Implications of the Higgs signal for BSM physics

Georg Weiglein, DESY

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What do we know about the signal at 126 GeV so far?

H Decay Channels – Event Rates

[Y. Sirois, DIS ’14]

Significance

7.4σ (4.3σ)

6.6σ (4.4σ)

3.8σ (3.8σ)

4.1σ (3.2σ)

0.36σ (1.64σ)

Obs. *(Exp.)*

3.2σ (4.2σ)

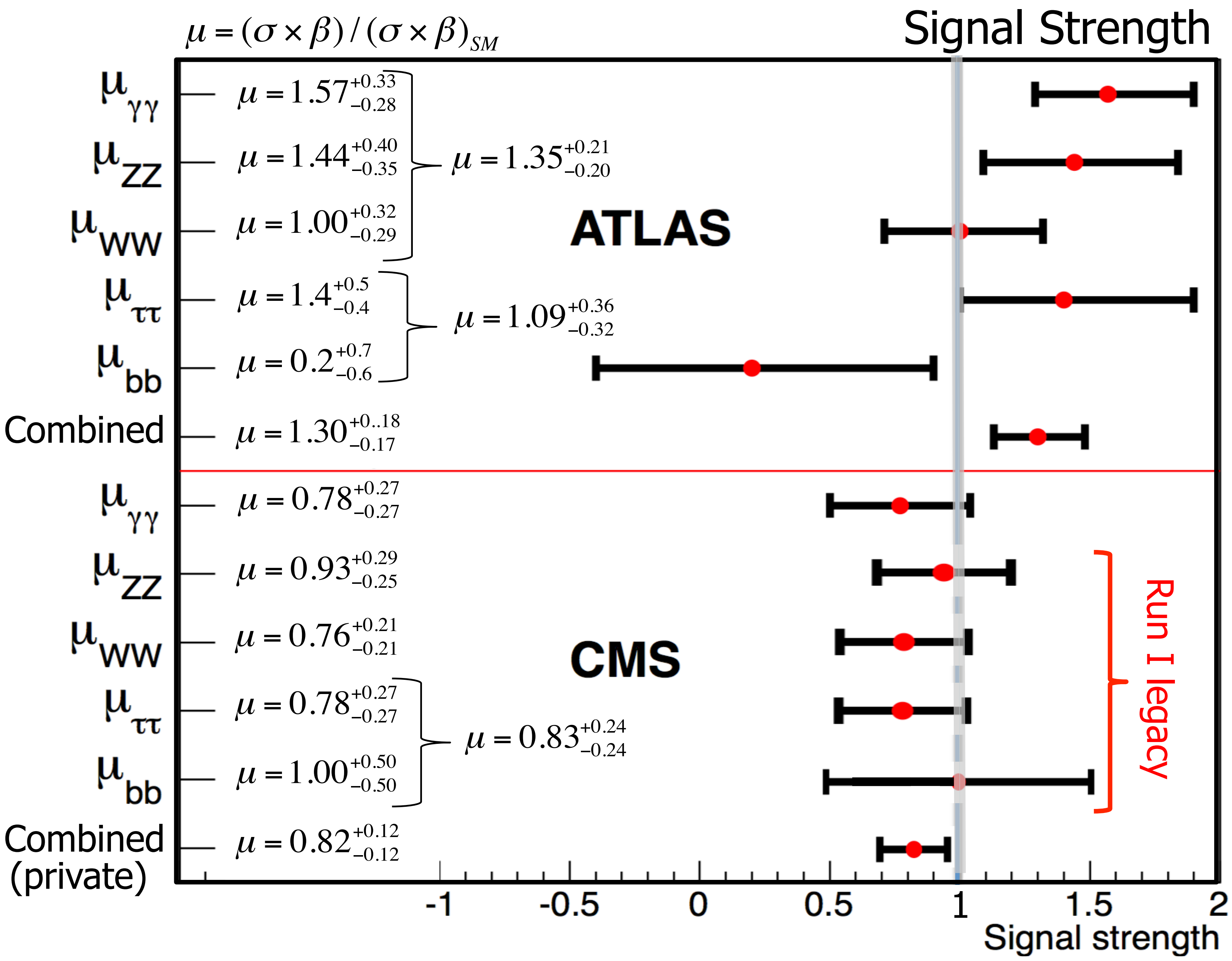
6.8σ (6.7σ)

4.3σ (5.8σ)

3.3σ (3.7σ)

2.1σ (2.1σ)

Obs. *(Exp.)*



	ATLAS γγ+ZZ combined	CMS γγ+ZZ combined*
Mass	$125.5 \pm 0.2(stat) \pm 0.55(syst.)$	$125.7 \pm 0.3(stat) \pm 0.3(syst.)$

* Results as of Moriond 2013

What do we know so far about the discovered signal?

Mass: statistical precision already remarkable with 2012 data

$\Rightarrow$ Need careful assessment of systematic effects for $\gamma\gamma$ and ZZ^* channels,

e.g. interference of signal and background, . . .

Spin: Observation in $\gamma\gamma$ channel $\Rightarrow$ spin 0 or spin 2?

At which level of significance can the hypothesis spin $= 1$ be excluded (2 γ's vs. 4 γ's)?

Spin can in principle be determined by discriminating between distinct hypotheses for spin 0, (1), 2 $\Rightarrow$ spin 0 preferred

Discrimination against two overlapping signals?

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

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

⇒ Need high-precision determination of M_H to exploit the sensitivity of BR(H → ZZ^*), ... to test BSM physics

CP properties

$\mathcal{CP}$-properties: more difficult situation, 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 BSM models a_3 would be loop-induced and heavily suppressed $\Rightarrow$ Realistic models often predict $a_3 \ll a_1$

CP properties

$\Rightarrow$ Observables involving HVV coupling provide only limited sensitivity to effects of a $\mathcal{CP}$-odd component

Hypothesis of a pure $\mathcal{CP}$-odd state is experimentally disfavoured

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

Channels involving only Higgs couplings to fermions provide much higher sensitivity

Couplings

- What is meant by measuring a coupling?
  A coupling is not directly a physical observable; what is measured is $\sigma \times \mathrm{BR}$ (within acceptances), etc.
  $\Rightarrow$ Need to specify a Lagrangian in order to define the meaning of coupling parameters

- The experimental results that have been obtained for the various channels are not model-independent
  Properties of the SM Higgs have been used for discriminating between signal and background
  Need the SM to correct for acceptances and efficiencies

Higgs coupling determination at the LHC

Problem: no absolute measurement of total production cross section (no recoil method like LEP, ILC: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$)

Production $\times$ decay at the LHC yields combinations of Higgs couplings ($\Gamma_{\text{prod, decay}} \sim g^2_{\text{prod, decay}}$):

$$\sigma(H) \times \text{BR}(H \to a + b) \sim \frac{\Gamma_{\text{prod}} \Gamma_{\text{decay}}}{\Gamma_{\text{tot}}},$$

Total Higgs width cannot be determined without further assumptions (see below)

⇒LHC can directly determine only ratios of couplings, e.g. $g^2_{H\tau\tau}/g^2_{HWW}$

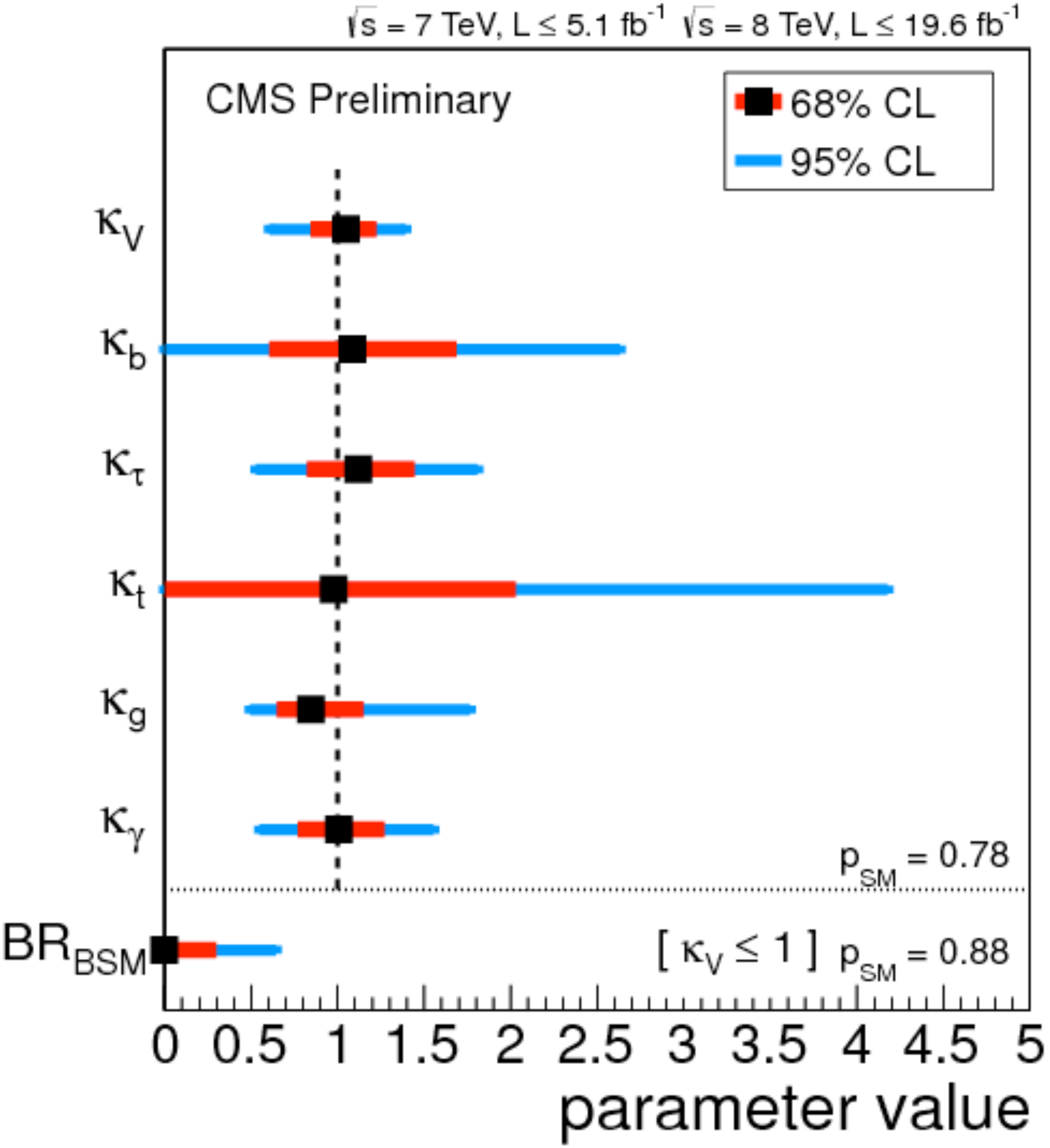
``Interim framework" for analyses so far

