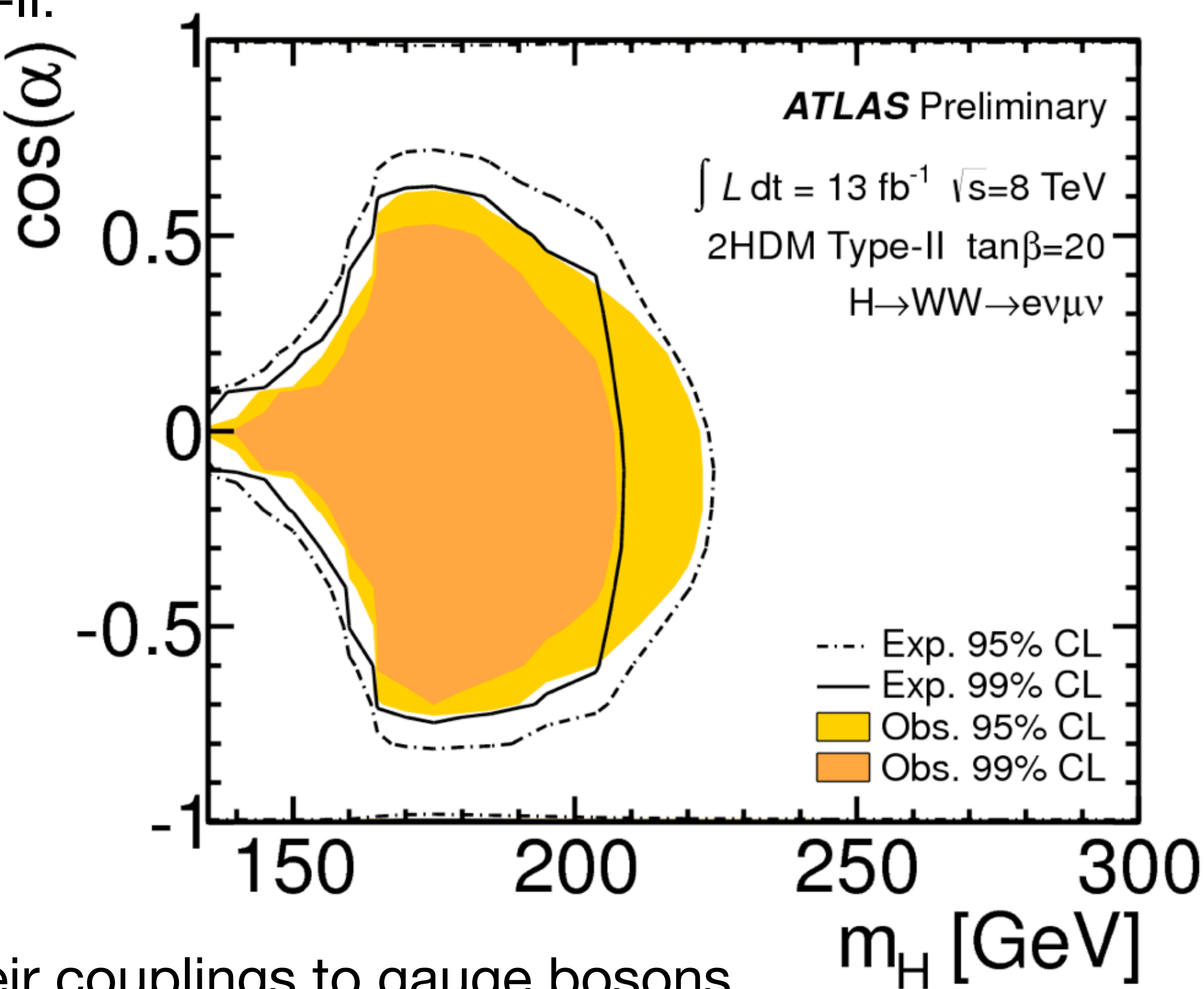
⇒ Searches for Higgs bosons of an extended Higgs sector need to test compatibility with the signal at 125 GeV (→ appropriate benchmark scenarios) and search for additional states



ATLAS analysis in the 2HDM, $H \to WW^*$

[ATLAS Collaboration '13]

2HDM, Type-II:

