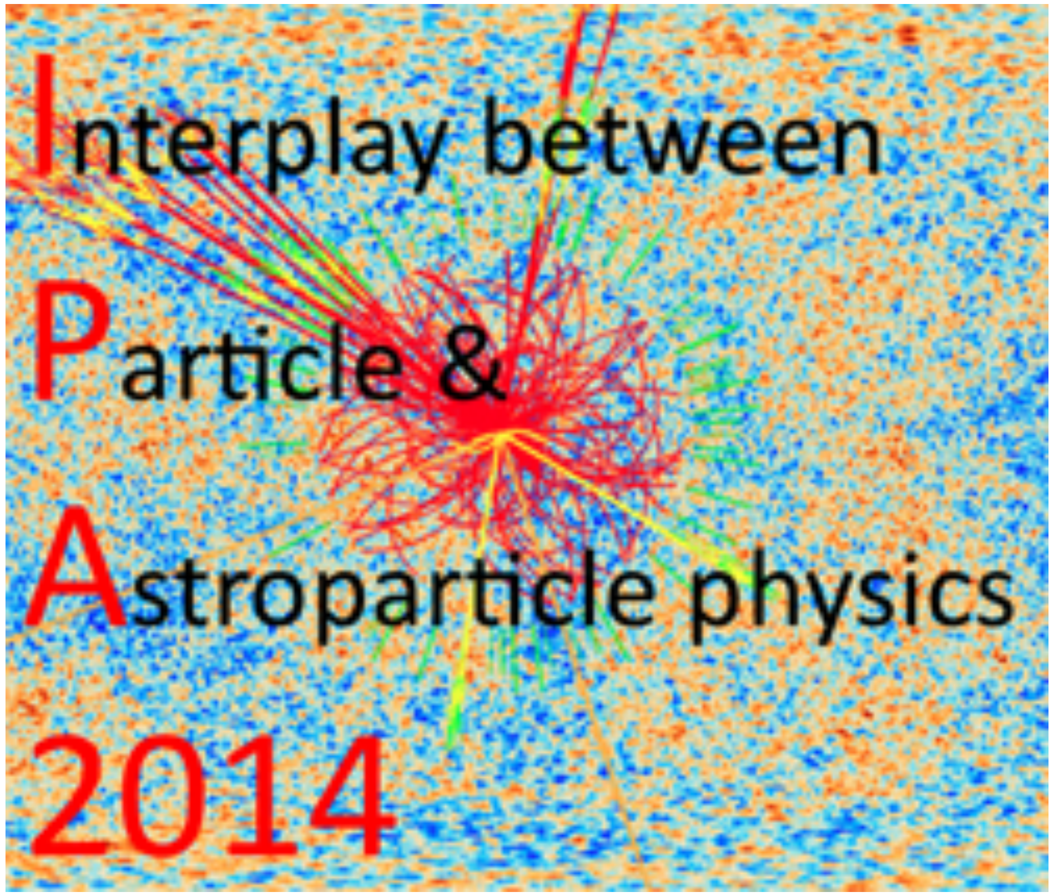


Higgs properties and prospects for CP-violation searches

Georg Weiglein, DESY

IPA 2014, QMU London,
08 / 2014

Exploring the Terascale: open questions

- How do elementary particles obtain the property of mass: what is the mechanism of electroweak symmetry breaking? What is the role of the discovered particle at ~ 126 GeV in this context?
- Do all the forces of nature arise from a single fundamental interaction?
- Are there more than three dimensions of space?
- Are space and time embedded into a "superspace"?
- What is dark matter? Can it be produced in the laboratory?
- Are there new sources of $\mathcal{CP}$-violation?
  Can they explain the asymmetry between matter and anti-matter in the Universe?

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?

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

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 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

Hypothesis of a pure CP-odd state is experimentally disfavoured

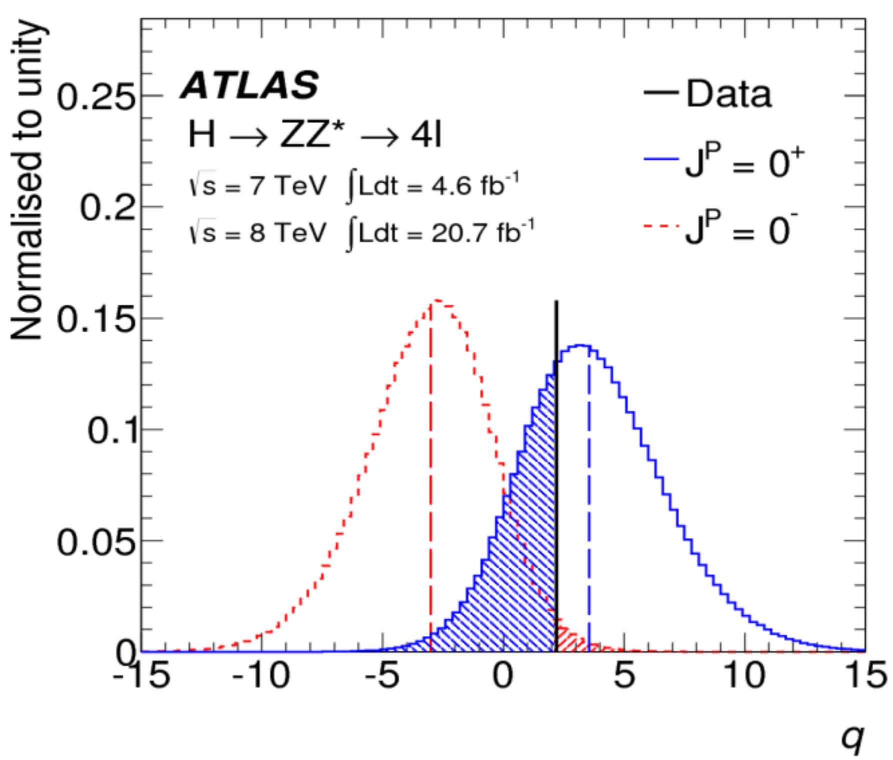
However, there are only very weak bounds so far on an admixture of CP-even and CP-odd components

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%**

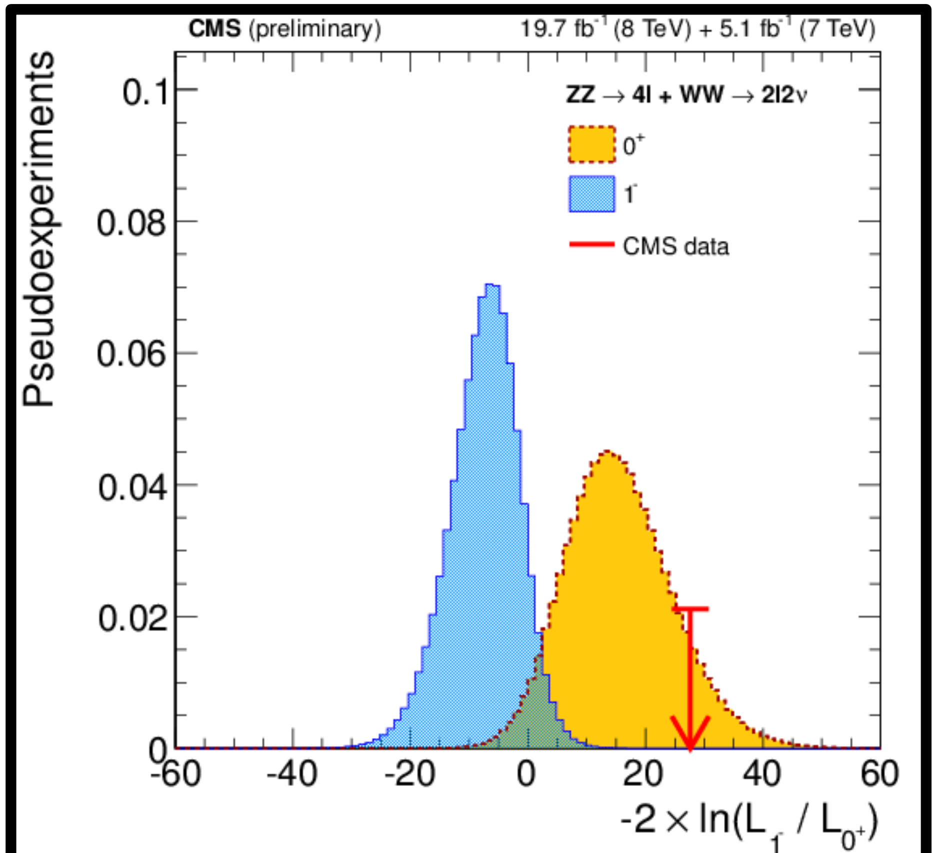
Channel	0^- assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 0^-)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 0^-)$	$CL_s(J^P = 0^-)$
$H \to ZZ^*$	$1.5 \cdot 10^{-3}$	$3.7 \cdot 10^{-3}$	0.31	0.015	0.022