- Deviations from the Standard Model will in general affect both the absolute values of the couplings and the tensor structure ⇒ need coherent treatment for determination of couplings and CP properties
- Simplified framework for analysis of LHC data so far; deviations from SM parametrised by ``scale factors" $\varkappa_i$. Assumptions:
- Signal corresponds to only one state, no overlapping resonances, etc.
- Zero-width approximation
- Only modifications of coupling strengths (absolute values of the couplings) are considered

⇒ Assume that the observed state is a CP-even scalar

Determination of coupling scale factors

[CMS Collaboration ’13]



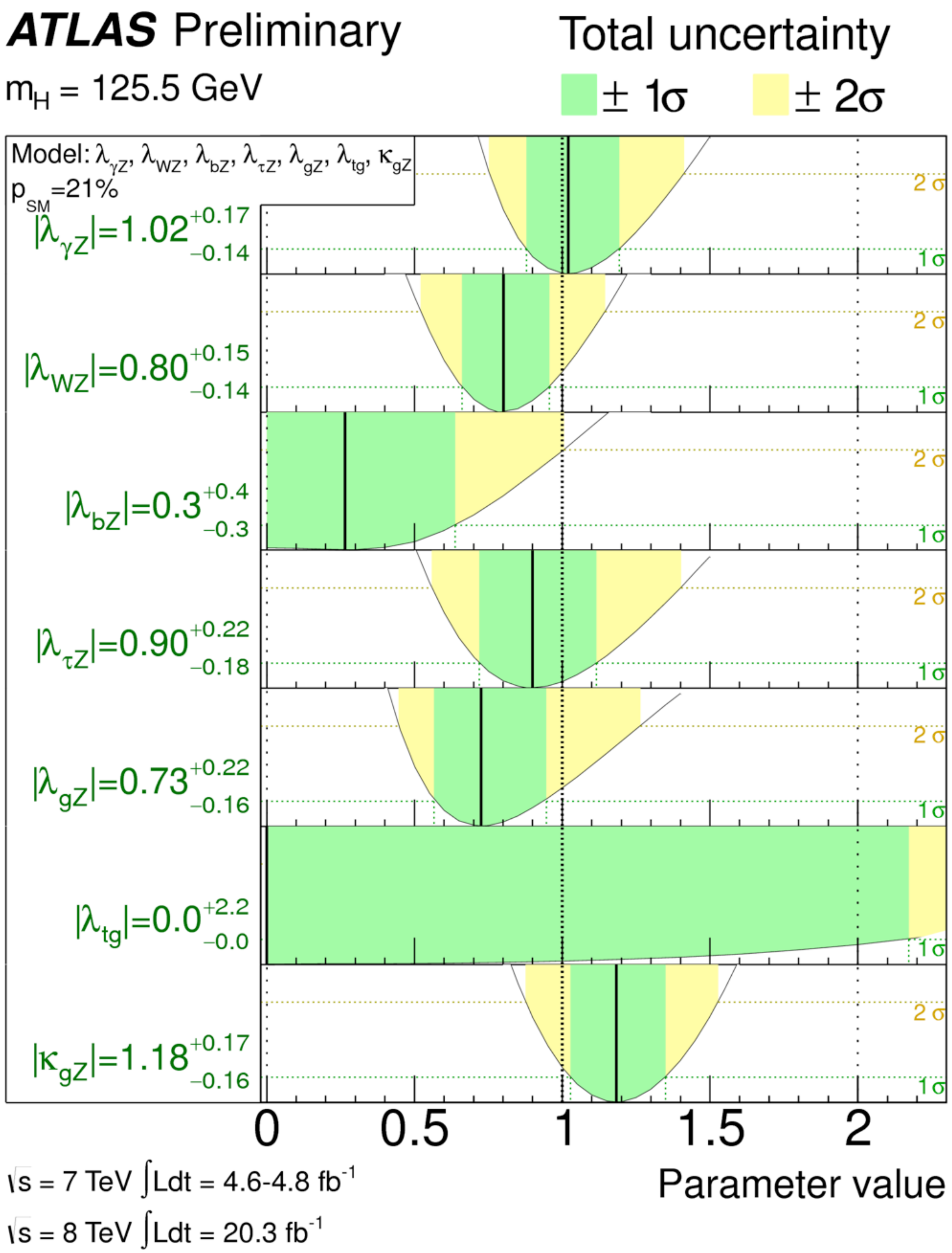
⇒ Compatible with the SM with rather large errors

Assumption $\varkappa_V \leqq 1$allows to set an upper bound on the total width

⇒ Upper limit on branching ratio into BSM particles: $BR_{BSM} \lesssim 0.6$ at 95% C.L.

Determination of coupling scale factors

[ATLAS Collaboration ’14]



⇒ Determination of ratios of coupling scale factors

$$
\begin{aligned}
\lambda_{\gamma Z} &= \kappa_\gamma / \kappa_Z \\
\lambda_{WZ} &= \kappa_W / \kappa_Z \\
\lambda_{bZ} &= \kappa_b / \kappa_Z \\
\lambda_{\tau Z} &= \kappa_\tau / \kappa_Z \\
\lambda_{gZ} &= \kappa_g / \kappa_Z \\
\lambda_{tg} &= \kappa_t / \kappa_g \\
\kappa_{gZ} &= \kappa_g \cdot \kappa_Z / \kappa_H
\end{aligned}
$$