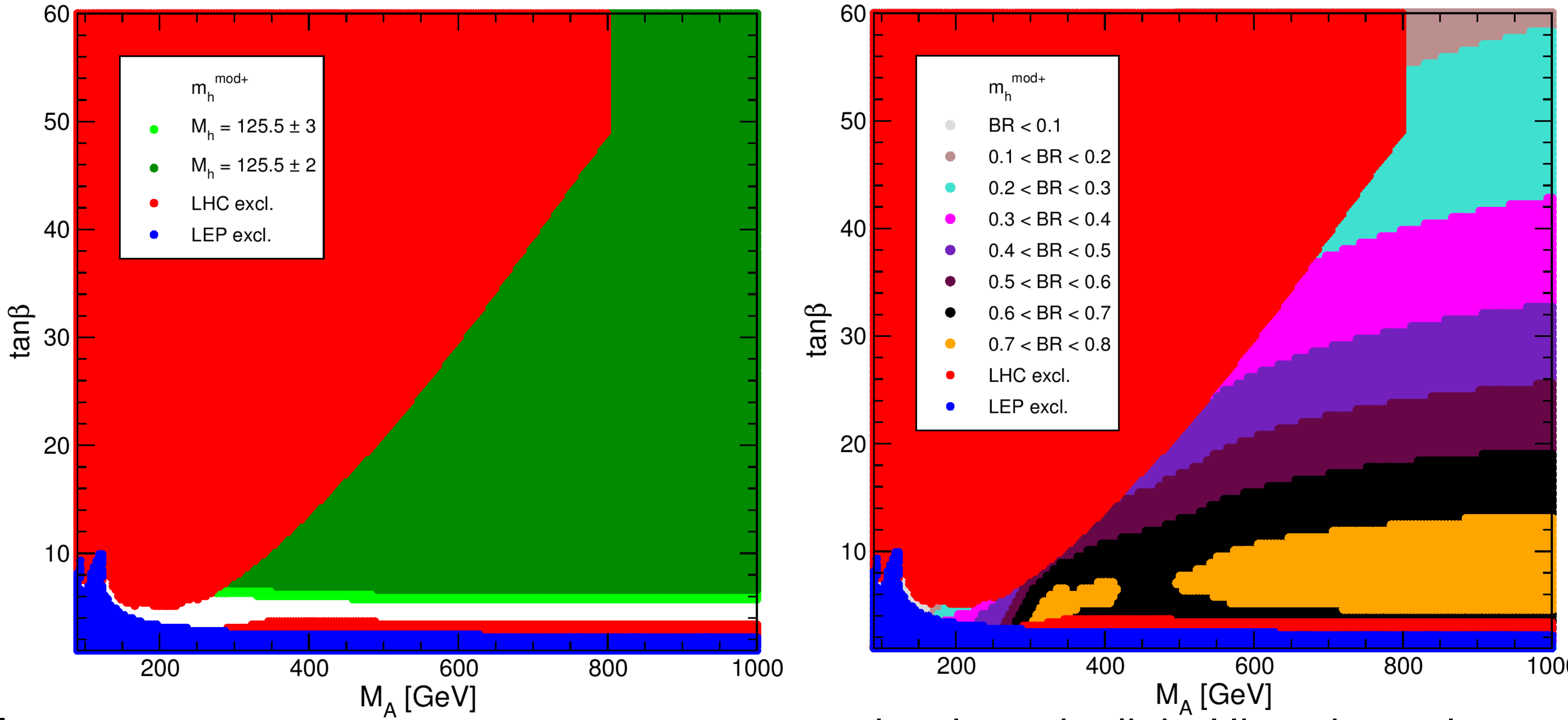


h and H ``share" their couplings to gauge bosons

⇒The analysis is most sensitive in the parameter region of the model that is least compatible with the signal at 126 GeV!

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) for rel. small tanβ possible

Complementarity between benchmark scenarios and cross section limits

- Cross-section limits for different search topologies:
  Fairly model-independent ⇒ test of different models

  Exclusion bounds can be tested channel by channel; combination?

- Benchmark scenarios of specific models (in particular: models that have a Higgs state that is compatible with the signal at 125 GeV):
  full strength of experimental analysis can be exploited for specific benchmark scenario, combination of channels, etc., but difficult to interpret in other models or w.r.t. changes in the input parameters or the theoretical predictions

⇒ Analyses in benchmark scenarios are important for exploring possible Higgs phenomenology

Benchmark results are crucial for validating implementation of cross section limits

Extended Higgs sectors, case II: signal interpreted as a state H of an extended Higgs sector that is not the lightest one

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

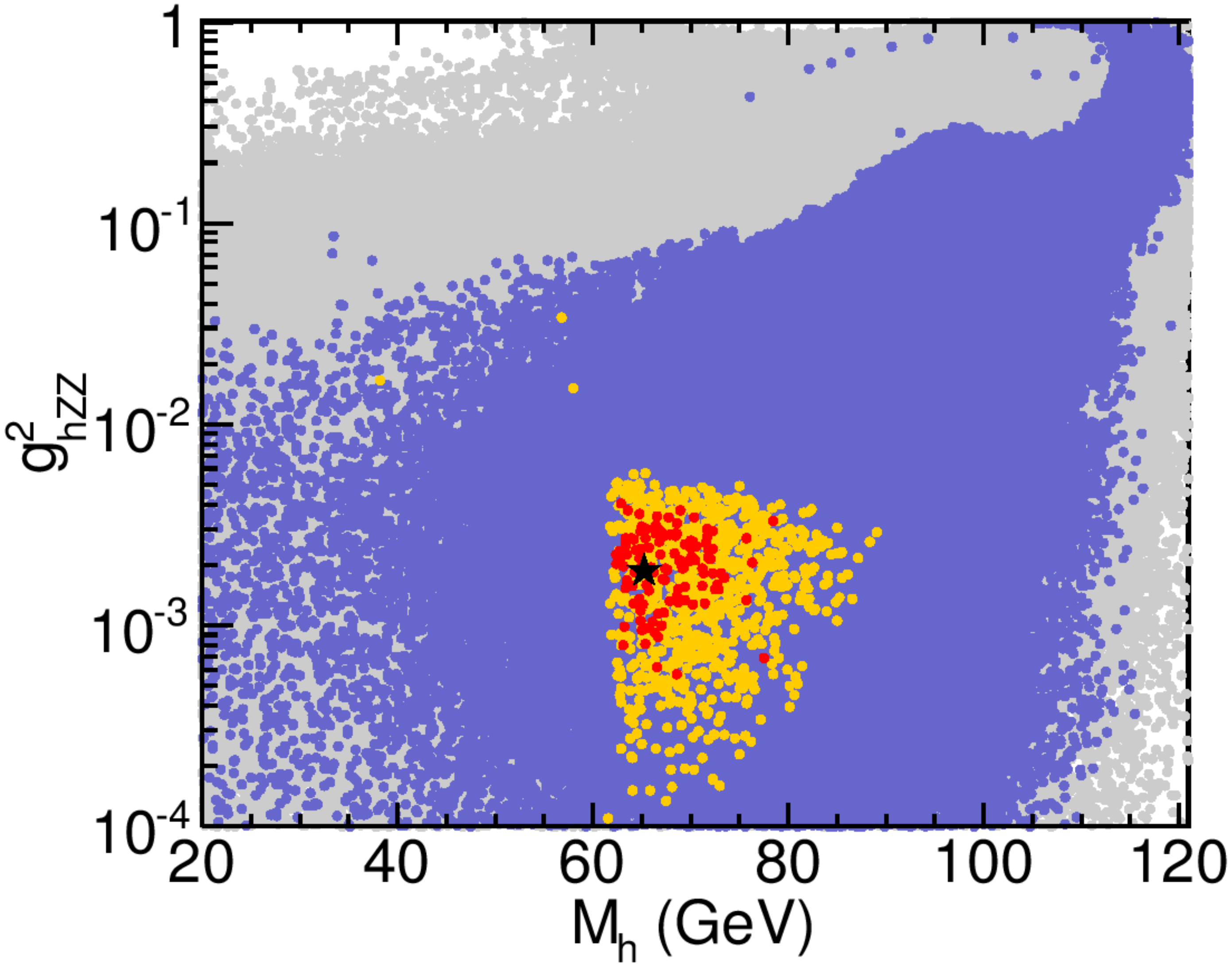
⇒ Lightest neutral Higgs with heavily suppressed couplings to gauge bosons, may have a mass below the LEP limit of 114.4 GeV for a SM-like Higgs (in agreement with LEP bounds)