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

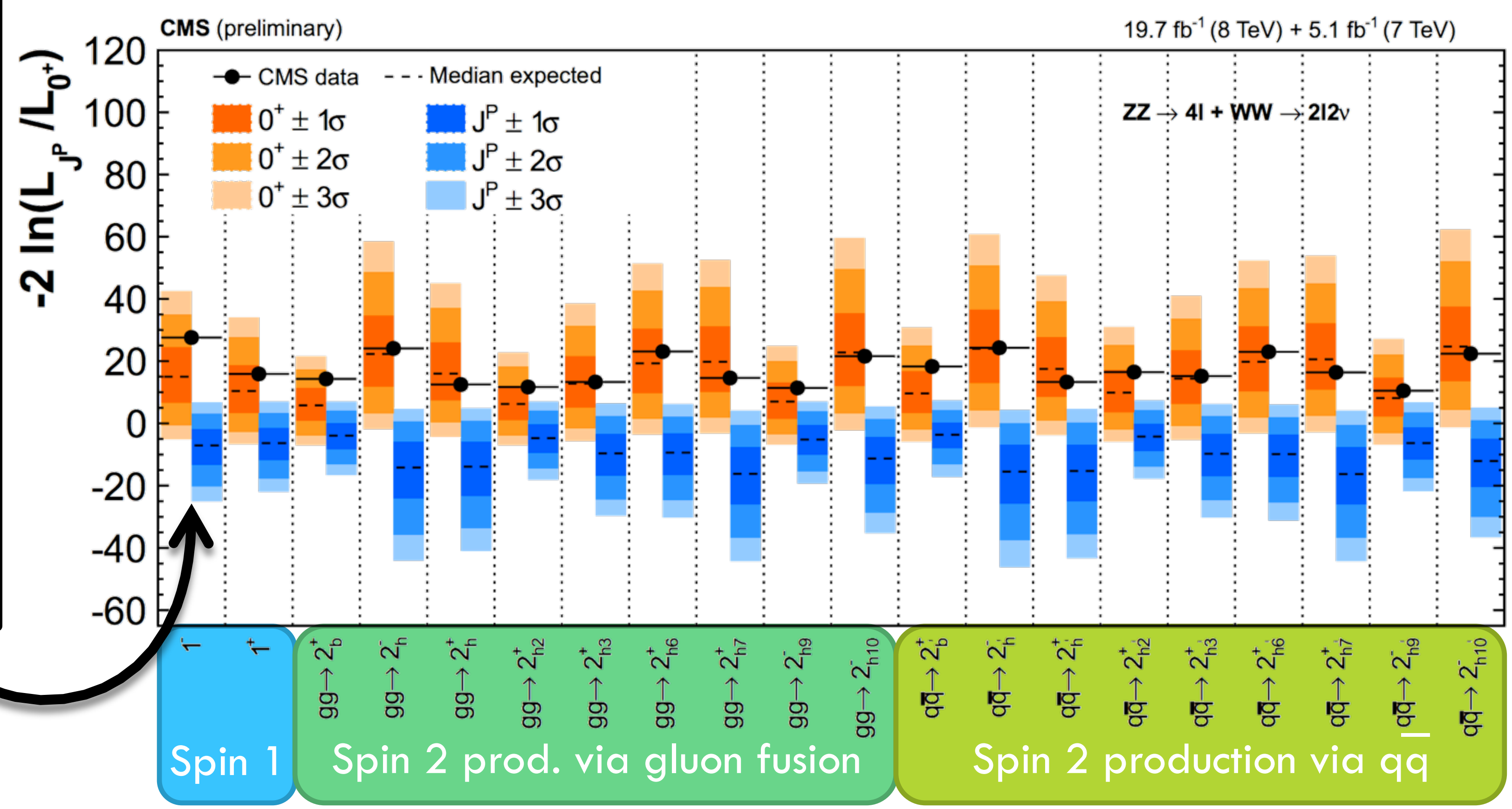
Test of spin and CP hypotheses

[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^-



CP properties

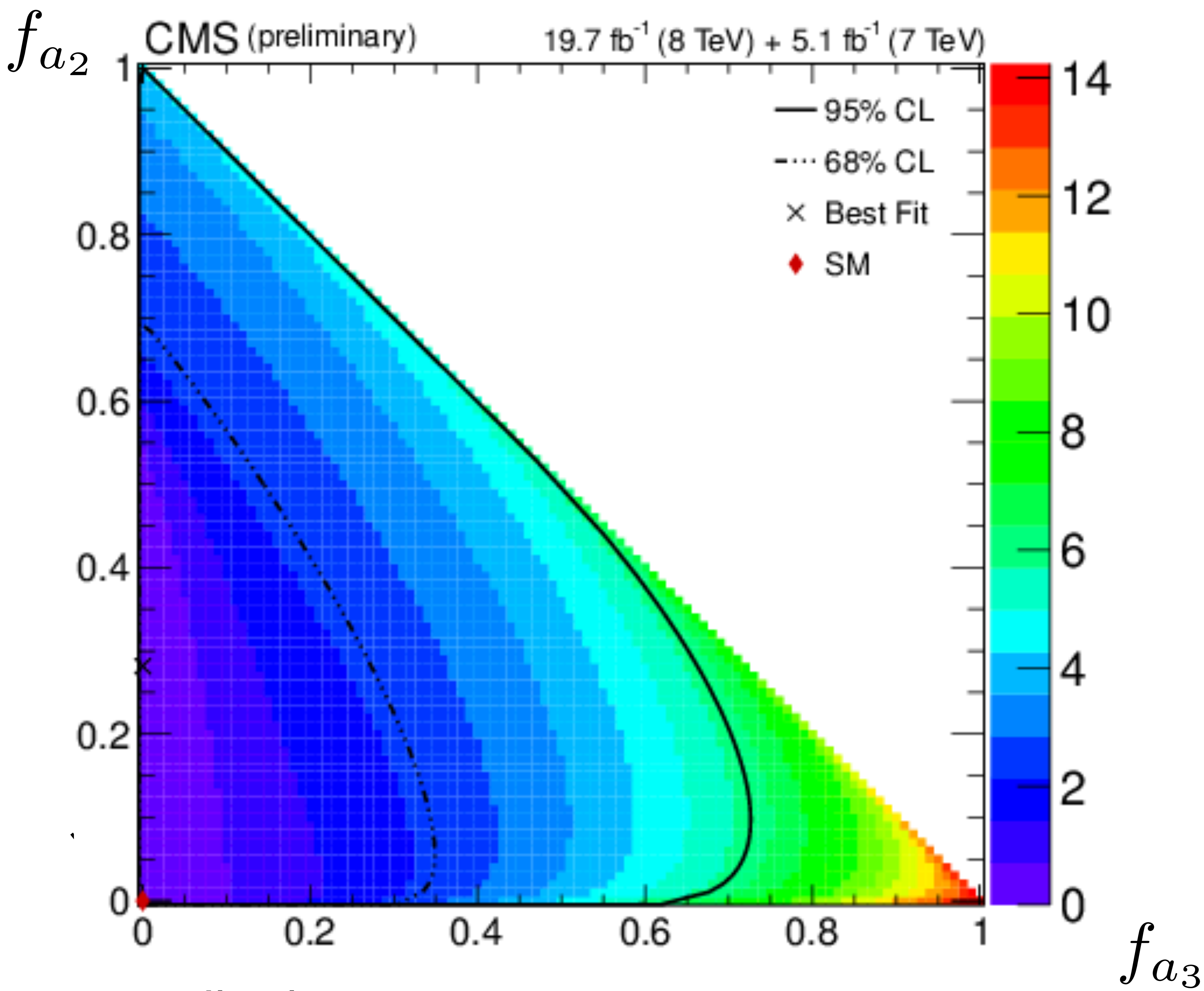
Strong suppression of CP-odd coupling in *HVV:*

⇒ 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

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

[CMS Collaboration '14]



Write $H \to VV^*$ amplitude as $A = A_1 + A_2 + A_3$,
where A_3 is the $\mathcal{CP}$-odd part

$$f_{a3} \equiv \frac{|A_3|^2}{|A_1|^2 + |A_3|^2}$$

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

$\Rightarrow$ Derive limits on

$$f_{a3} \equiv \frac{|A_3|^2}{|A_1|^2 + |A_3|^2}$$

Note: f_{a3} is not the $\mathcal{CP}$-odd admixture of the signal!

Since HVV coupling "projects" to the $\mathcal{CP}$-even component:

$|A_3| \ll |A_1|, A_2|$ (i.e., $f_{a3} \ll 1$) does not necessarily imply that the $\mathcal{CP}$-odd admixture is small!

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 ($\Gamma_{\mathrm{prod,\,decay}} \sim g^2_{\mathrm{prod,\,decay}}$):

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

Total Higgs width cannot be determined without further assumptions

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

Determination of couplings and CP properties need to be addressed together

Deviations from the SM: in general both the absolute value of the couplings and the tensor structure of the couplings (affects $\mathcal{CP}$ properties) will change

$\Rightarrow$ Determination of couplings and determination of $\mathcal{CP}$ properties can in general not be treated separately from each other

Deviations from the SM would in general change kinematic distributions

$\Rightarrow$ No simple rescaling of MC predictions possible

$\Rightarrow$ Not feasible for analysis of 2012 data set

$\Rightarrow$ LHC Higgs XS WG: Proposal of “interim framework”

``Interim framework" for analyses so far

Simplified framework for analysis of LHC data so far; deviations from SM parametrised by ``scale factors" $\varkappa_i$.

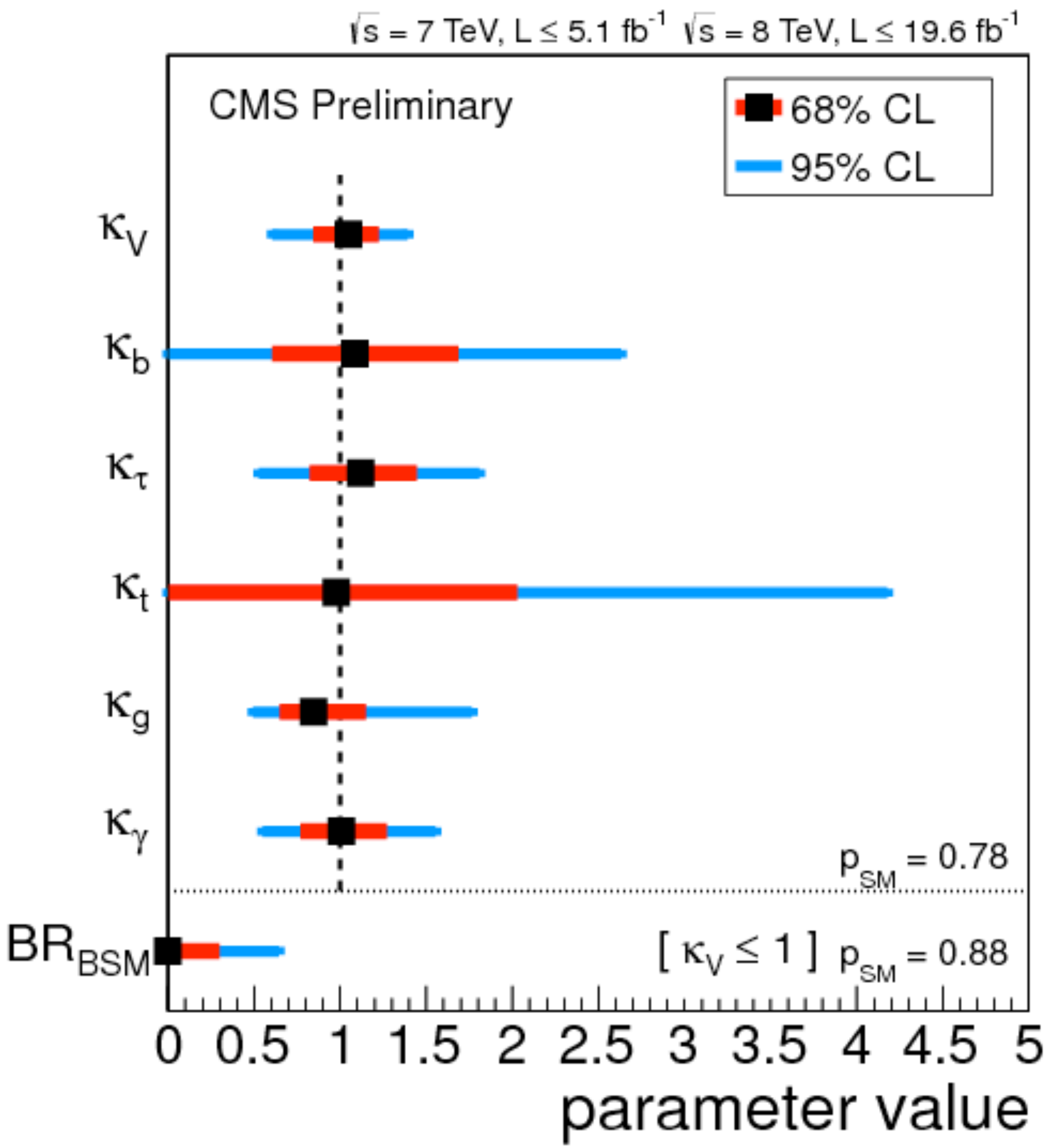
Assumptions:

- 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]



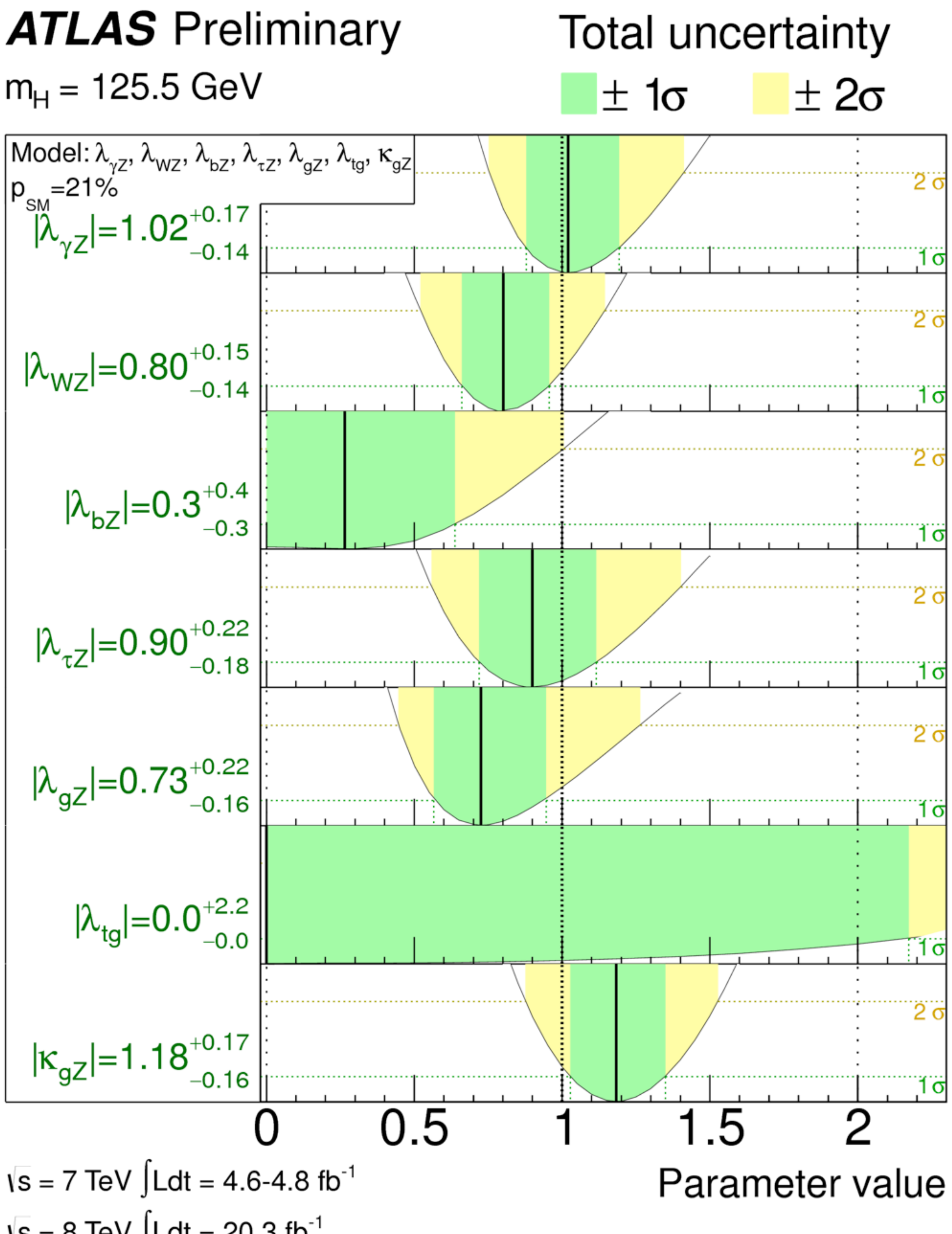
⇒ Compatible with the SM with rather large errors