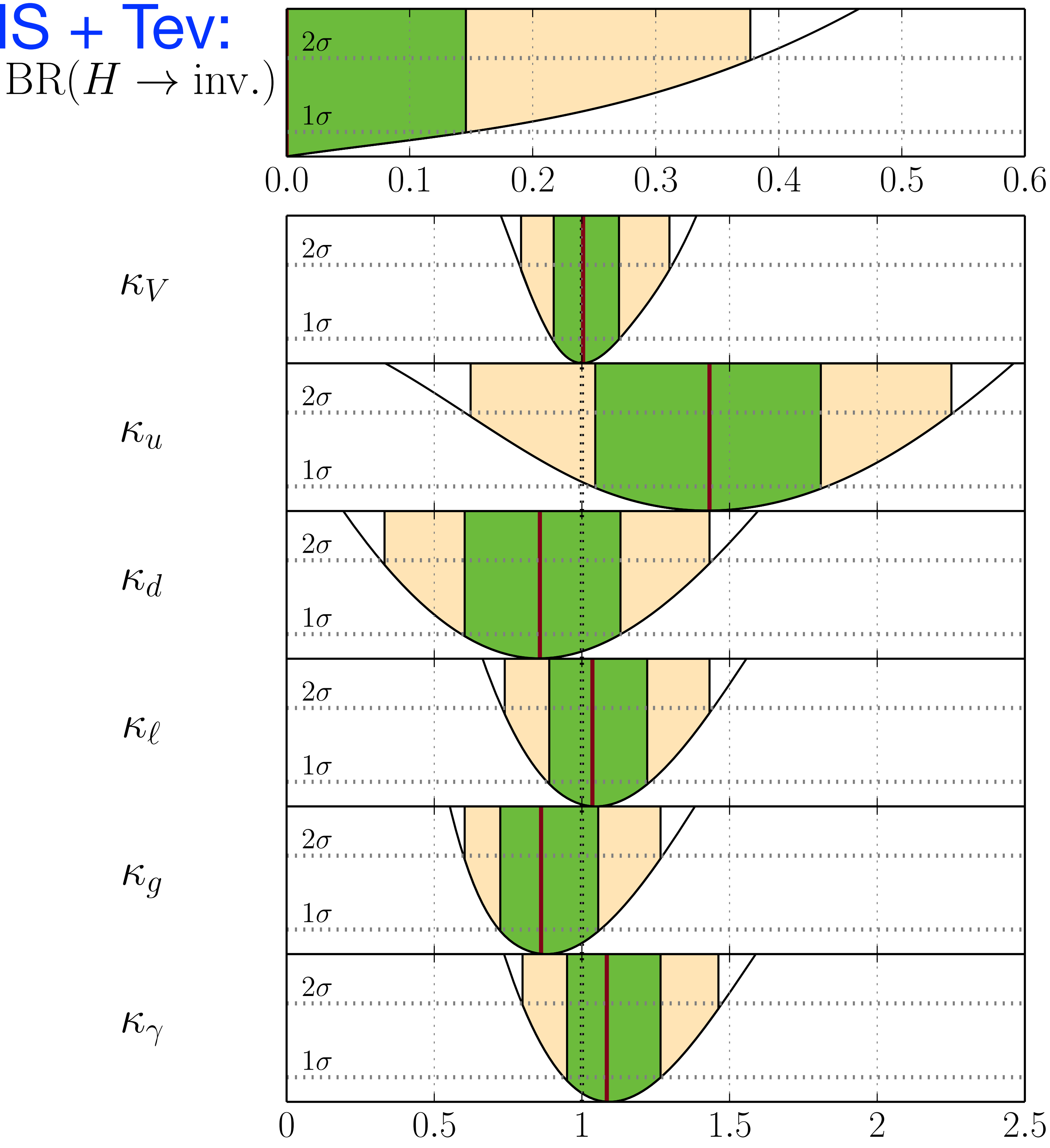
HiggsBounds and *HiggsSignals*

- 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

Future analyses of couplings and CP properties

Effective Lagrangian approach, obtained from integrating out heavy particles

Assumption: new physics appears only at a scale $\Lambda \gg M_\mathrm{h} \sim 126\ \mathrm{GeV}$

Systematic approach: expansion in inverse powers of Λ; parametrises deviations of coupling strenghts and tensor structure

$$\Delta\mathcal{L} = \sum_i \frac{a_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum_j \frac{a_j}{\Lambda^4}\mathcal{O}_j^{d=8} + \ldots$$

How about light BSM particles?

Difficult to incorporate in a generic way, need full structure of particular models

$\Rightarrow$ Analyses in terms of SM + effective Lagrangian and in specific BSM models: MSSM, . . . are complementary

Requirements for a suitable effective Lagrangian

- Needs to be sufficiently general (e.g.: should not assume a CP-even scalar from the start) and at the same time number of parameters needs to be practically feasible

- Predictions obtained within the effective Lagrangian approach need to recover the best Standard Model prediction, including all relevant higher-order corrections (QCD and electroweak), in the SM limit

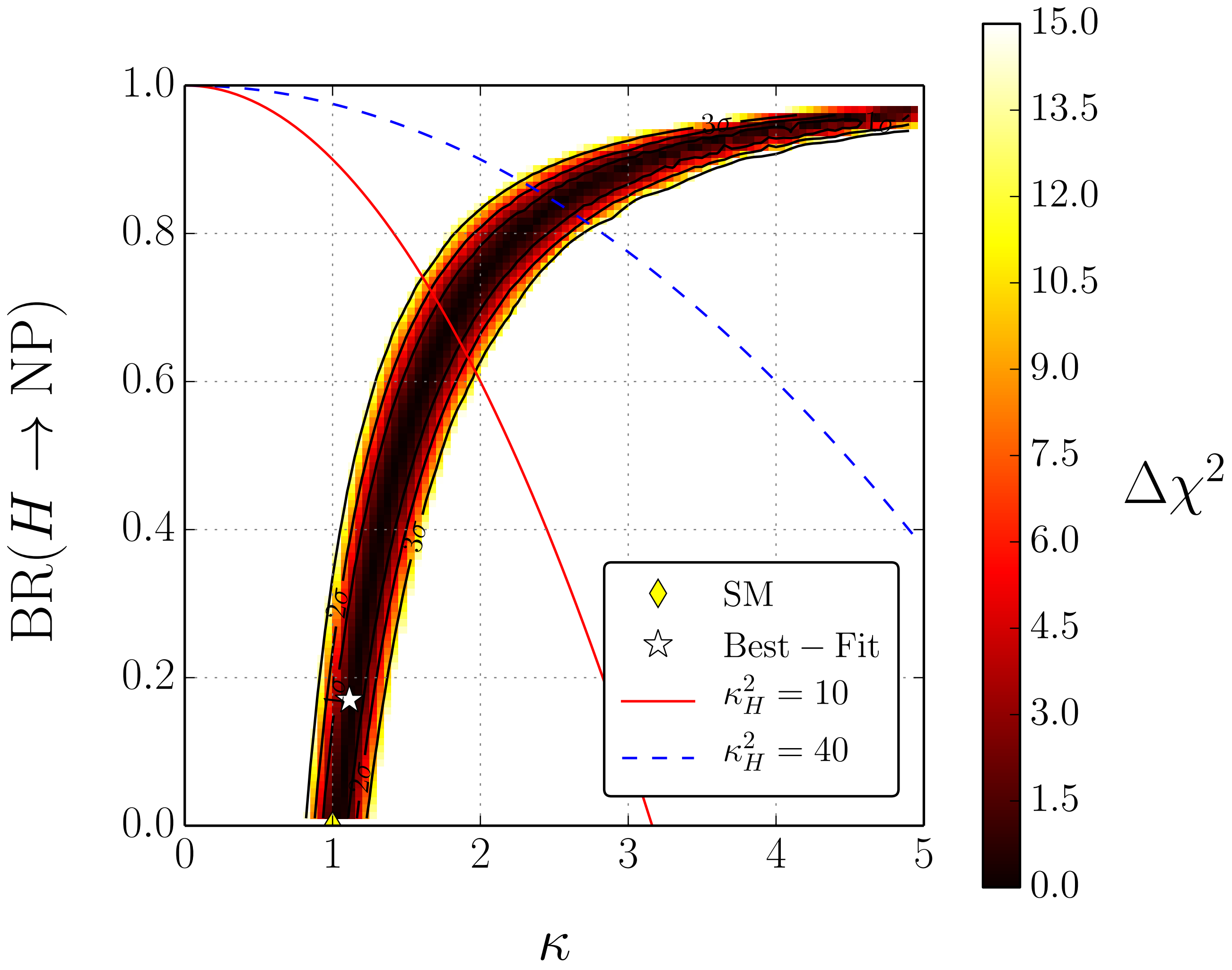
Current bounds from ATLAS + CMS on decays into new physics states

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

Common scale factor ϰ for all Higgs couplings

No assumptions on undetectable / invisible decays

HiggsSignals



⇒
- 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!

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]*

Some implications for SUSY models

"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

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

⇒ Upper bound on lightest Higgs mass, M_{h}:

Lowest order: $M_{\mathrm{h}} \leq M_{\mathrm{Z}}$

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

Interpretation of the signal at 126 GeV within the MSSM?

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 126 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.

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

⇒ Need very high precision for the couplings

What if the signal at 126 GeV corresponds to a state of an extended Higgs sector which is not the lightest one?

Extended Higgs sector where the second-lightest Higgs at $\sim 126\ \mathrm{GeV}$ has SM-like couplings to gauge bosons

$\Rightarrow$ Lightest neutral Higgs with heavily suppressed couplings to gauge bosons, may have mass below the LEP limit of $M_{\mathrm{H_{SM}}} > 114.4\ \mathrm{GeV}$ (in agreement with LEP bounds)

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

Example: "Low M_{H} benchmark scenario" of the MSSM

$\Rightarrow$ Observation of a SM-like signal at $\sim 126\ \mathrm{GeV}$ provides a strong motivation to look for non SM-like Higgses elsewhere

$\Rightarrow$ The best way of experimentally proving that the observed state is not the SM Higgs would be to find in addition (at least one) non-SM like Higgs!

Would such a light Higgs be detectable at the LHC?