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.

MSSM realisation: very exotic scenario, where all five Higgs states are light

Lightest Higgs: mass and couplings to gauge bosons (blue: *HiggsBounds*-allowed)
[*P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '12*]

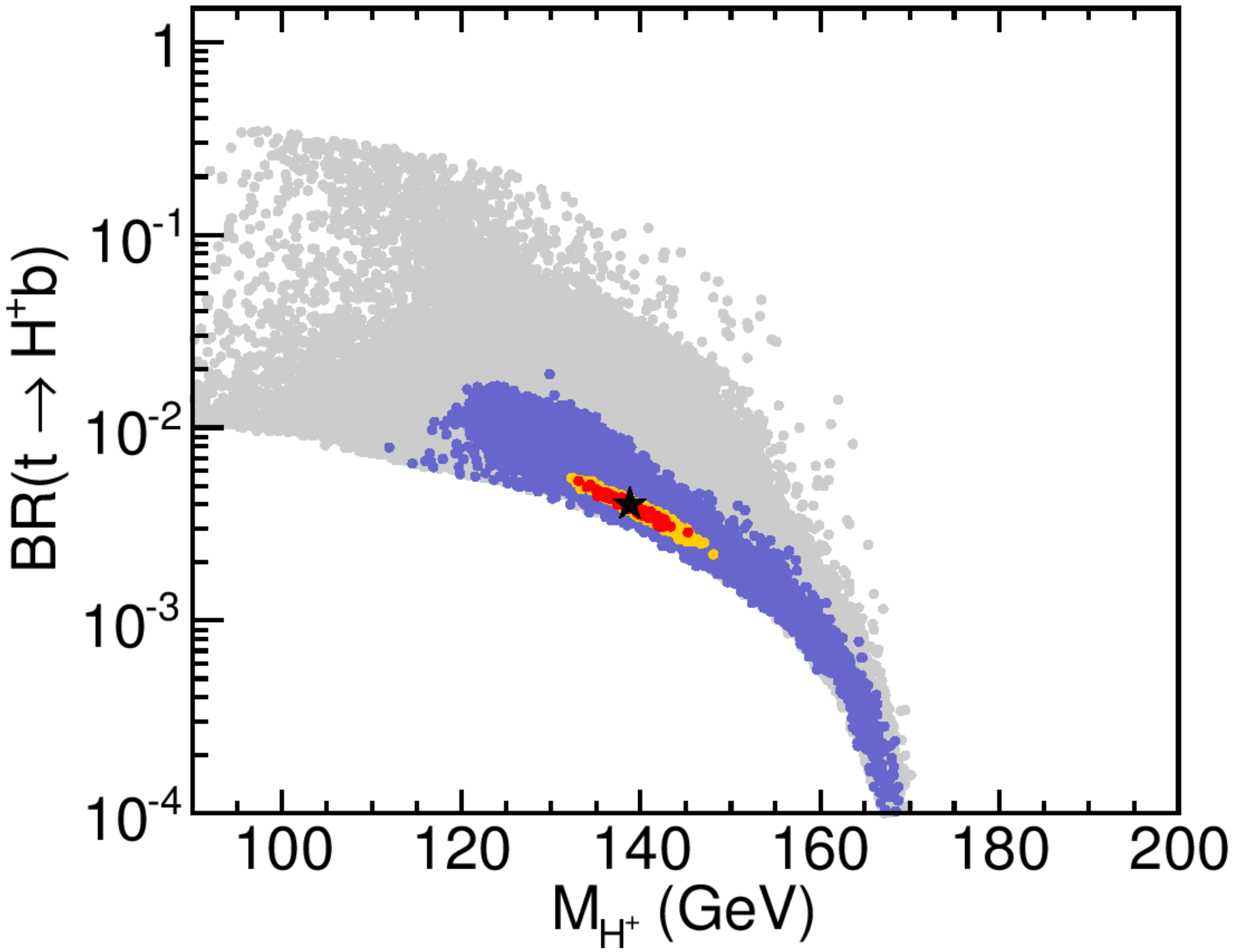


⇒ Light Higgs with $M_\mathrm{h} \approx 70\ \mathrm{GeV}$, in agreement with LEP limits

Before charged Higgs results from ATLAS: global fit yielded acceptable fit probability

MSSM scenario can directly be probed with charged Higgs searches

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '12]