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]

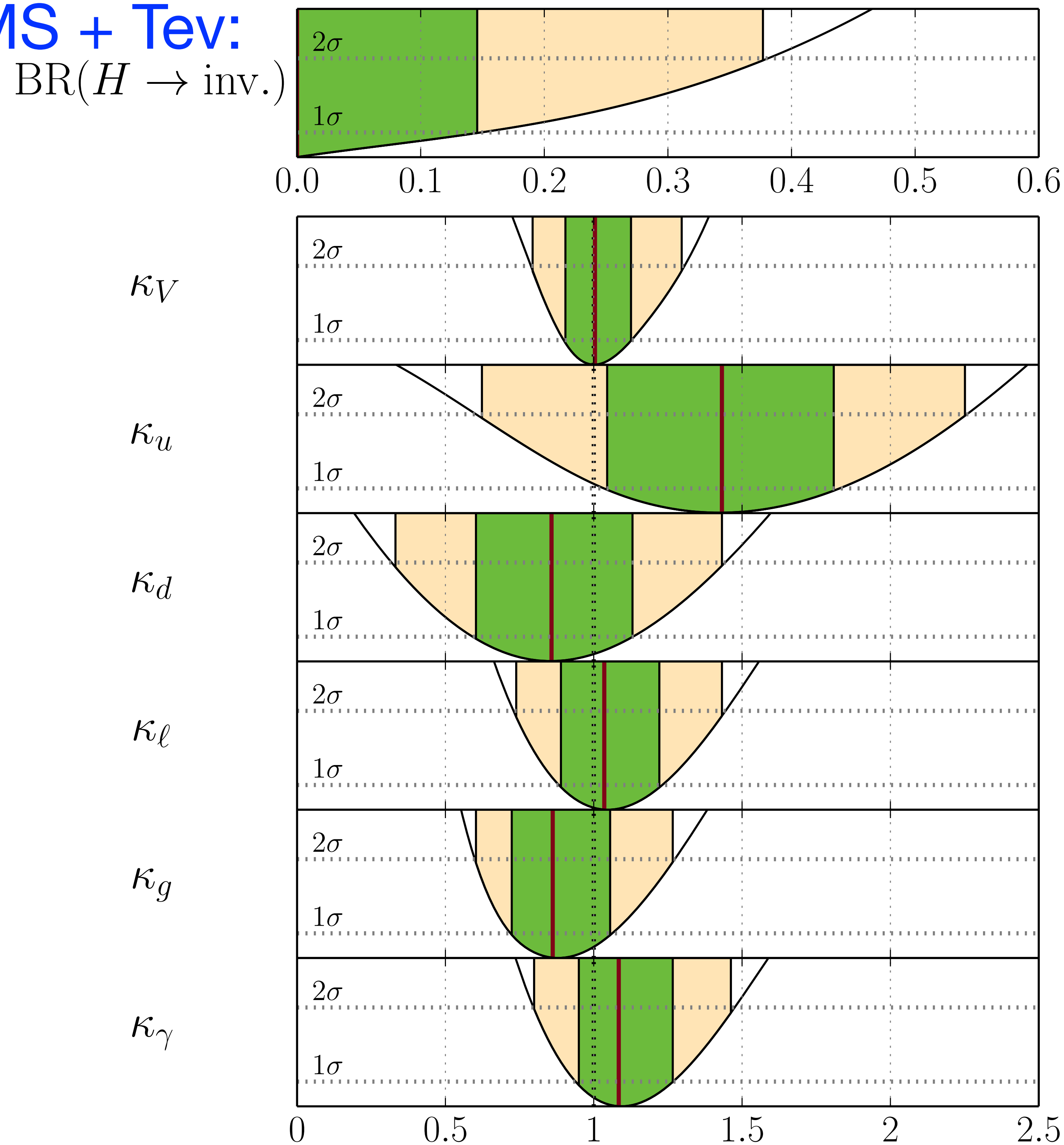


⇒ Determination of ratios of coupling scale factors

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

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]

$\Rightarrow$ 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 $\Lambda \gg M_{\mathrm{h}} \sim 126 \text{ GeV}$

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

Present status, with a broad brush

The properties of the signal are so far compatible with the predictions for the Higgs boson of the SM, but many other interpretations are possible, corresponding to very different underlying physics

⇒ Need to discriminate between the different possible options in order to identify the nature of electroweak symmetry breaking!

Phenomenology of CP-violation in the Higgs sector: SUSY as an example

"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 125 GeV within the MSSM?

Higgs potential of the MSSM

MSSM Higgs potential contains two Higgs doublets:

$$V_H = m_1^2 H_{1i}^* H_{1i} + m_2^2 H_{2i}^* H_{2i} - \epsilon^{ij}(m_{12}^2 H_{1i} H_{2j} + m_{12}^{2\,*} H_{1i}^* H_{2j}^*)$$

$$+ \frac{1}{8}(g_1^2 + g_2^2)(H_{1i}^* H_{1i} - H_{2i}^* H_{2i})^2 + \frac{1}{2} g_2^2 |H_{1i}^* H_{2i}|^2$$

$$\begin{pmatrix} H_{11} \\ H_{12} \end{pmatrix} = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 - i\chi_1) \\ -\phi_1^- \end{pmatrix}$$

$$\begin{pmatrix} H_{21} \\ H_{22} \end{pmatrix} = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + i\chi_2) \end{pmatrix}$$

Complex phases $\arg(m_{12}^2)$, ξ can be rotated away

$\Rightarrow$ Higgs sector is $\mathcal{CP}$-conserving at tree level

Higher-order corrections in the MSSM Higgs sector

- Quartic couplings in the Higgs sector are given by the gauge couplings, g_1, g_2 (SM: free parameter)

  $\Leftrightarrow$ Upper bound on the lightest Higgs mass

- Large higher-order corrections from Yukawa sector:

Yukawa couplings: $\frac{e\, m_t}{2 M_W s_W}, \frac{e\, m_t^2}{M_W s_W}, \ldots$

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

$\Rightarrow$ Higher-order corrections are phenomenologically very important (constraints on parameter space from Higgs sector observables)
Can induce CP-violating effects

MSSM interpretation of the observed signal, 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

MSSM interpretation of the observed signal, 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.

Higgs physics in the MSSM with complex parameters

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

Complex parameters enter via (often large) loop corrections:

– μ: Higgsino mass parameter

– $A_{t,b,\tau}$: trilinear couplings

– $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)

– M_3: gluino mass $m_{\tilde{g}}$ + complex phase

$\Rightarrow$ $\mathcal{CP}$-violating mixing between neutral Higgs bosons h_1, h_2, h_3

Lowest-order Higgs sector has two free parameters

$\Rightarrow$ choose $\tan\beta \equiv \frac{v_2}{v_1}$, $M_{\mathrm{H}^\pm}$ as input parameters

Experimental constraints on phases that are important for Higgs phenomenology

- Most important for Higgs phenomenology: $\varphi_{A_\mathrm{t}}, \varphi_{A_\mathrm{b}}, \varphi_{M_3}$

- EDM constraints affect mainly the phases of the first and second generation sfermions (depending on their mass scale) and φ_μ

- Constraints on $\varphi_{A_\mathrm{t}}, \varphi_{A_\mathrm{b}}, \varphi_{M_3}$ are generally weaker, depend on the mass scale, $\tan\beta$ + theoretical uncertainties of the EDM predictions

CP-violating MSSM: complex parameters + unstable particles

Occurrence of imaginary parts:

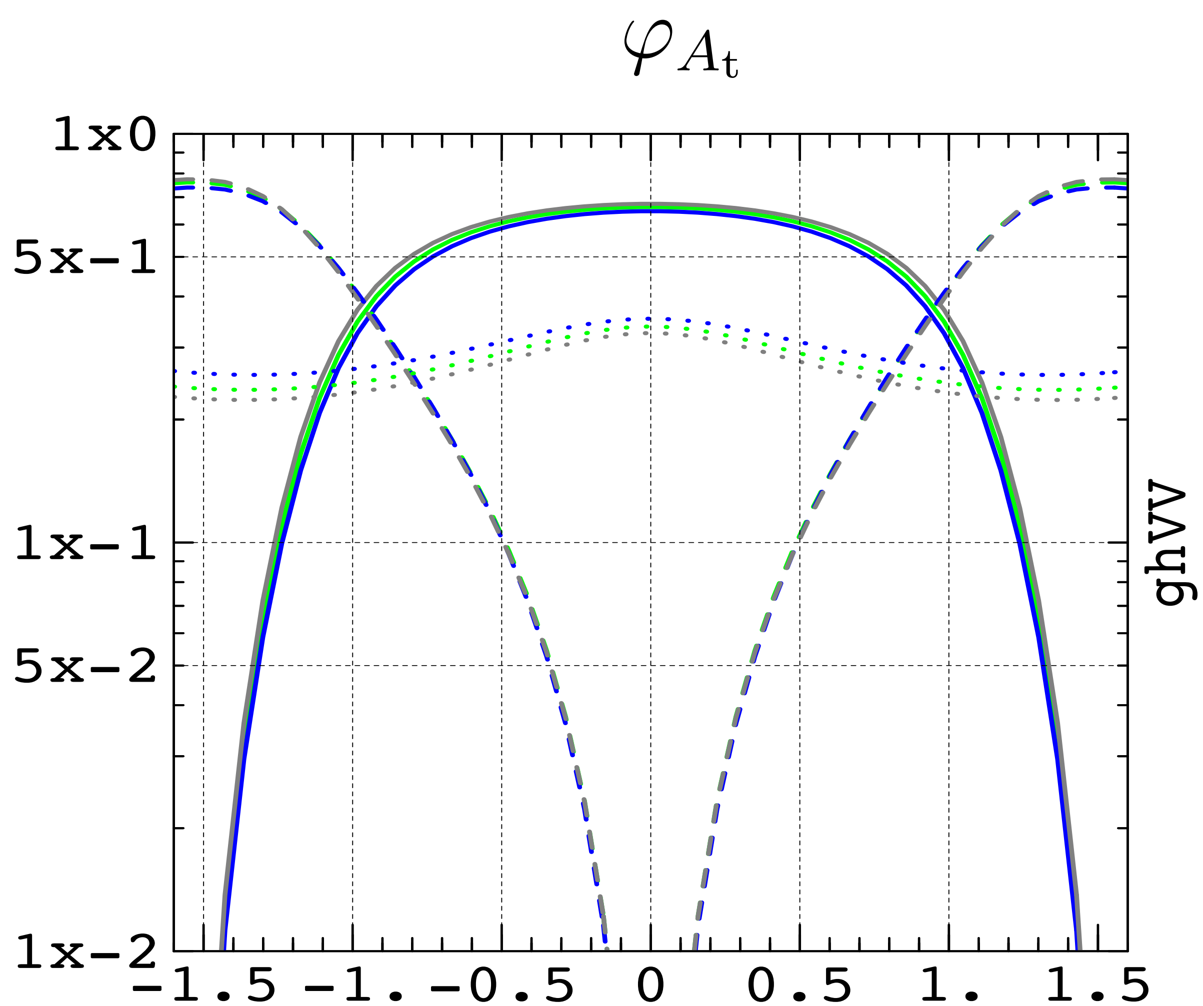
- From complex parameters
- From absorptive parts of loop integrals
  $\leftrightarrow$ unstable particles