- Not in decays of the state at $\sim 126 \text{ GeV}$ if mass of lightest Higgs $\gtrsim 63 \text{ GeV}$

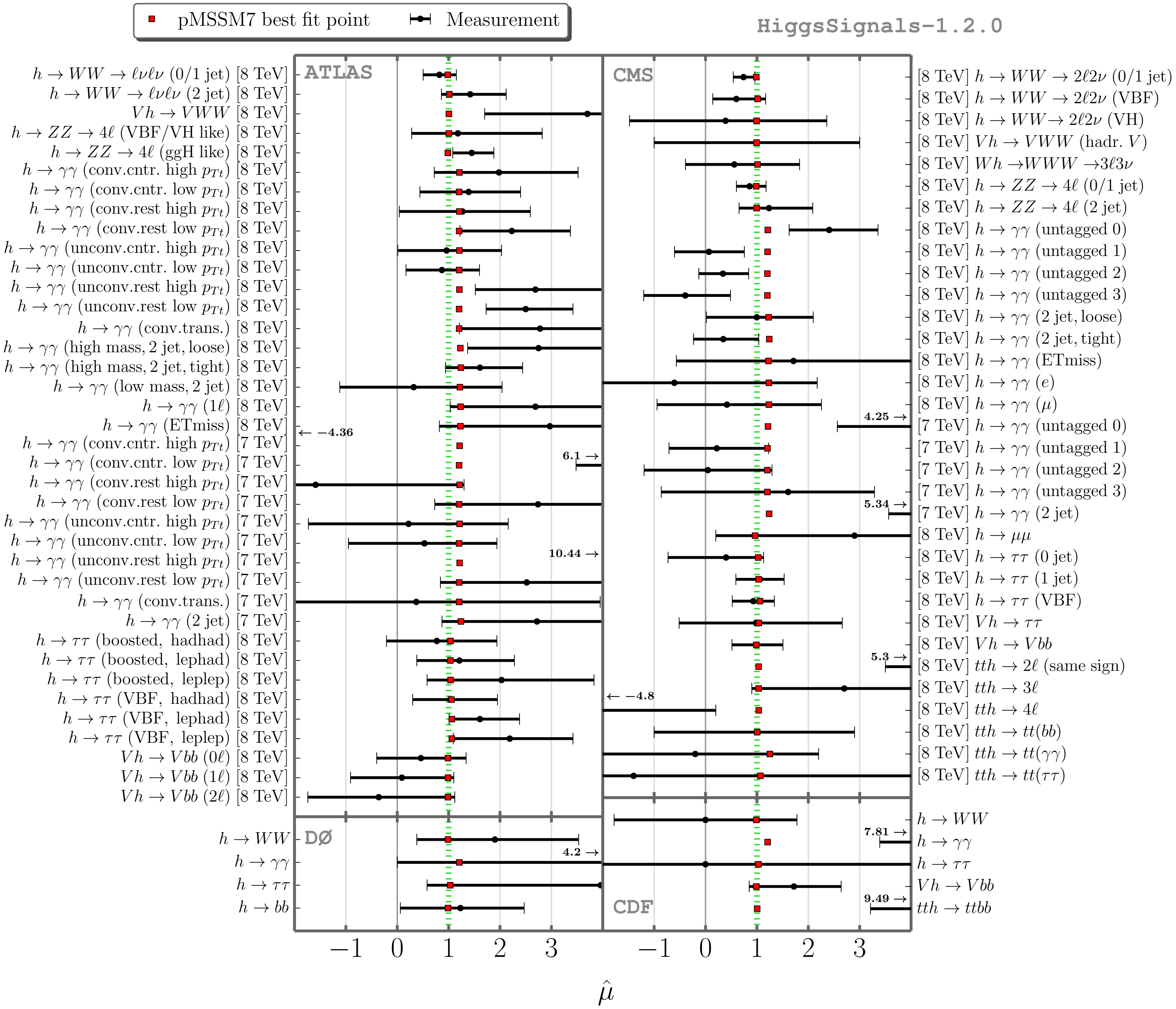
- This possibility has not been explored at the LHC so far; first LHC searches for light Higgses in this mass range are in progress

- In case of SUSY, such a light Higgs could be produced in a SUSY cascade, e.g. $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$; could be similar for other types of BSM physics

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:



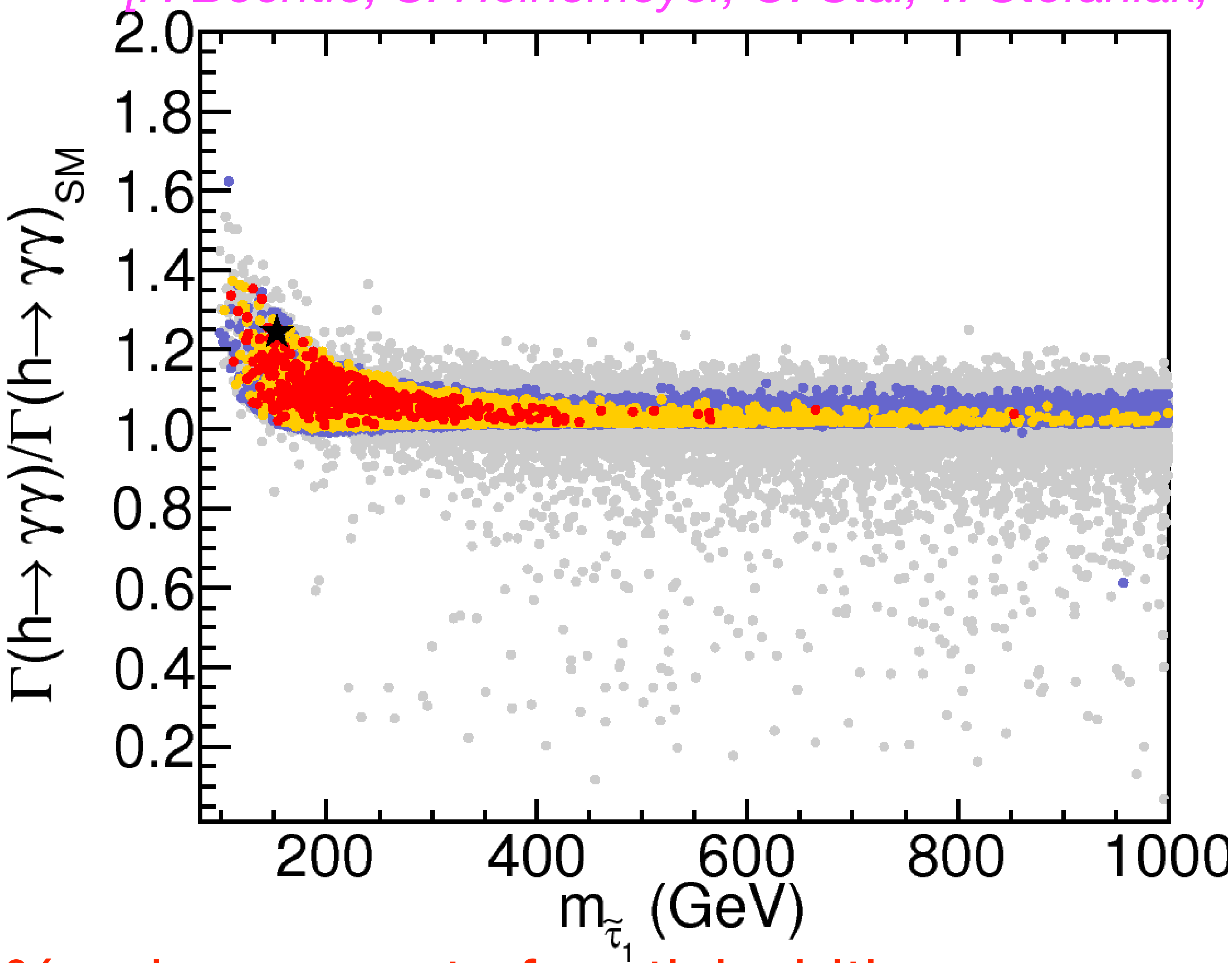
HiggsSignals

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

⇒ 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]