Low M_H scenario: dedicated benchmark scenario for charged Higgs searches

NMSSM: extension of the MSSM by a singlet + superpartner

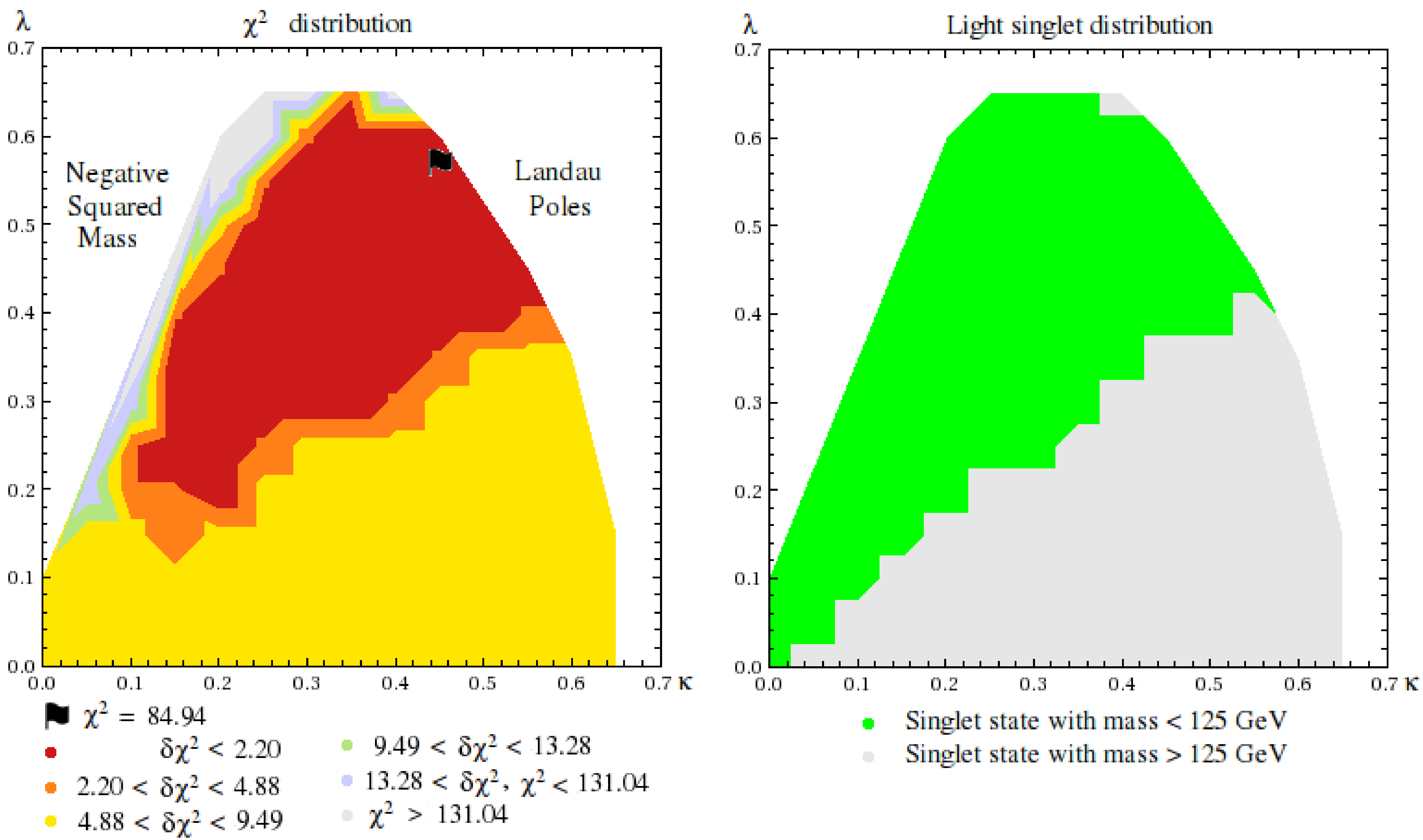
- The case that the signal at 125 GeV corresponds to a Higgs boson which is not the lightest one in the spectrum happens generically in the NMSSM if the singlet is light (singlet-doublet mixing → upward shift of the SM-like Higgs)

- Analysis of possible NMSSM phenomenology in view of the existing limits from the Higgs searches and the properties of the signal at 125 GeV (implemented via *HiggsBounds* and *HiggsSignals*) *[F. Domingo, G. W. '14]*

  Other work in this context: *[G. Belanger, U. Ellwanger, J. Gunion, Y. Jiang, S. Kraml, J. Schwarz '13], [M. Badziak, M. Olechowski, S. Pokorski '13], [J. Gunion, Y. Jiang, S. Kraml '12], [N. Christensen, T. Han, S. Su '13], ...*