$\Rightarrow$ MSSM with complex parameters:
absorptive parts of loop integrals can contribute to real part of 1-loop quantities

$\Rightarrow$ Consistent renormalisation procedure needed for complex parameters and unstable particles
[*A. Bharucha, A. Fowler, G. Moortgat-Pick, G. W. '12*]
[*A. Fowler, G. W. '09*]

Impact of complex phases

Example: g^2_{hVV} for h_1, h_2, h_3: [M. Frank, S. Heinemeyer, W. Hollik, G. W. '03]



full: h_1, dashed: h_2, dotted: h_3

Parameters:

$M_{\text{SUSY}} = 500$ GeV,

$M_2 = 500$ GeV,

$\mu = 2000$ GeV,

$|A_t| = 1000$ GeV,

$M_{H^\pm} = 150$ GeV, $\tan\beta = 5$

⇒ Complex phases can have large effects on Higgs couplings

Possible consequence: a light Higgs with suppressed couplings to gauge bosons

Example from the past: ``holes” in the LEP coverage for light Higgs masses

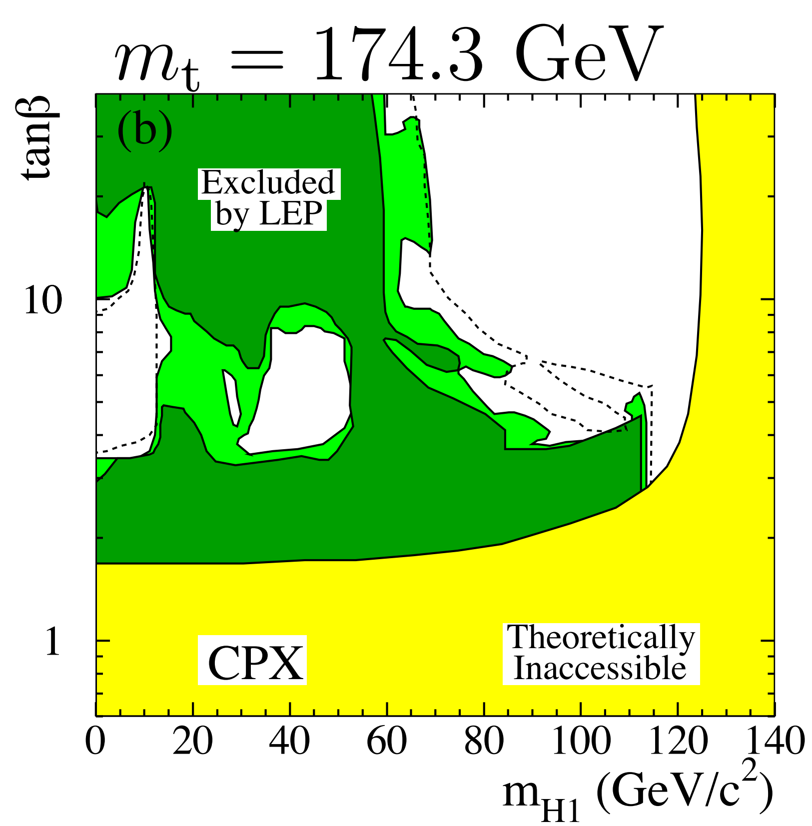
MSSM with $\mathcal{CP}$-violating phases (CPX scenario):

Light Higgs, h_1: strongly suppressed h_1VV couplings

Second-lightest Higgs, h_2, possibly within LEP reach (with reduced VVh_2 coupling), h_3 beyond LEP reach

Large $\mathrm{BR}(h_2 \to h_1h_1)$ $\Rightarrow$ difficult final state

[*LEP Higgs WG ’06*]



$\Rightarrow$ Light SUSY Higgs not ruled out!

CP-violating Higgs phenomenology: mixing between all three neutral Higgs bosons

Mixing between h, H, A

$\Rightarrow$ loop-corrected masses obtained from propagator matrix

$$\Delta_{hHA}(p^2) = -\left(\hat{\Gamma}_{hHA}(p^2)\right)^{-1}, \quad \hat{\Gamma}_{hHA}(p^2) = i\left[p^2 \mathbb{1} - \mathrm{M}_\mathrm{n}(p^2)\right]$$

where (up to sub-leading two-loop corrections)

$$\mathrm{M}_\mathrm{n}(p^2) = \begin{pmatrix} m_\mathrm{h}^2 - \hat{\Sigma}_{hh}(p^2) & -\hat{\Sigma}_{hH}(p^2) & -\hat{\Sigma}_{hA}(p^2) \\ -\hat{\Sigma}_{hH}(p^2) & m_\mathrm{H}^2 - \hat{\Sigma}_{HH}(p^2) & -\hat{\Sigma}_{HA}(p^2) \\ -\hat{\Sigma}_{hA}(p^2) & -\hat{\Sigma}_{HA}(p^2) & m_\mathrm{A}^2 - \hat{\Sigma}_{AA}(p^2) \end{pmatrix}$$

$\Rightarrow$ Higgs propagators: $\Delta_{ii}(p^2) = \dfrac{i}{p^2 - m_i^2 + \hat{\Sigma}_{ii}^{\mathrm{eff}}(p^2)}$

Determination of the Higgs masses from the complex poles

$$\hat{\Sigma}^{\text{eff}}_{ii}(p^2) = \hat{\Sigma}_{ii}(p^2) - i\,\frac{2\hat{\Gamma}_{ij}(p^2)\hat{\Gamma}_{jk}(p^2)\hat{\Gamma}_{ki}(p^2) - \hat{\Gamma}^2_{ki}(p^2)\hat{\Gamma}_{jj}(p^2) - \hat{\Gamma}^2_{ij}(p^2)\hat{\Gamma}_{kk}(p^2)}{\hat{\Gamma}_{jj}(p^2)\hat{\Gamma}_{kk}(p^2) - \hat{\Gamma}^2_{jk}(p^2)}$$

Complex pole $\mathcal{M}^2$ of each propagator is determined from

$$\mathcal{M}_i^2 - m_i^2 + \hat{\Sigma}^{\text{eff}}_{ii}(\mathcal{M}_i^2) = 0,$$

where

$$\mathcal{M}^2 = M^2 - iM\Gamma,$$

Expansion around the real part of the complex pole:

$$\hat{\Sigma}_{jk}(\mathcal{M}^2_{h_a}) \approx \hat{\Sigma}_{jk}(M^2_{h_a}) + i\,\text{Im}\left[\mathcal{M}^2_{h_a}\right]\hat{\Sigma}'_{jk}(M^2_{h_a})$$

$j, k = h, H, A,\; a = 1, 2, 3$

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

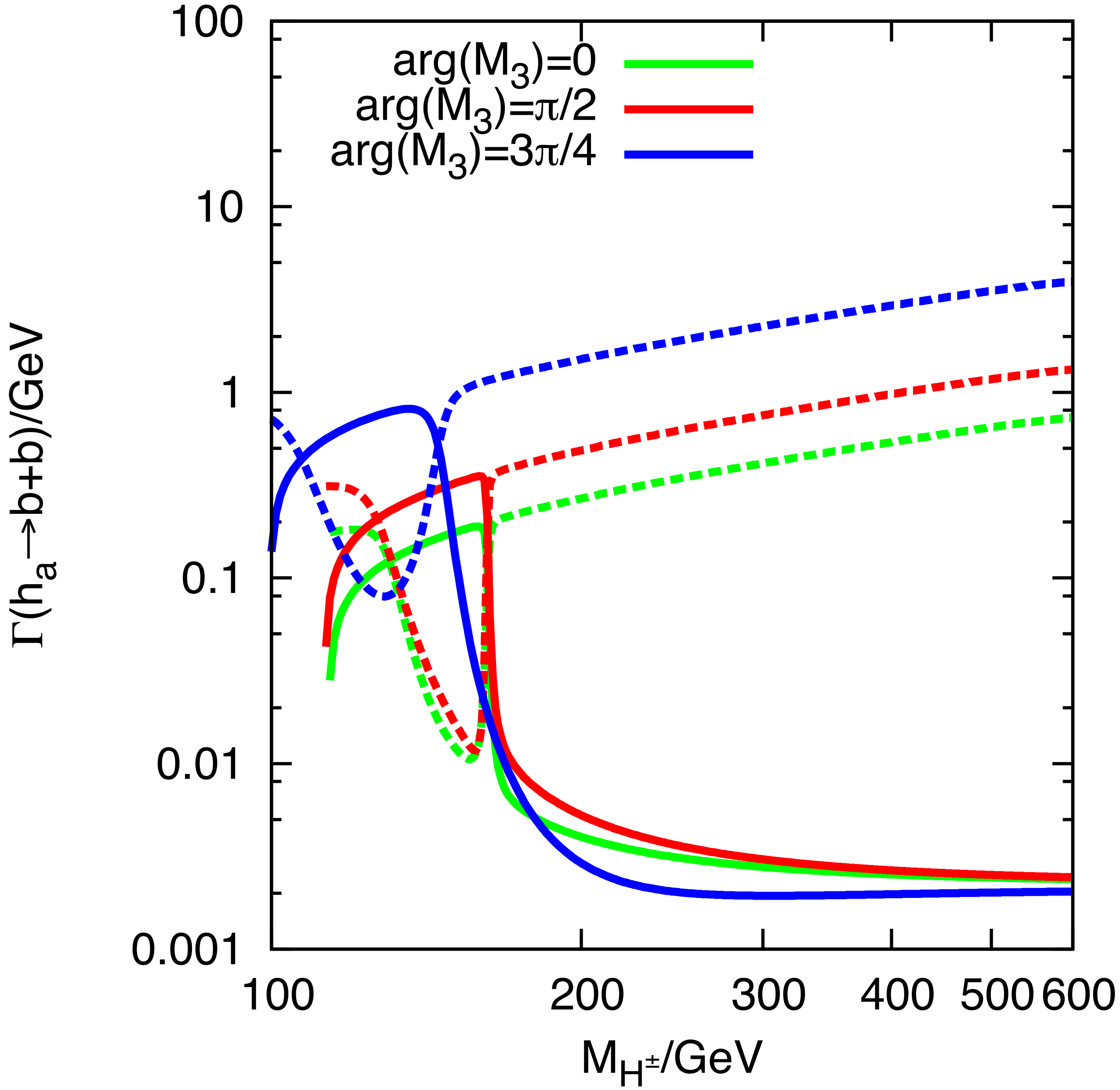
Two Higgs states, nearly mass degenerate, large mixing

$\Rightarrow$ Large (destructive) interference possible

Higgs decays into bottom quarks: impact of the gluino phase φ_{M_3}

Decay widths of h_1 (solid) and h_2 (dashed) into $b\bar{b}$:

[K. Williams, H. Rzehak, G. W. '13]