⇒ ≈20% enhancement of partial width

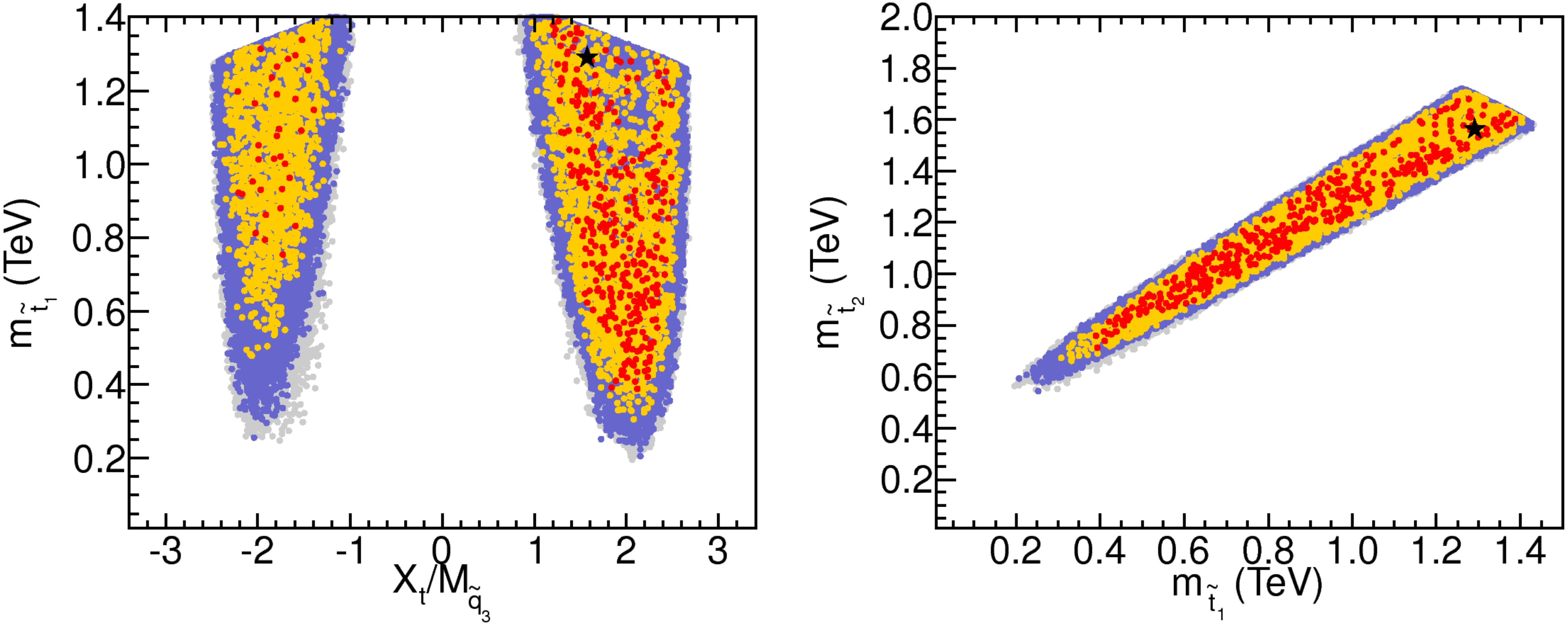
Fit assumes slepton mass universality: $M_{\tilde{E}_{1,2}} = M_{\tilde{L}_{1,2}} = M_{\tilde{l}_3}$

⇔ 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]



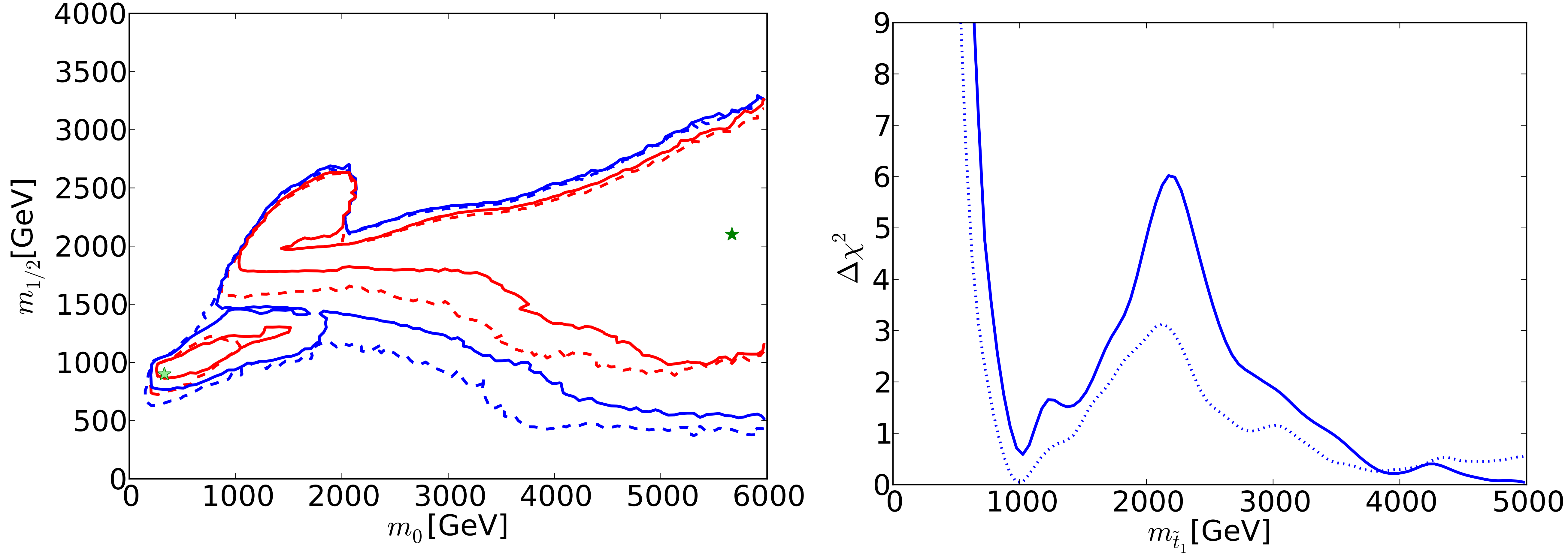
⇒ Large stop mixing required
Best fit prefers heavy stops beyond 1 TeV
But good fit also for light stop down to ≈300 GeV

Global fit in constrained Model: CMSSM
Signal at 126 GeV interpreted as light Higgs h

MasterCode

[O. Buchmueller et al ’14]

Result based on Run 1 data (solid) and on 7 TeV data only (dashed)



⇒ Preferred region extends to very large scalar masses

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:

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

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

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

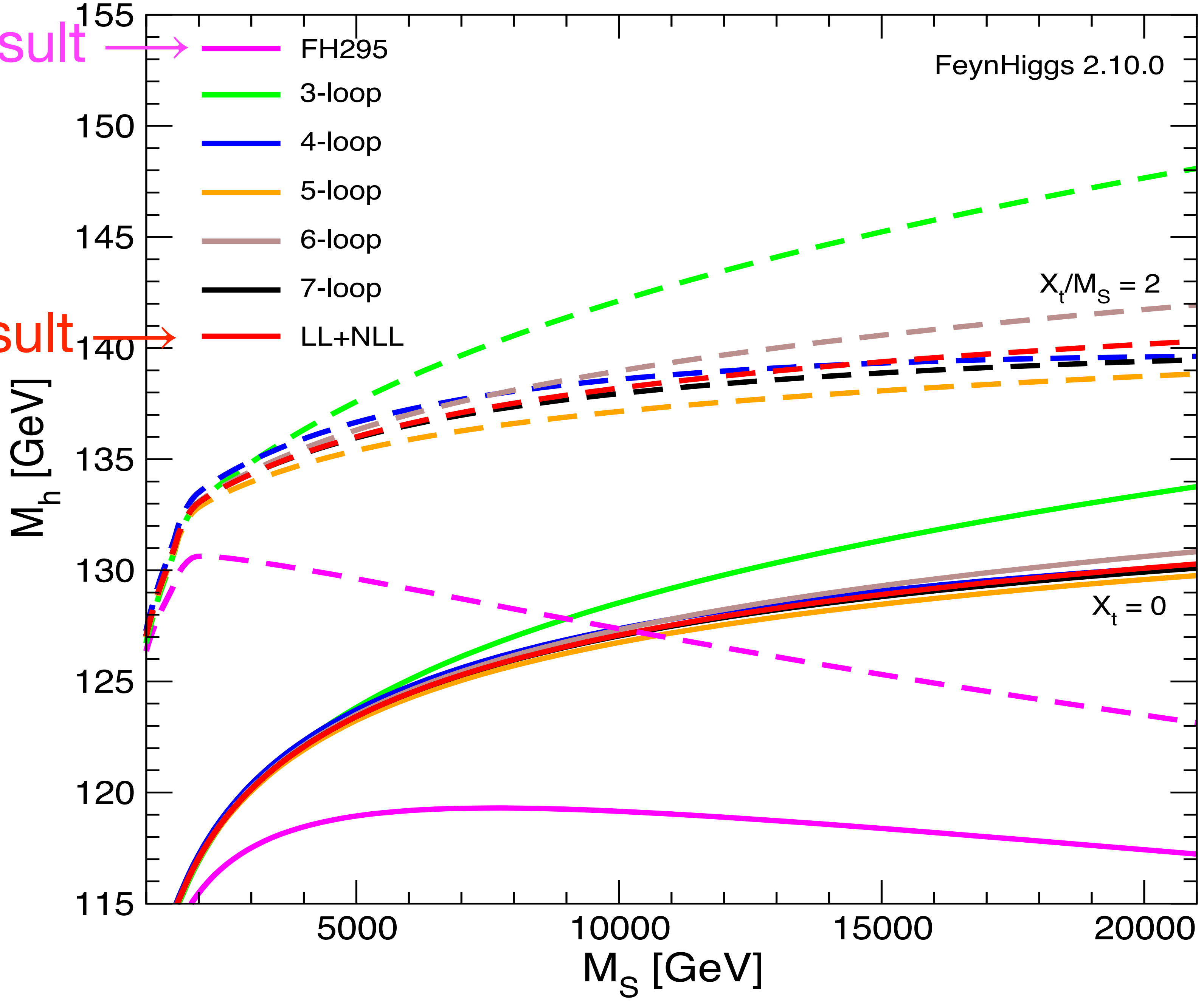
- Results are implemented in the public code *FeynHiggs*
  [T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. W. '14]

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

Conclusions

⇒ Higgs physics may be the key to revealing the physics behind the Standard Model

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MSSM: Improved prediction for the light Higgs mass in the region of heavy stop masses, combination of Feynman-diagrammatic result with all-order resummation of leading and next-to-leading logarithmic effects