Best fit point and preferred region in $\varkappa$ - λ plane

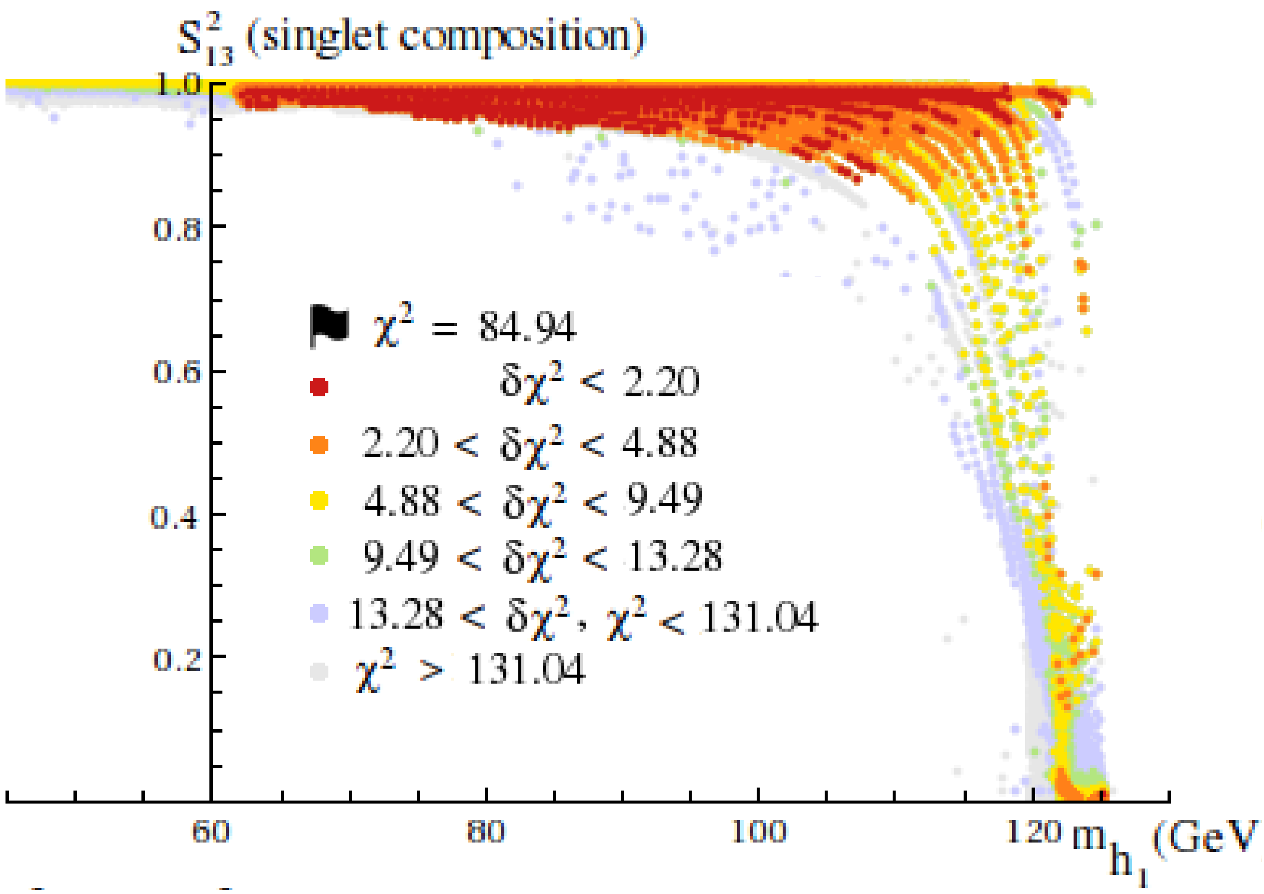
[F. Domingo, G. W. '14]

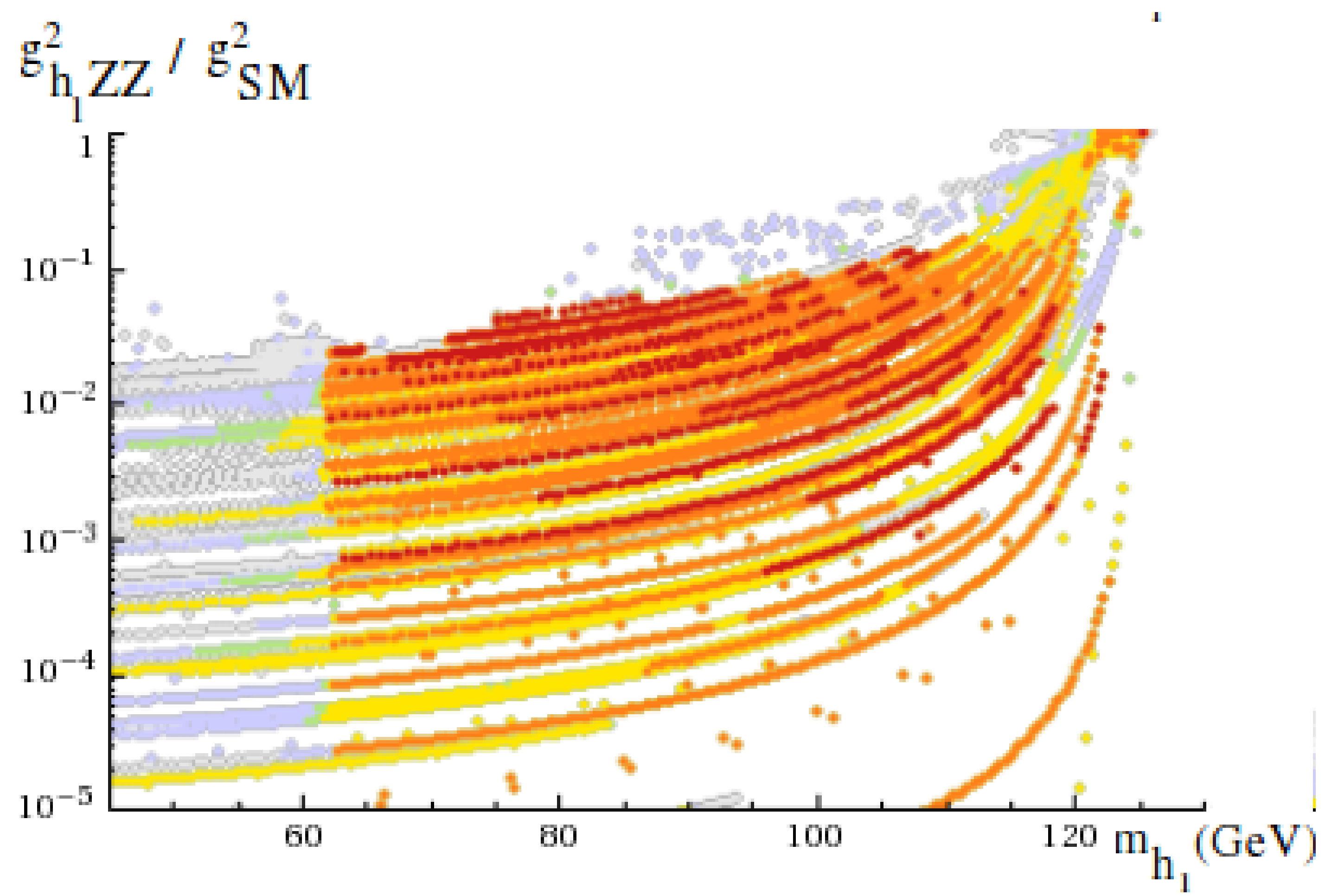


⇒ Preferred region spans over wide range of $\varkappa$ and λ, coincides largely with region where singlet mass is below 125 GeV