CPX scenario,

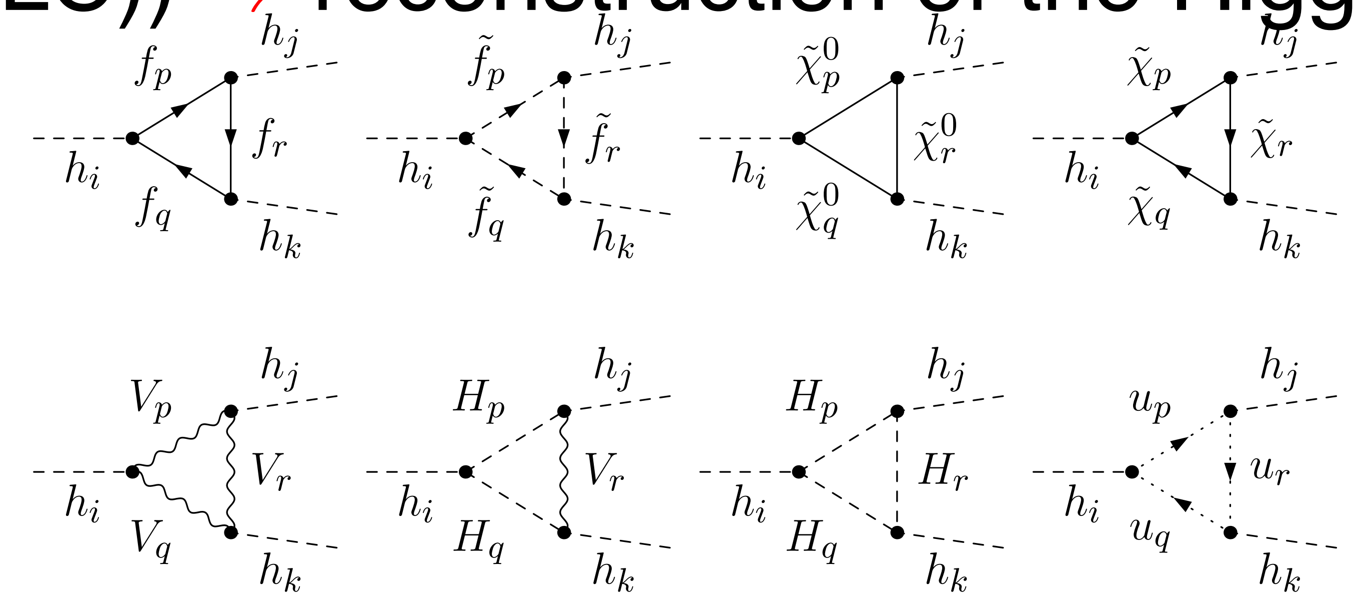
$\tan\beta = 20$

⇒ Large impact of gluino phase, arises from large correction Δ_b to the relation between b-quark mass and b-Yukawa coupling

Higgs cascade decays: h_2 → h_1 h_1, ...

Higgs cascade decays:

- Important for Higgs searches: $h_2 \to h_1 h_1$ is in general the dominant channel where it is kinematically allowed
- Access to Higgs self-coupling (difficult for SM Higgs at LHC (and LC)) $\Rightarrow$ reconstruction of the Higgs potential



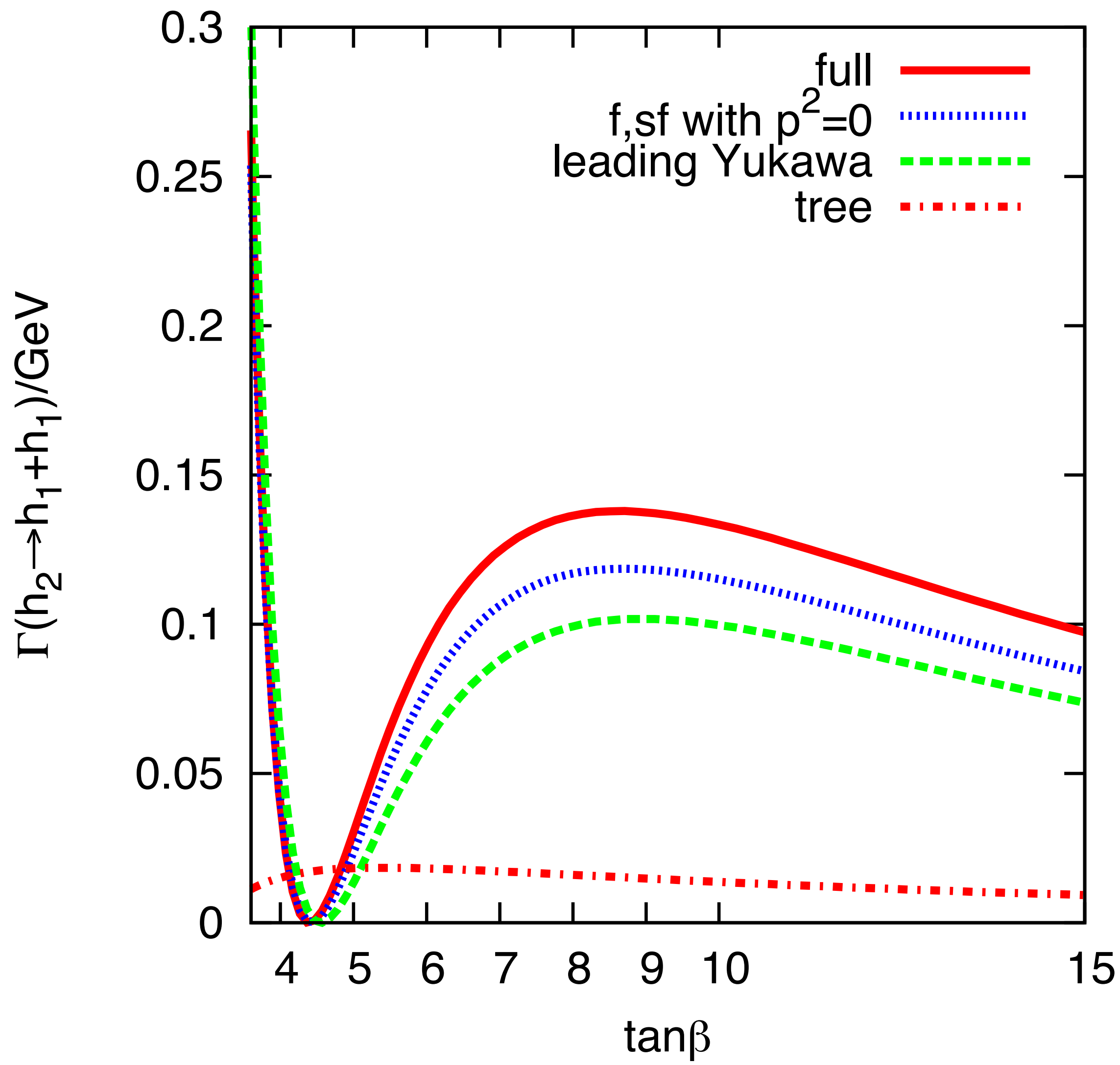
For h_1 = h(125): important channel for the search for heavy Higgses

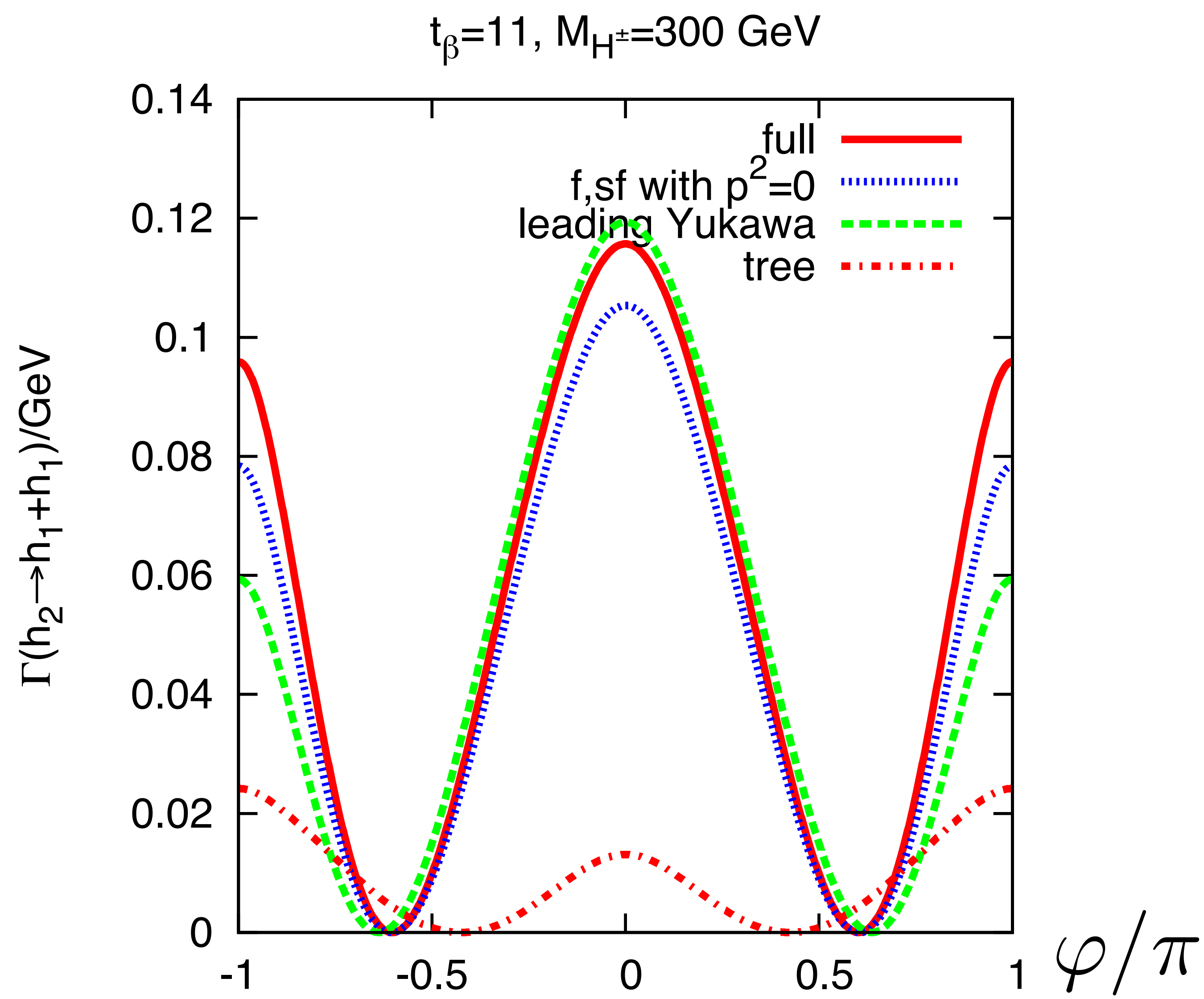
For h_2 = h(125): constraints on light Higgses below 63 GeV

Higgs cascade decays: impact of higher-order corrections and complex phase

CPX scenario

[K. Williams, H. Rzehak, G. W. '13]



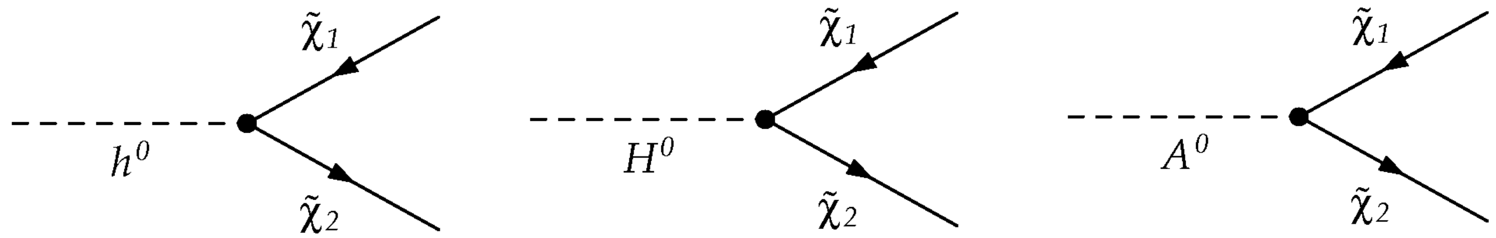


$$\varphi = \varphi_{A_t} = \varphi_{A_b} = \varphi_{A_\tau} = \varphi_{A_{M_3}}$$