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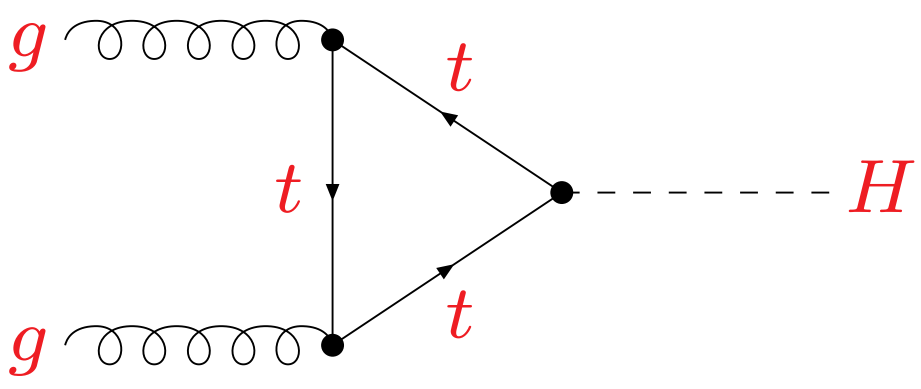
Backup

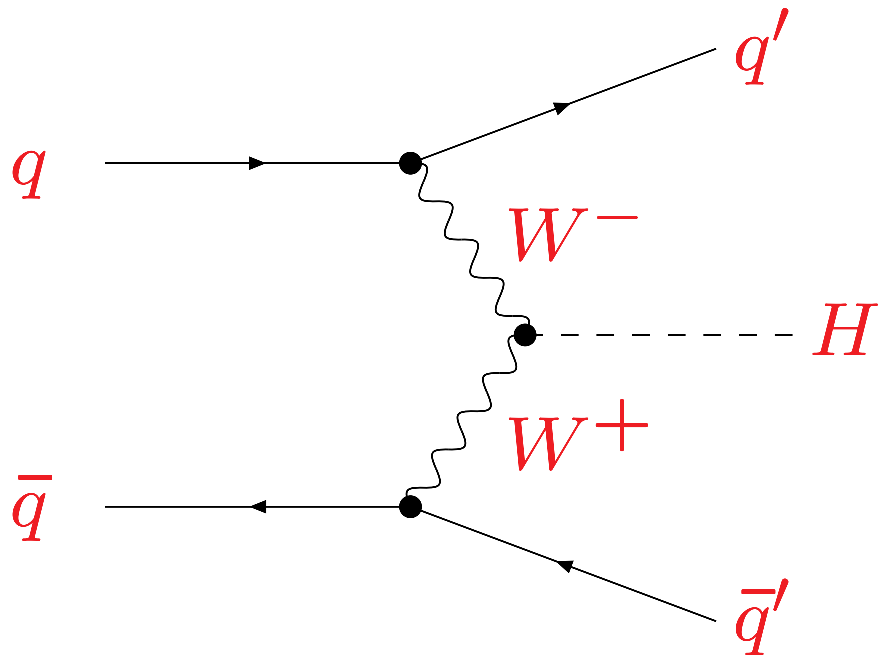
What has been discovered?

Search channels at the LHC:

Dominant production processes for a SM-like Higgs at the LHC:

gluon fusion: $gg \to H$, weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}'H$





Most important decay channels

Good mass resolution:

- $H \to \gamma\gamma$ (loop induced)
- $H \to ZZ^* \to l^+l^-l^+l^-$, $l = e, \mu$

Poor mass resolution:

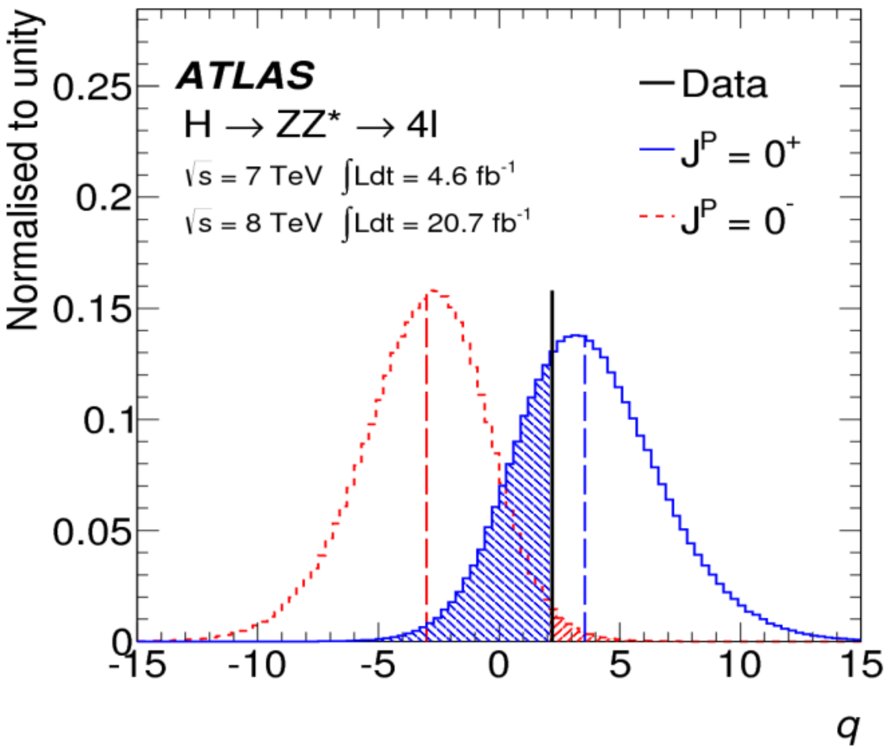
- $H \to WW^* \to \bar{\nu}l^-\nu l^+$, $l = e, \mu$
- $H \to \tau^+\tau^-$
- $H \to b\bar{b}$

Test of spin and CP hypotheses

[ATLAS Collaboration ’13]

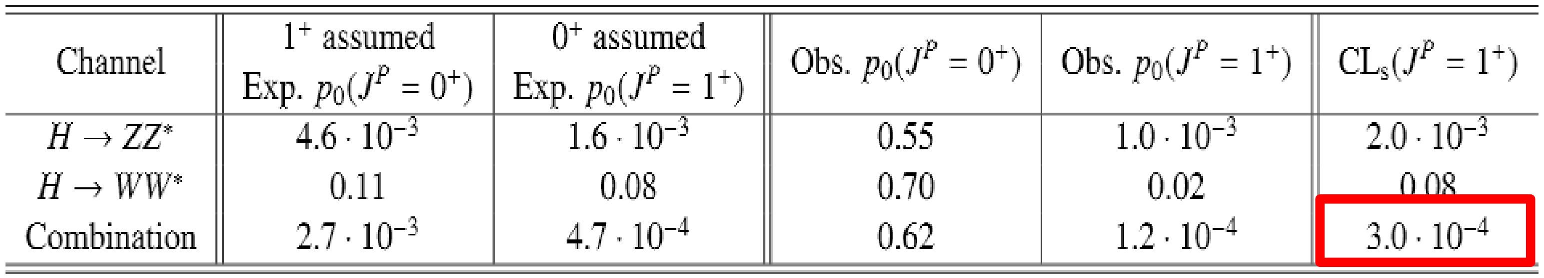
The SM 0^+ has been tested against different J^P hypotheses using the three ATLAS discovery channels

0^+ against 0^-



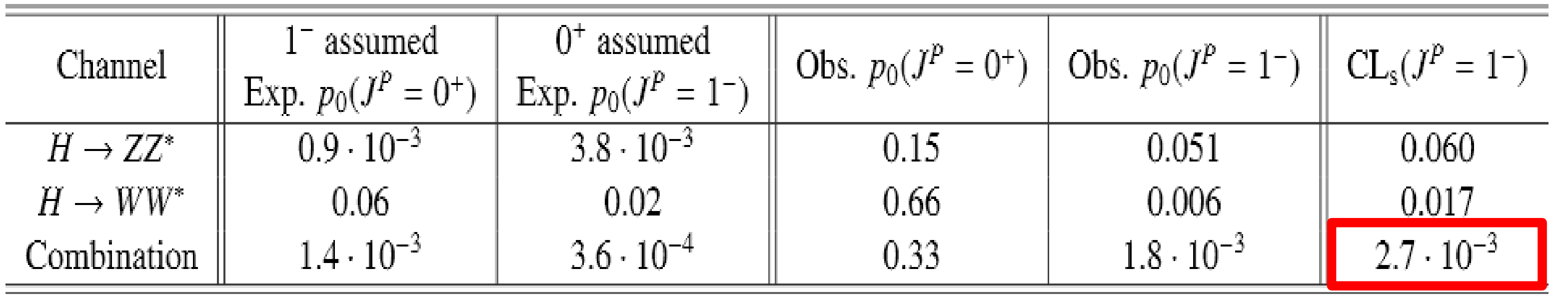
0^+ against $1^{+/-}$

Combined H→ZZ and H→WW analysis excludes those hypotheses up to 99.7%



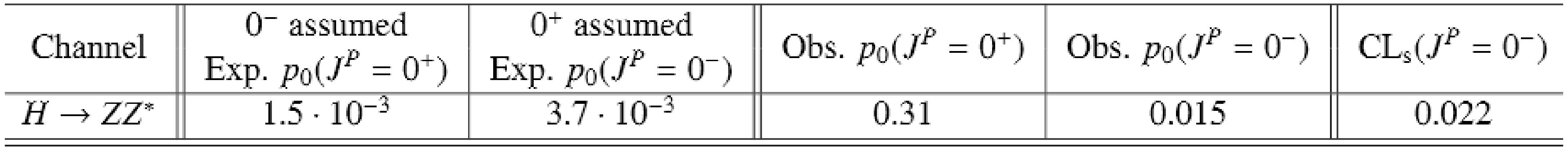
Channel	1^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^+)$	$\mathrm{CL_s}(J^P = 1^+)$
$H \to ZZ^*$	$4.6 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	0.55	$1.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$
$H \to WW^*$	0.11	0.08	0.70	0.02	0.08
Combination	$2.7 \cdot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