Composition of the lightest CP-even state

[F. Domingo, G. W. '14]





⇒ Large singlet component, strong suppression of the coupling to gauge bosons

Conclusions

Extended Higgs sectors are a well-motivated alternative to the SM

Most obvious interpretation of the signal at 125 GeV: lightest Higgs in the spectrum

MSSM: $M_h = 125$ GeV implies $M_A >> M_Z$: decoupling region, SM-like Higgs; MSSM provides good fit to the data, slightly improved fit quality w.r.t. SM

Search for Higgs states of extended Higgs sector: need to test compatibility with signal at 125 GeV; MSSM: m_h^{mod} benchmark scenario

Extended Higgs sector where the second-lightest Higgs is identified with the signal at 125 GeV: additional light Higgs with suppressed couplings to gauge bosons; ``exotic scenario" within the MSSM, can essentially be ruled out with charged Higgs searches; can be realised generically in the NMSSM

⇒ The fact that there is no clear indication yet of BSM Higgs physics is no surprise from the point of view of extended Higgs sectors

⇒ Need to push both on properties of h(125) and on Higgs searches!

Backup

Total Higgs width: recent CMS analysis

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

- CMS quote an upper bound of $\Gamma/\Gamma_{\text{SM}} < 4.2$ at 95% C.L., where 8.5 was expected
  [CMS Collaboration '14]

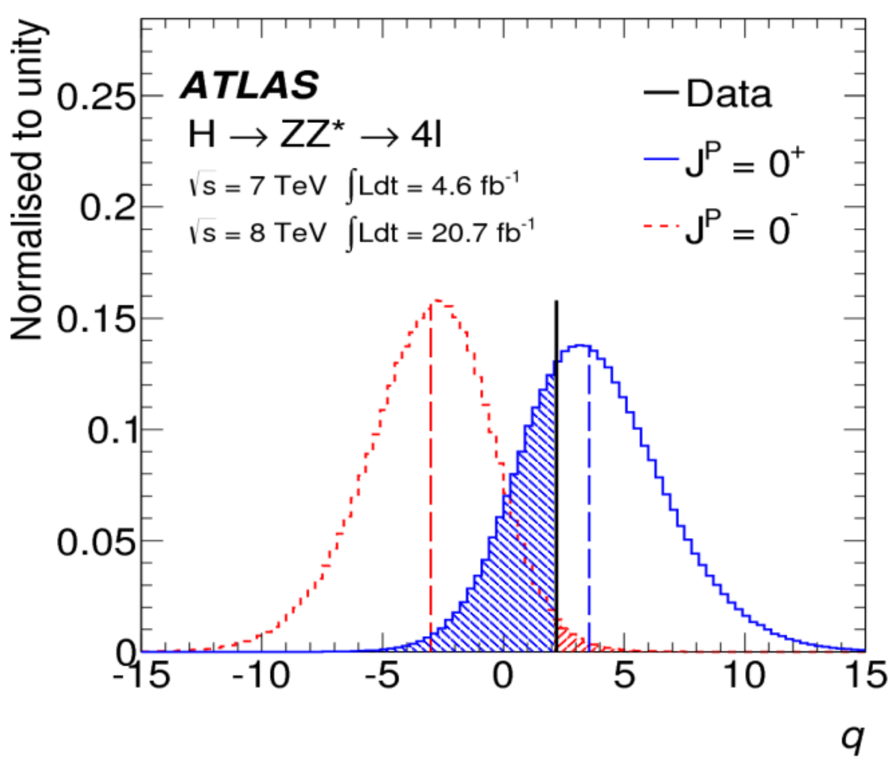
- Problem: assumes equality of on-shell and far off-shell couplings; relation can be severely affected by new physics contributions, in particular via threshold effects (note: effects of this kind may be needed to give rise to a Higgs-boson width that differs from the SM one by the currently probed amount)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

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^-



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

Combined H→ZZ and H→WW 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. $p_0(J^P = 1^+)$	$CL_s(J^P = 1^+)$
$H \to ZZ^*$	$4.6 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	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	$1.2 \cdot 10^{-4}$	$3.0 \cdot 10^{-4}$

- **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. $p_0(J^P = 1^-)$	$CL_s(J^P = 1^-)$
$H \to ZZ^*$	$0.9 \cdot 10^{-3}$	$3.8 \cdot 10^{-3}$	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	$1.8 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$