⇒ Very large higher-order corrections, strong phase dependence

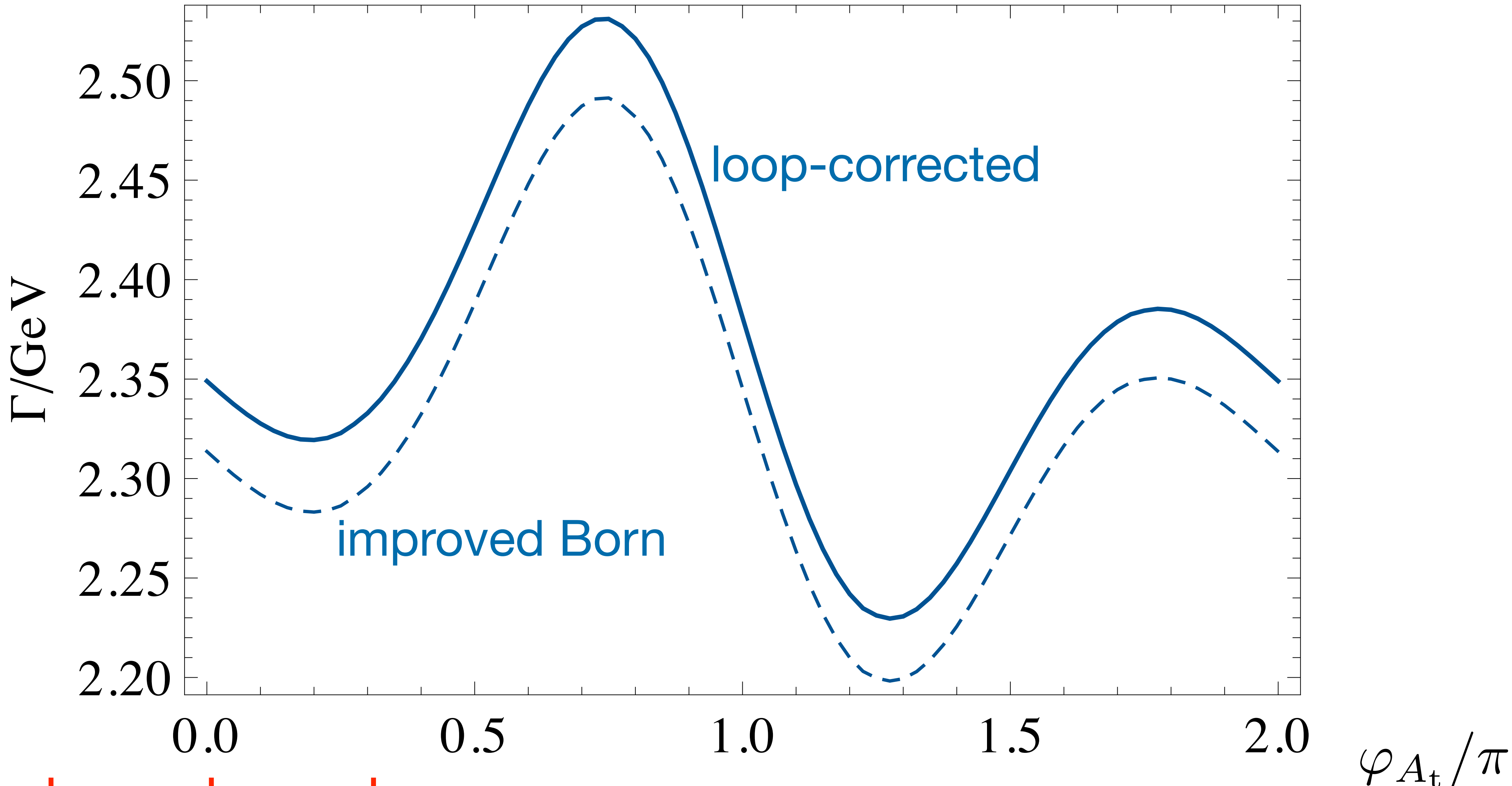
Higgs decays into neutralinos and charginos

[A. Bharucha, A. Fowler, G. Moortgat-Pick, G. W.’13]



+ higher-order corrections

Dependence on φ_{A_t} of the sum of decay widths: $h_2 \to \tilde{\chi}_1^+ \tilde{\chi}_2^-$ and $h_3 \to \tilde{\chi}_1^+ \tilde{\chi}_2^-$



⇒ Sizable phase dependence

Higgs decays into charginos and neutralinos

[A. Bharucha, A. Fowler, G. Moortgat-Pick, G. W.'13]

Loop corrections, impact of absorptive parts: $h_2 \to \tilde{\chi}^+_{1,L} \tilde{\chi}^-_{2,R}$

absorptive parts included

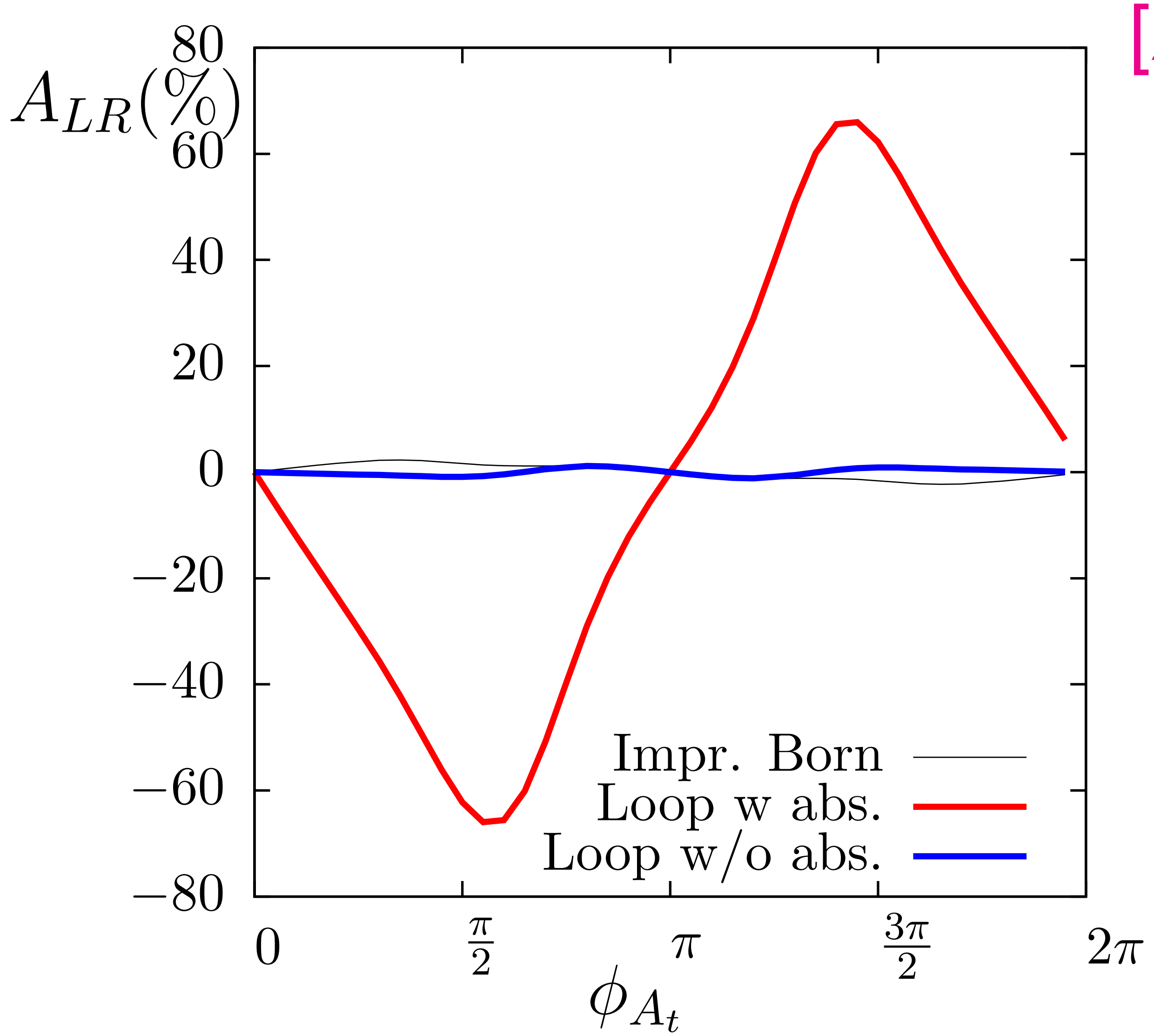
without absorptive parts

φ_{A_t}/π

$\Rightarrow$ Importance of absorptive parts for analysis of CP-violating effects

CP-violating asymmetry

[A. Fowler, G. W. '10]



⇒ Large asymmetries possible

Condition for sizable asymmetries:

$\mathcal{CP}$ violation (complex parameters) + absorptive parts

Conclusions

The discovered signal is compatible with a SM-like Higgs, but a variety of interpretations is possible, corresponding to very different underlying physics

⇒ Significant room for possible effects of CP violation in the Higgs sector

- Signal at 125 GeV: Mixed CP state or pure state? Modifications of couplings from CP-violating phases? Decay mode into a pair of additional light Higgses?

- States of extended Higgs sector: Neutral heavy Higgses, nearly mass degenerate, large mixing between *H*, *A* states, resonance-type behaviour possible! $h_2 \to h(125)\, h(125)$ decays!
  $h_2 \to \chi\chi$, high sensitivity to CP phases, CP asymmetries!

⇒ Good prospects for exploring possible effects of new CPV sources

Backup

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

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.

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

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

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

⇒ 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

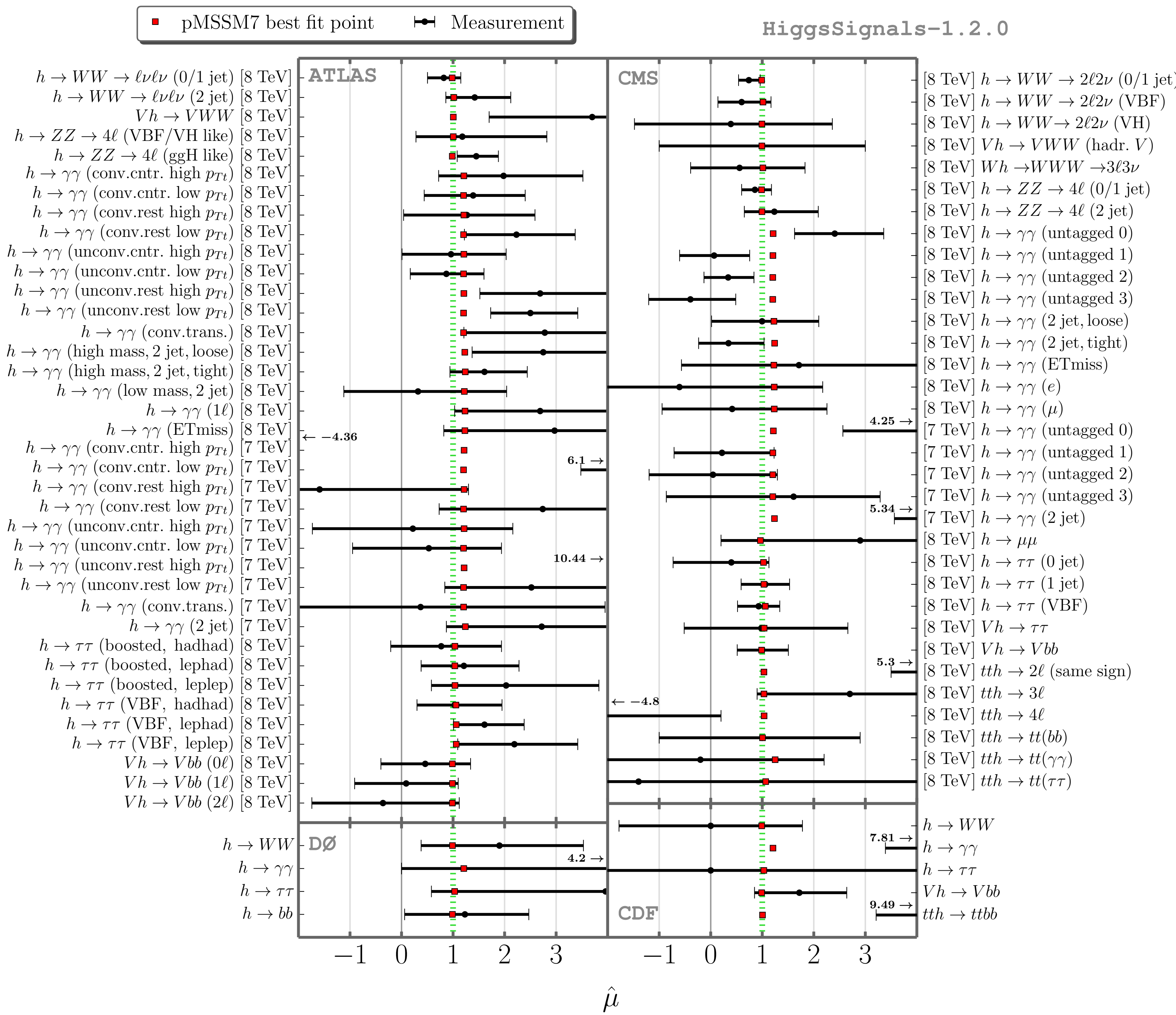
- If dark matter consists of one or more particles with a mass below about 63 GeV, then the decay of the state at 125 GeV into a pair of dark matter particles is kinematically open
- The detection of an invisible decay mode of the state at 125 GeV could be a manifestation of BSM physics
  - Direct search for $H \to$ invisible
  - Suppression of all other branching ratios