- **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	$1.8 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$

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

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

Test of spin and CP hypotheses

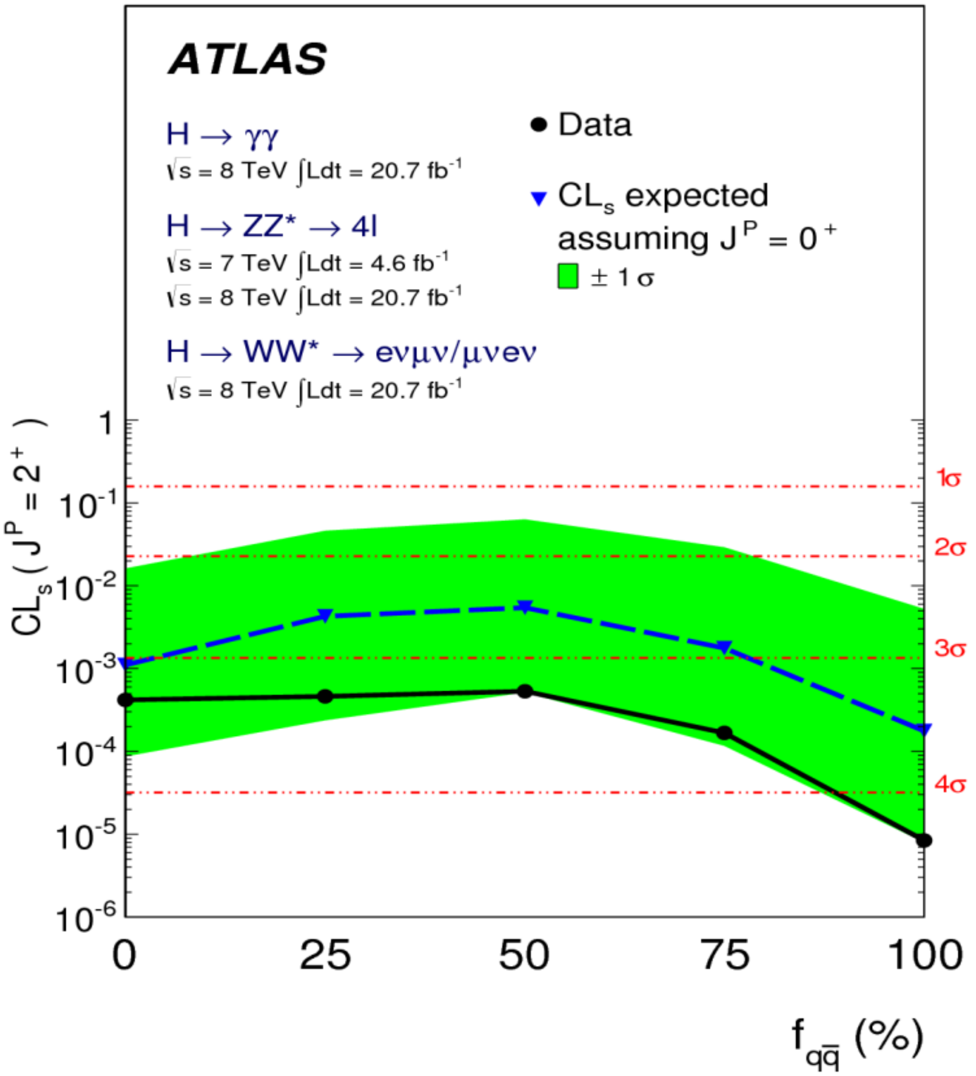
[ATLAS Collaboration '13]

0^+ against 2^+

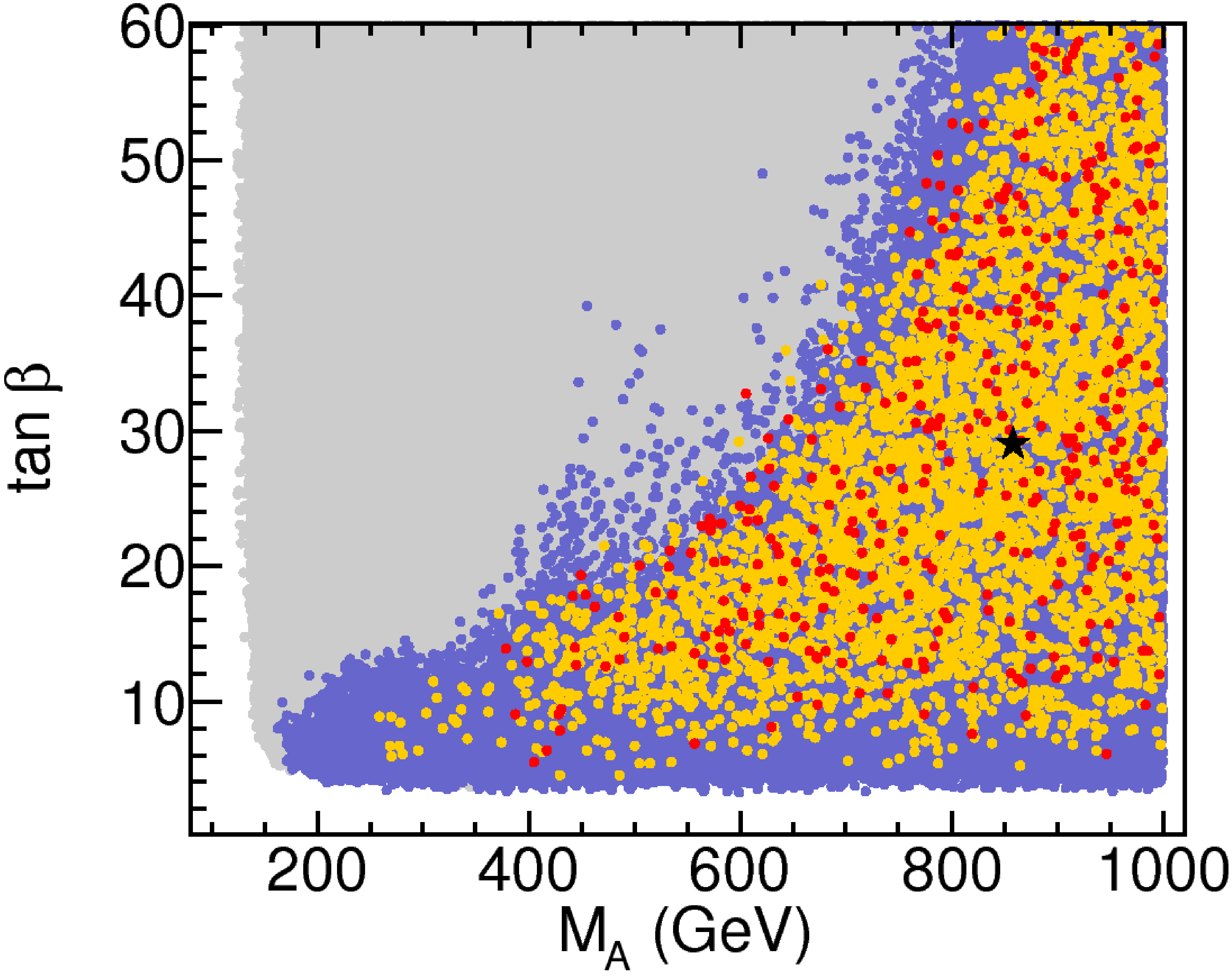
- ➢ All three analysis have excluded the 2^+ model with different qq fractions in favour of SM 0^+.