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

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

H→ZZ analysis excludes the 0^- hypothesis at 97.8% CLs

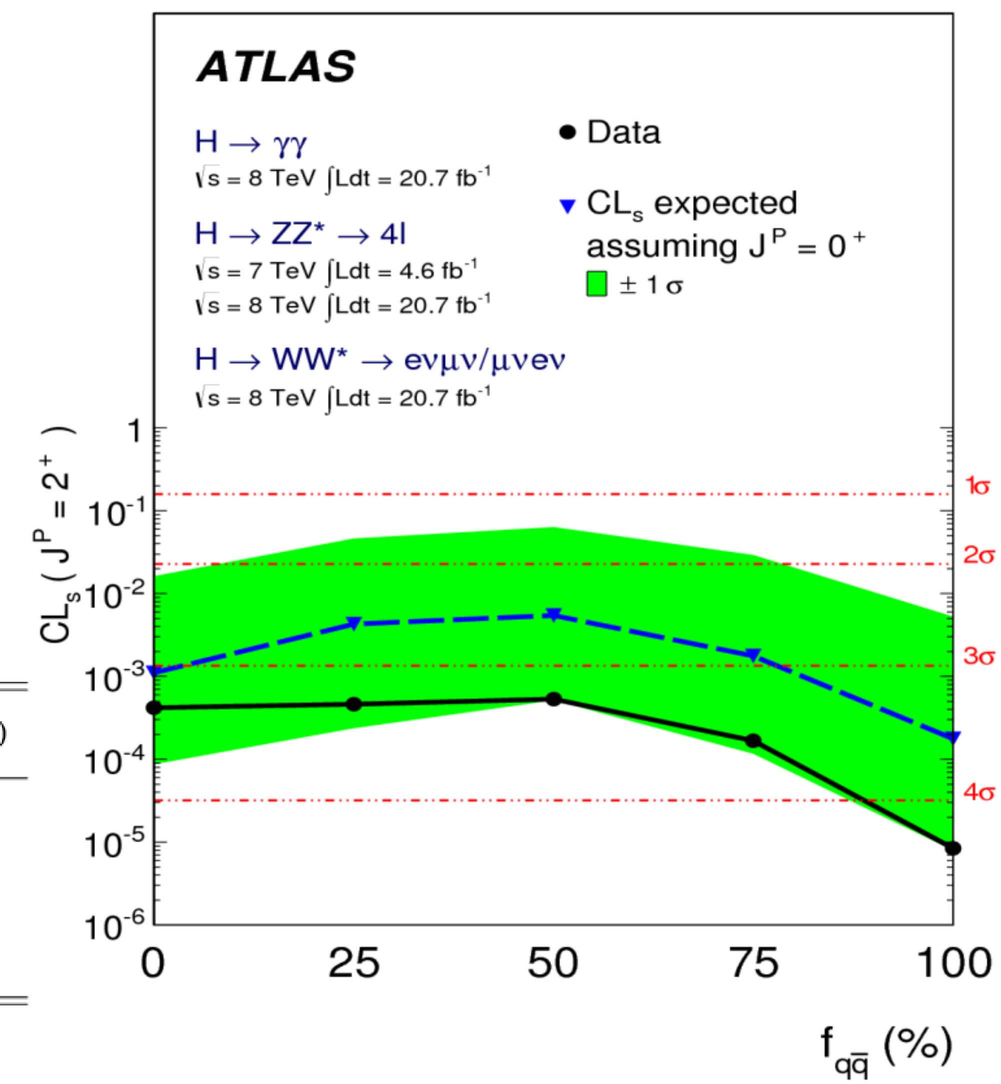
Test of spin and CP hypotheses

[ATLAS Collaboration ’13]

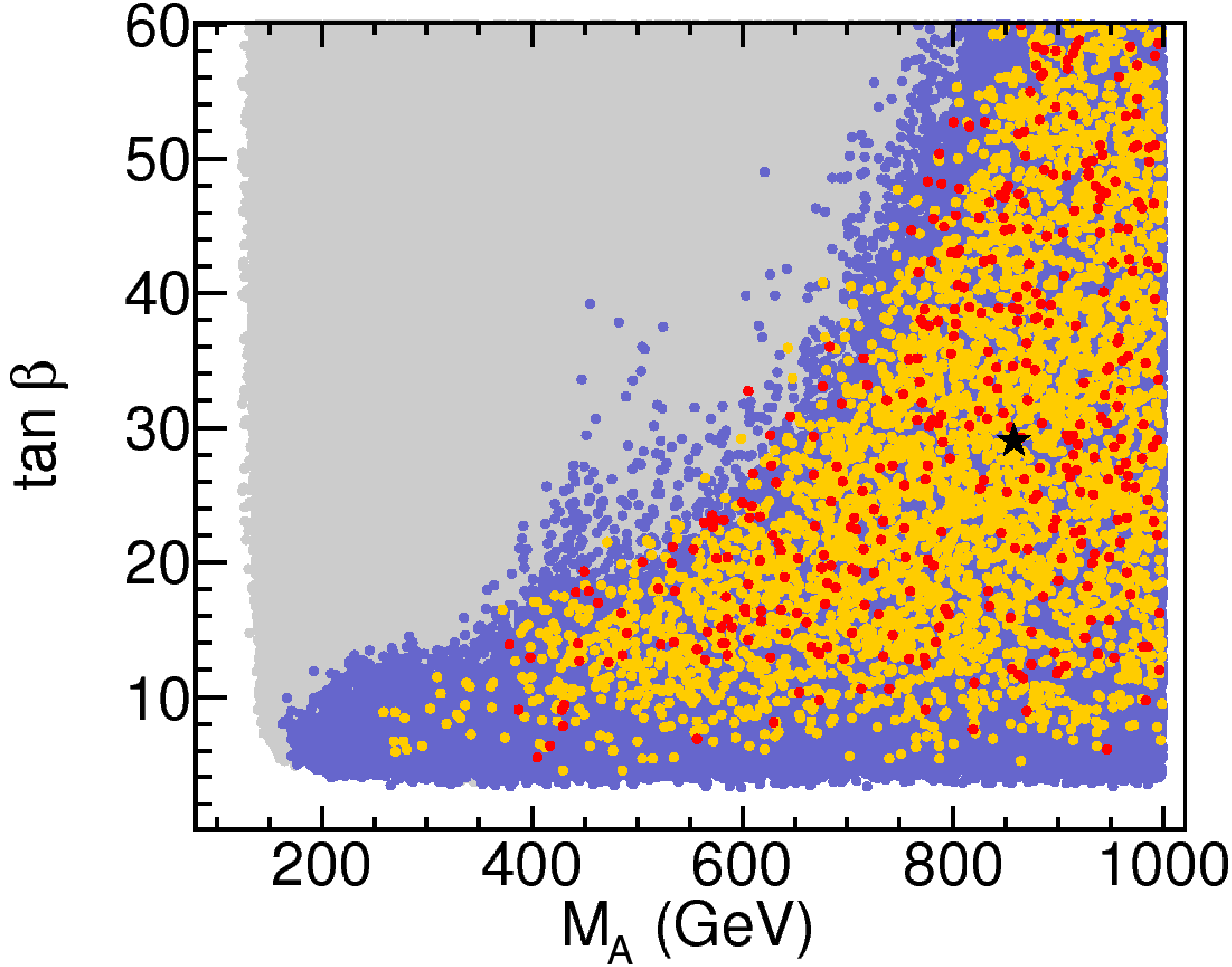
0^+ against 2^+

- ➢ All three analysis have excluded the 2^+ model with different qq fractions in favour of SM 0^+.
- ➢ From the combination of all of them, the 2^+ hypothesis is rejected up to **99.9%** CLs for all fractions of qq.