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:



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

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

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

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

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

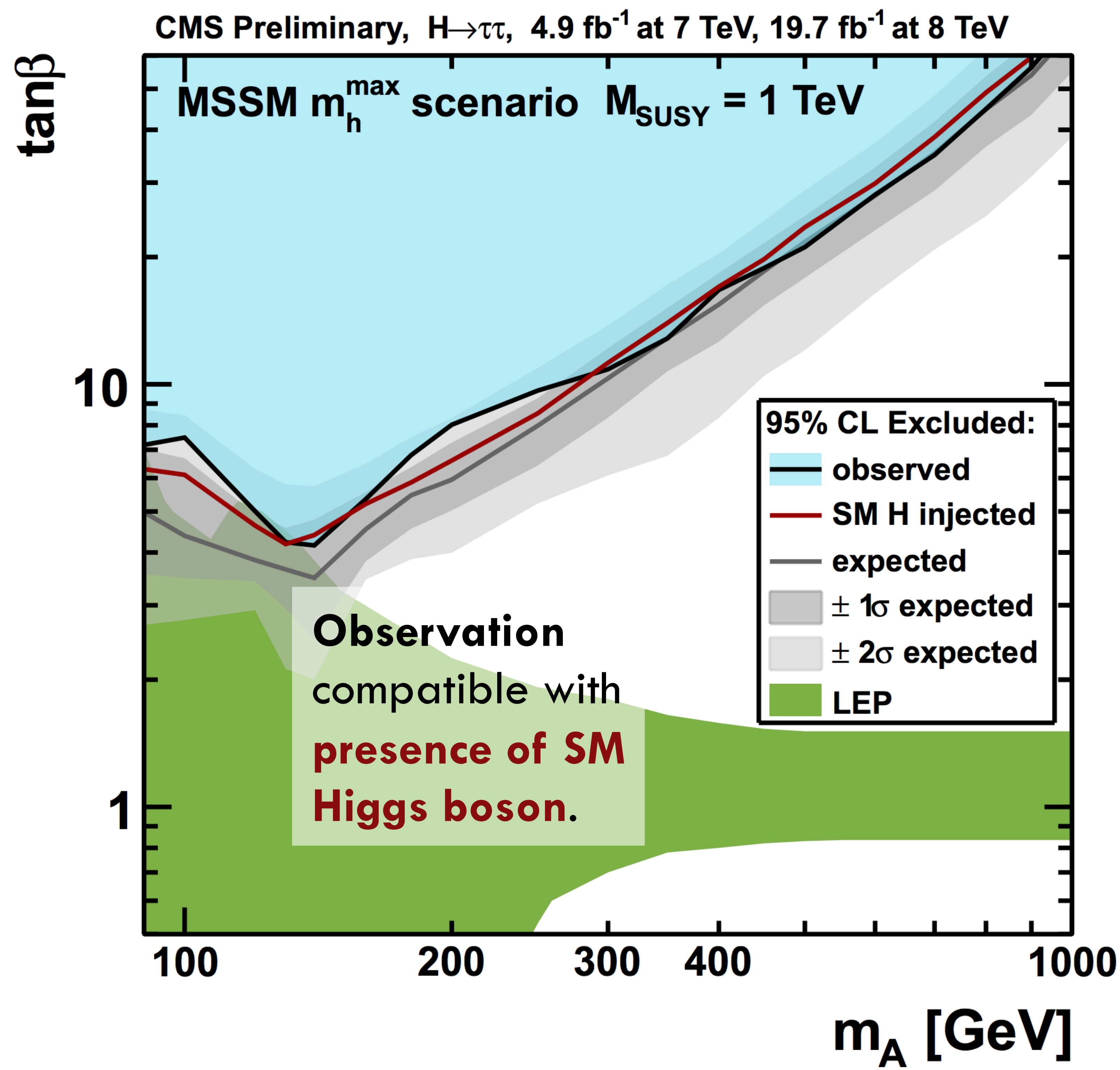
• Non-standard search channels can play an important role: $H \to hh$, $H, A \to \chi\chi$, ...

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

[CMS Collaboration '14]

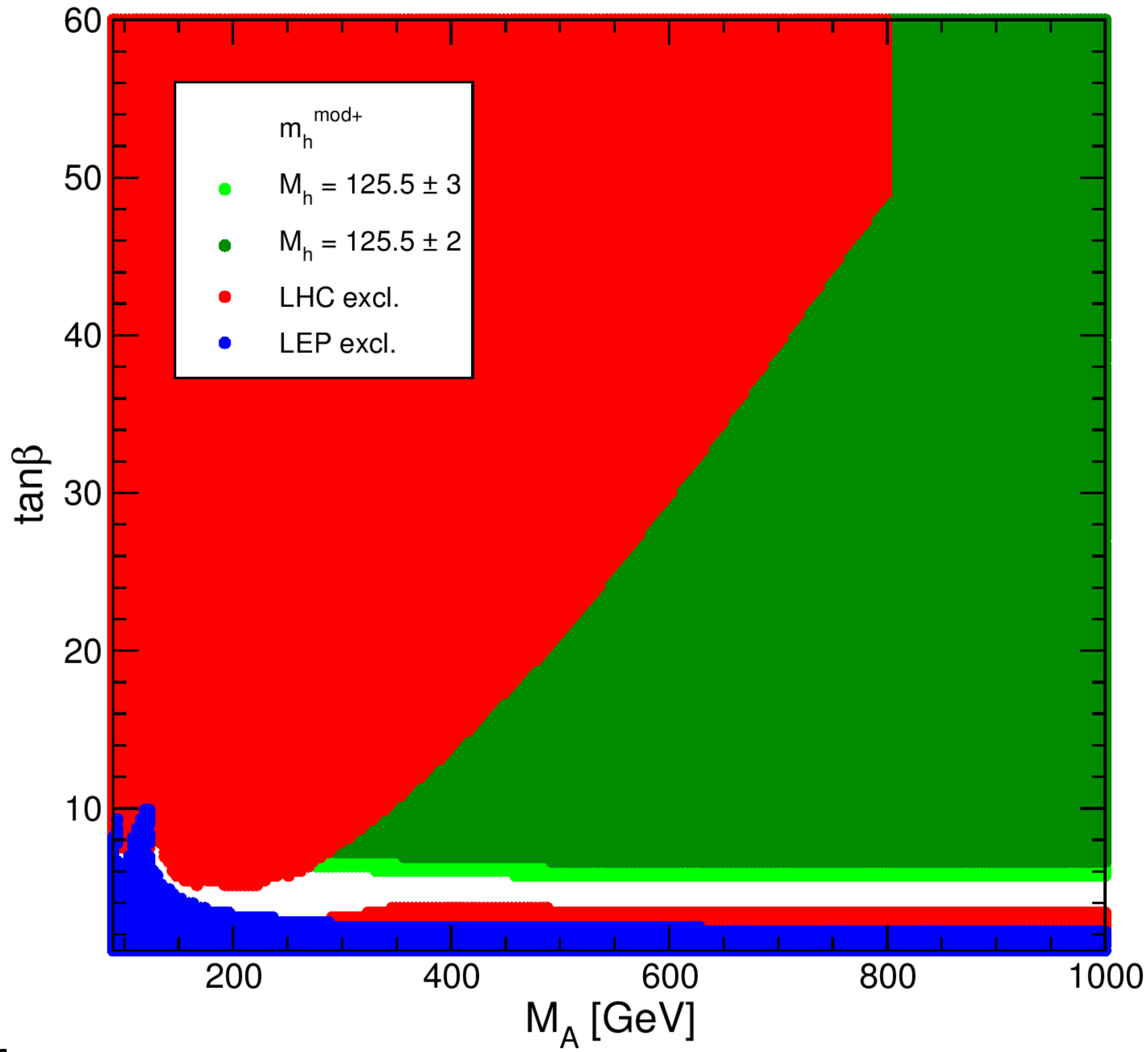
Analysis starts to become sensitive to the presence of the signal at 125 GeV

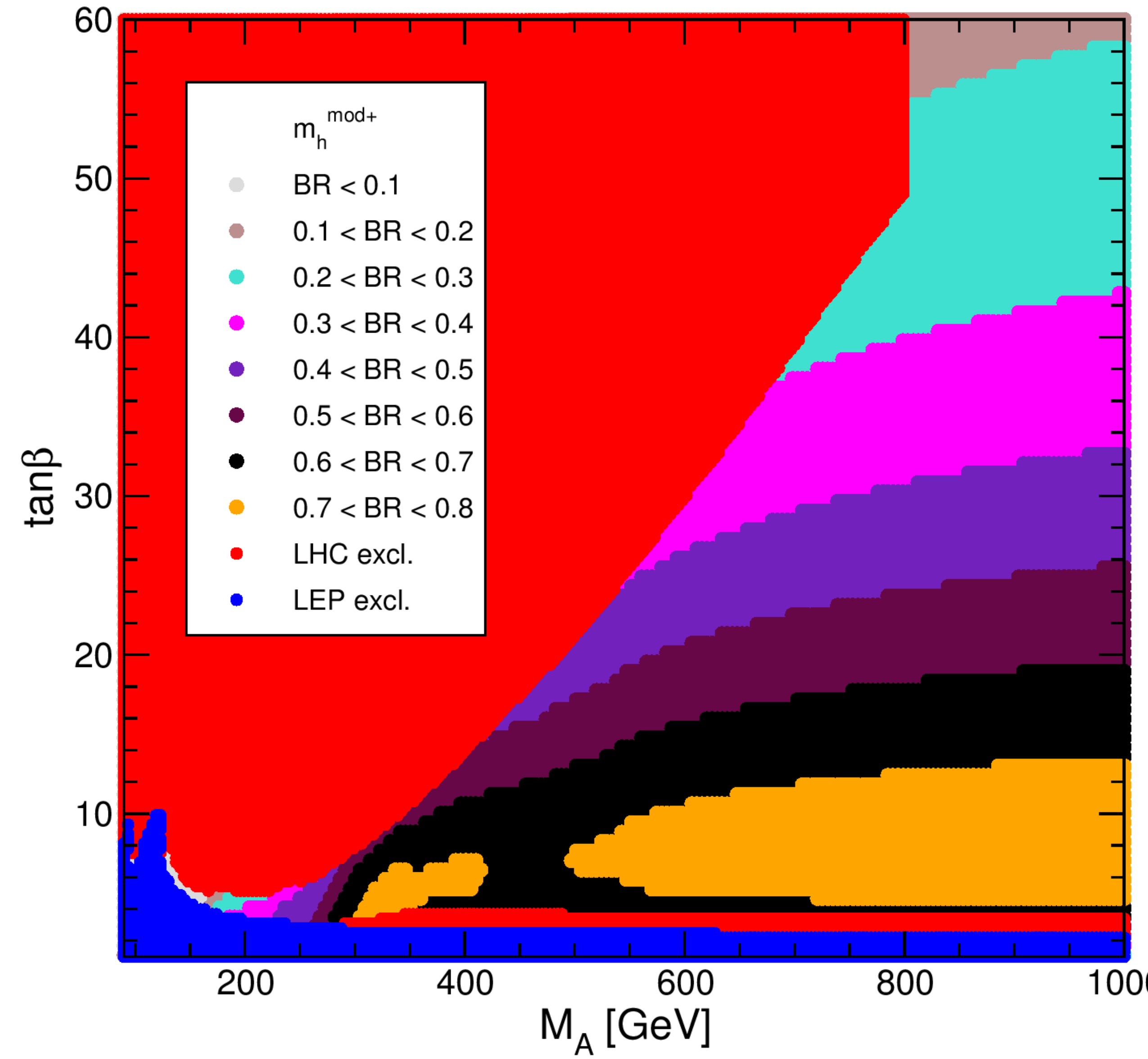
⇒ Searches for Higgs bosons of an extended Higgs sector need to test compatibility with the signal at 125 GeV (→ appropriate benchmark scenarios) and search for additional states