- ➢ 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. $p_0(J^P = 2^+)$	$\mathrm{CL_s}(J^P = 2^+)$
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	$1.5 \cdot 10^{-4}$	$4.2 \cdot 10^{-4}$



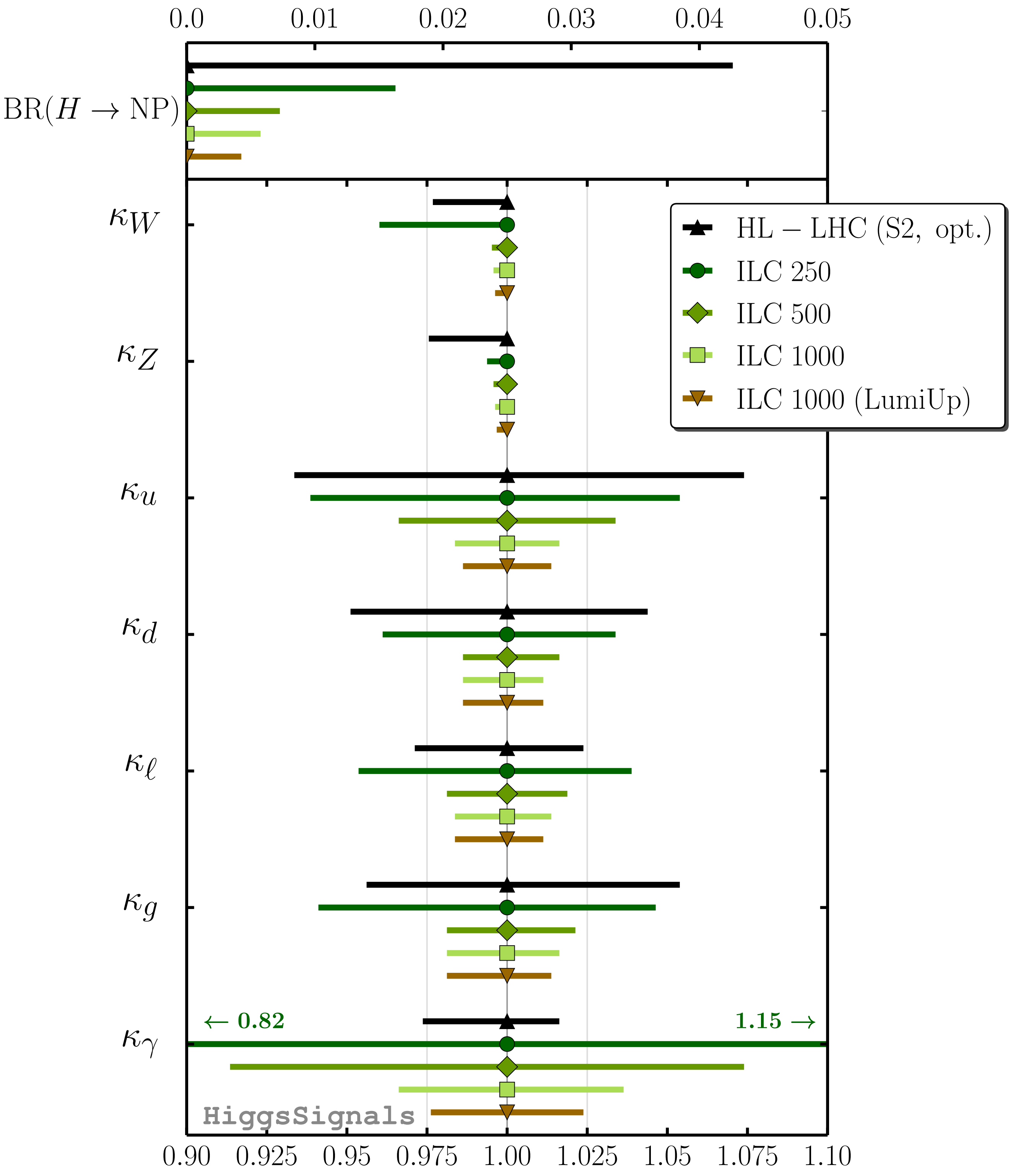
MSSM fit: preferred region for M_A and tanβ



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

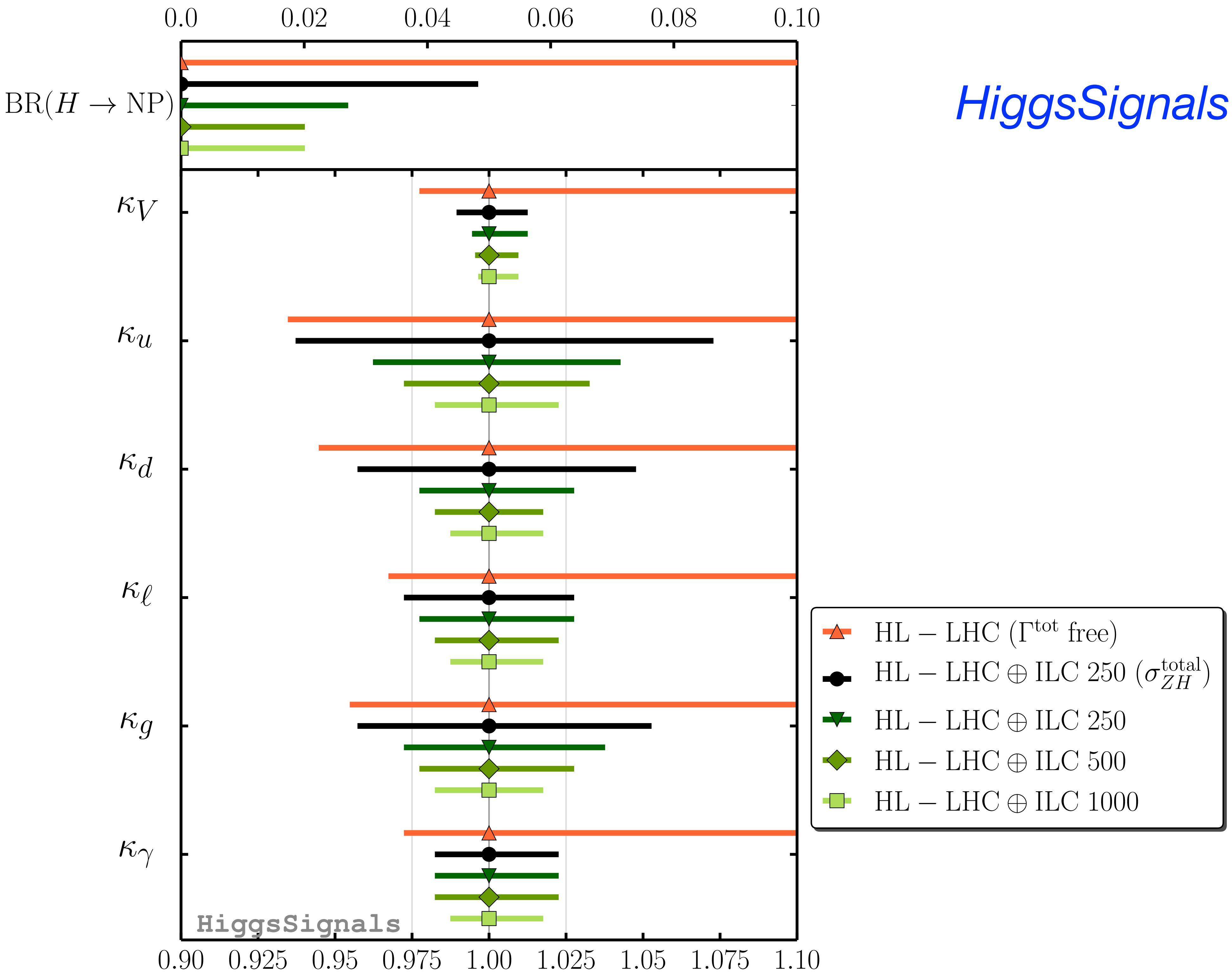
Assumed:

$\kappa_V \leq 1$



HiggsSignals

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



HiggsSignals

Couplings to gauge bosons and fermions

[Higgs Working Group Report, Snowmass process 2013]

Model-independent (not possible at the LHC):

Facility	ILC			ILC(LumiUp)
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	$1150{+}1600{+}2500^{\ddagger}$
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)
Γ_H	12%	5.0%	4.6%	2.5%
κ_γ	18%	8.4%	4.0%	2.4%
κ_g	6.4%	2.3%	1.6%	0.9%
κ_W	4.9%	1.2%	1.2%	0.6%
κ_Z	1.3%	1.0%	1.0%	0.5%
κ_μ	91%	91%	16%	10%
κ_τ	5.8%	2.4%	1.8%	1.0%
κ_c	6.8%	2.8%	1.8%	1.1%
κ_b	5.3%	1.7%	1.3%	0.8%
κ_t	–	14%	3.2%	2.0%
BR_{inv}	0.9%	$< 0.9\%$	$< 0.9\%$	0.4%

Couplings to gauge bosons and fermions

[Higgs Working Group Report, Snowmass process 2013]

Model-dependent, no non-SM production or decay modes assumed:

Facility	LHC	HL-LHC	ILC500	ILC500-up
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500
$\int \mathcal{L} dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%

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

For “non-standard” Higgs states:

$\Rightarrow$ Cannot use weak-boson fusion channels for production

$\Rightarrow$ Possible production channels: $gg \to H$, $b\bar{b}H$, . . .

Cannot use LHC “gold plated” decay mode $H \to ZZ \to 4\mu$

$\Rightarrow$ Search for heavy Higgs bosons $H, A, H^{\pm}$ is very different from the SM case