$f_{q\bar{q}}$	2^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	$3.0 \cdot 10^{-3}$	$8.8 \cdot 10^{-5}$	0.81	$1.6 \cdot 10^{-6}$	$0.8 \cdot 10^{-5}$
75%	$9.5 \cdot 10^{-3}$	$8.8 \cdot 10^{-4}$	0.81	$3.2 \cdot 10^{-5}$	$1.7 \cdot 10^{-4}$
50%	$1.3 \cdot 10^{-2}$	$2.7 \cdot 10^{-3}$	0.84	$8.6 \cdot 10^{-5}$	$5.3 \cdot 10^{-4}$
25%	$6.4 \cdot 10^{-3}$	$2.1 \cdot 10^{-3}$	0.80	$0.9 \cdot 10^{-4}$	$4.6 \cdot 10^{-4}$
0%	$2.1 \cdot 10^{-3}$	$5.5 \cdot 10^{-4}$	0.63	$1.5 \cdot 10^{-4}$	$4.2 \cdot 10^{-4}$

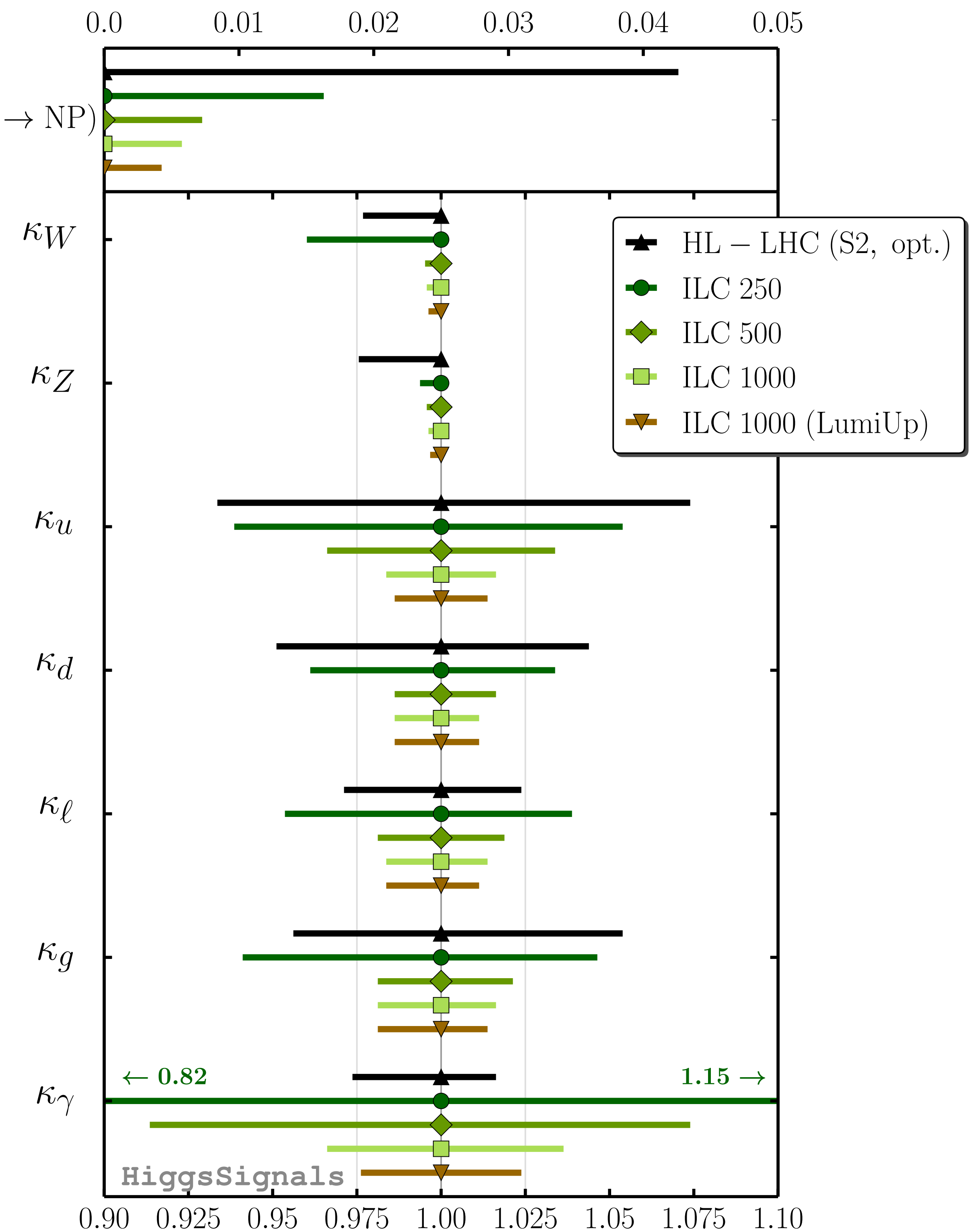


MSSM fit: preferred region for M_A and tanβ



Prospects for Higgs-coupling determinations at HL-LHC and ILC

Assumed: $\kappa_V \leq 1$



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Prospects for Higgs-coupling determinations at HL-LHC and ILC