m_h^{mod} benchmark scenario

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



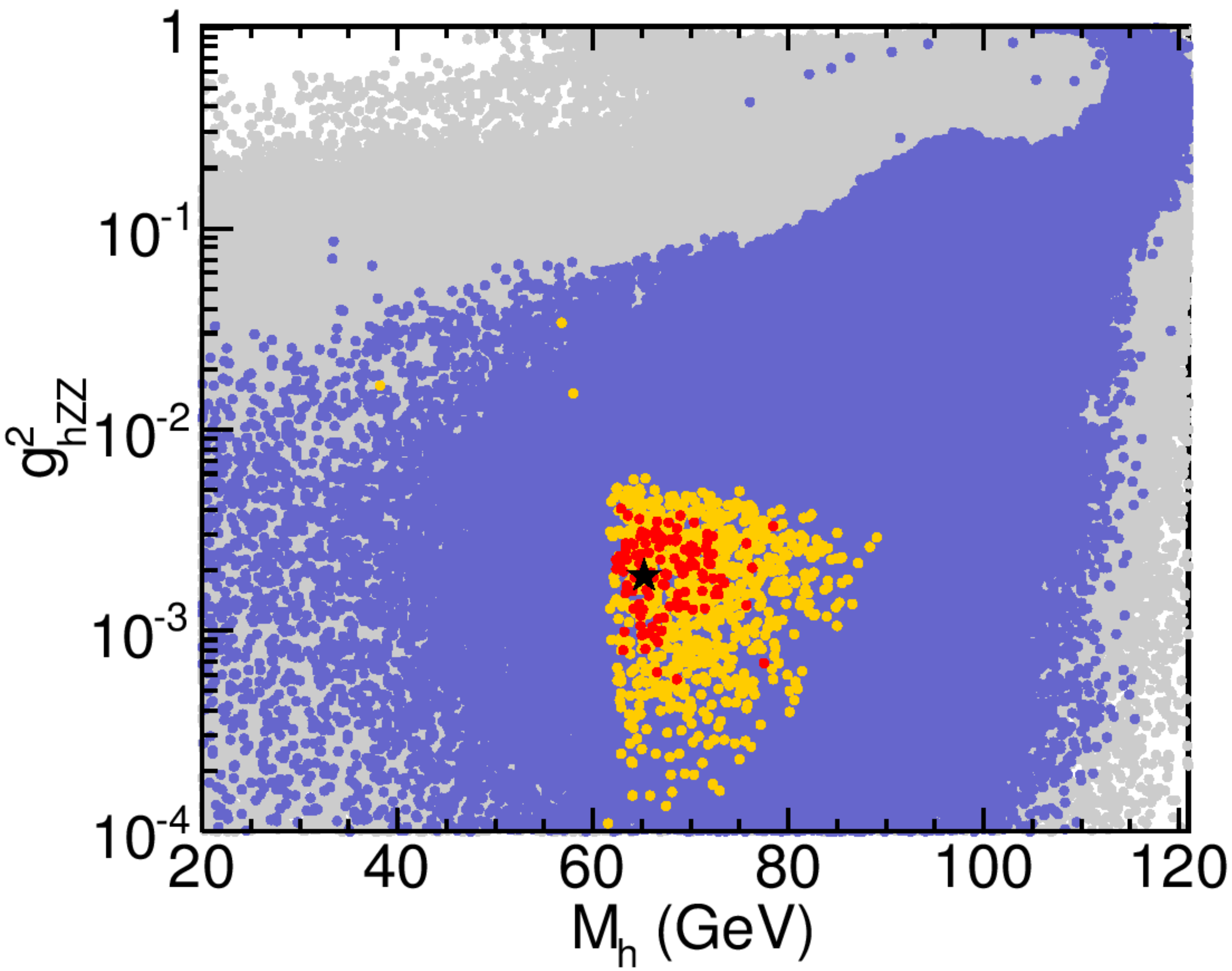


- Small modification of well-known m_h^{max} scenario where the light Higgs h can be interpreted as the signal at 125 GeV over a wide range of the parameter space

- Large branching ratios into SUSY particles (right plot) and sizable BR(H → hh) for rel. small tanβ possible

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 $M_{\rm h} \approx 70$ GeV, in agreement with LEP limits

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

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 $\Gamma/\Gamma_{\rm SM} < 4.2$ 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]

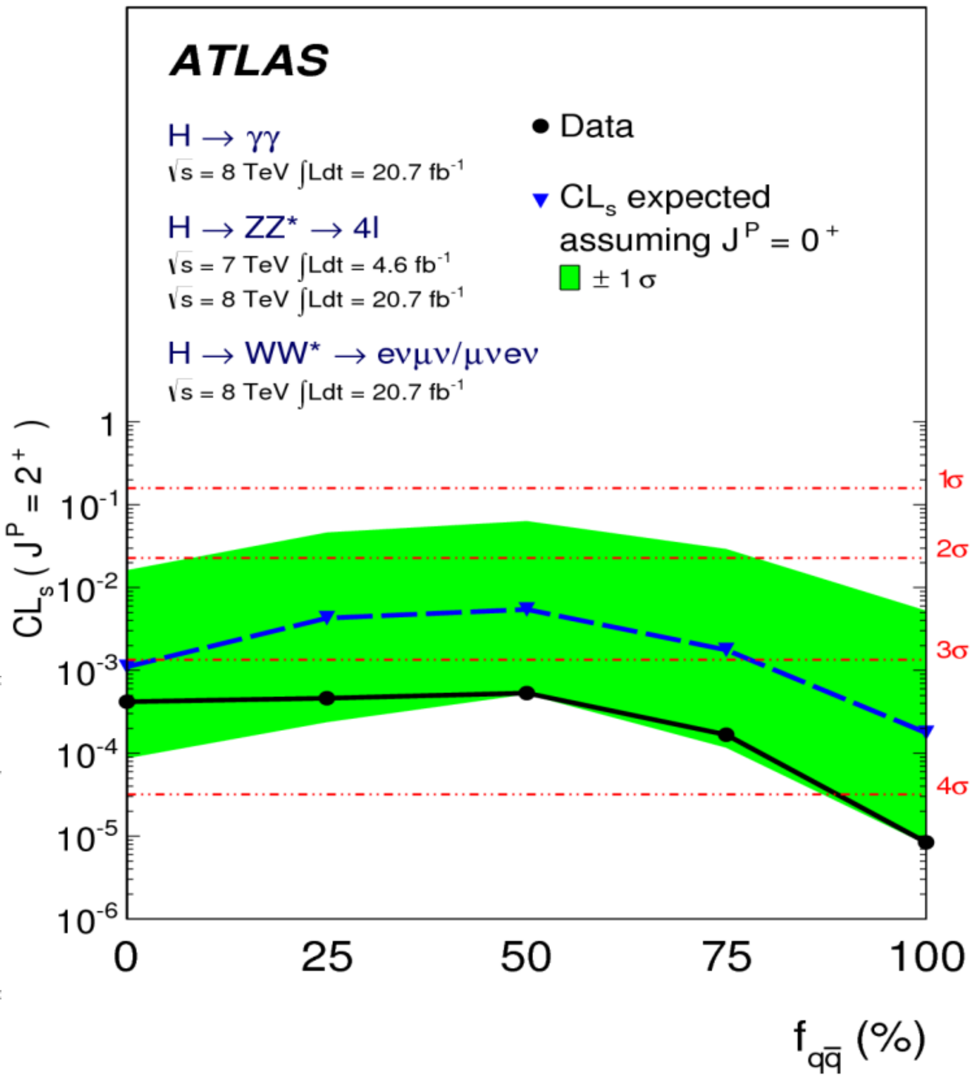
Test of spin and CP hypotheses

[ATLAS Collaboration '13]

0^+ against 2^+

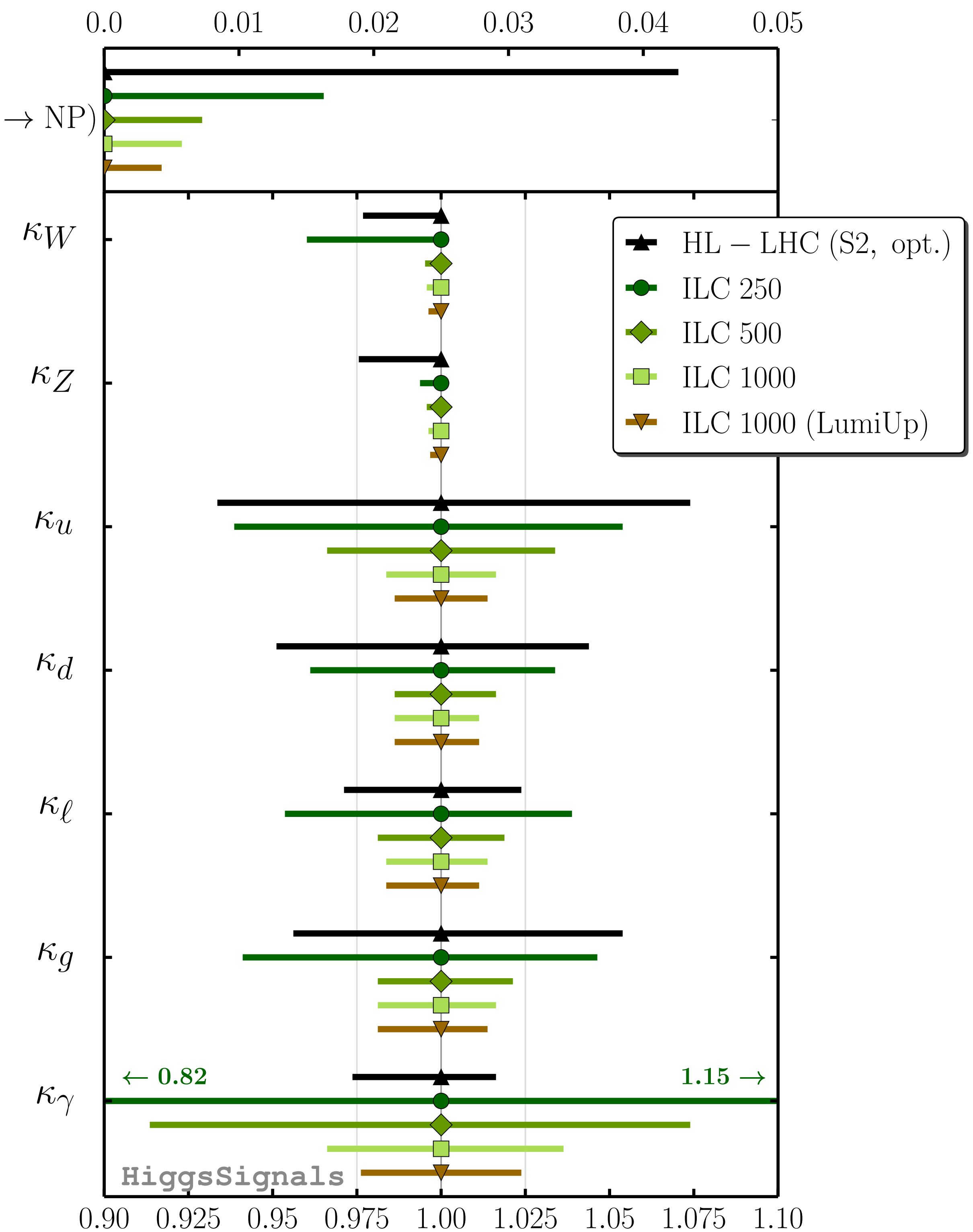
- ➢ All three analysis have excluded the 2^+ model with different qq fractions in favour of SM 0^+.
- ➢ From the combination of all of them, the 2^+ hypothesis is rejected up to **99.9%** CLs for all fractions of qq.

$f_{q\bar{q}}$	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	$1.5 \cdot 10^{-4}$	$4.2 \cdot 10^{-4}$



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