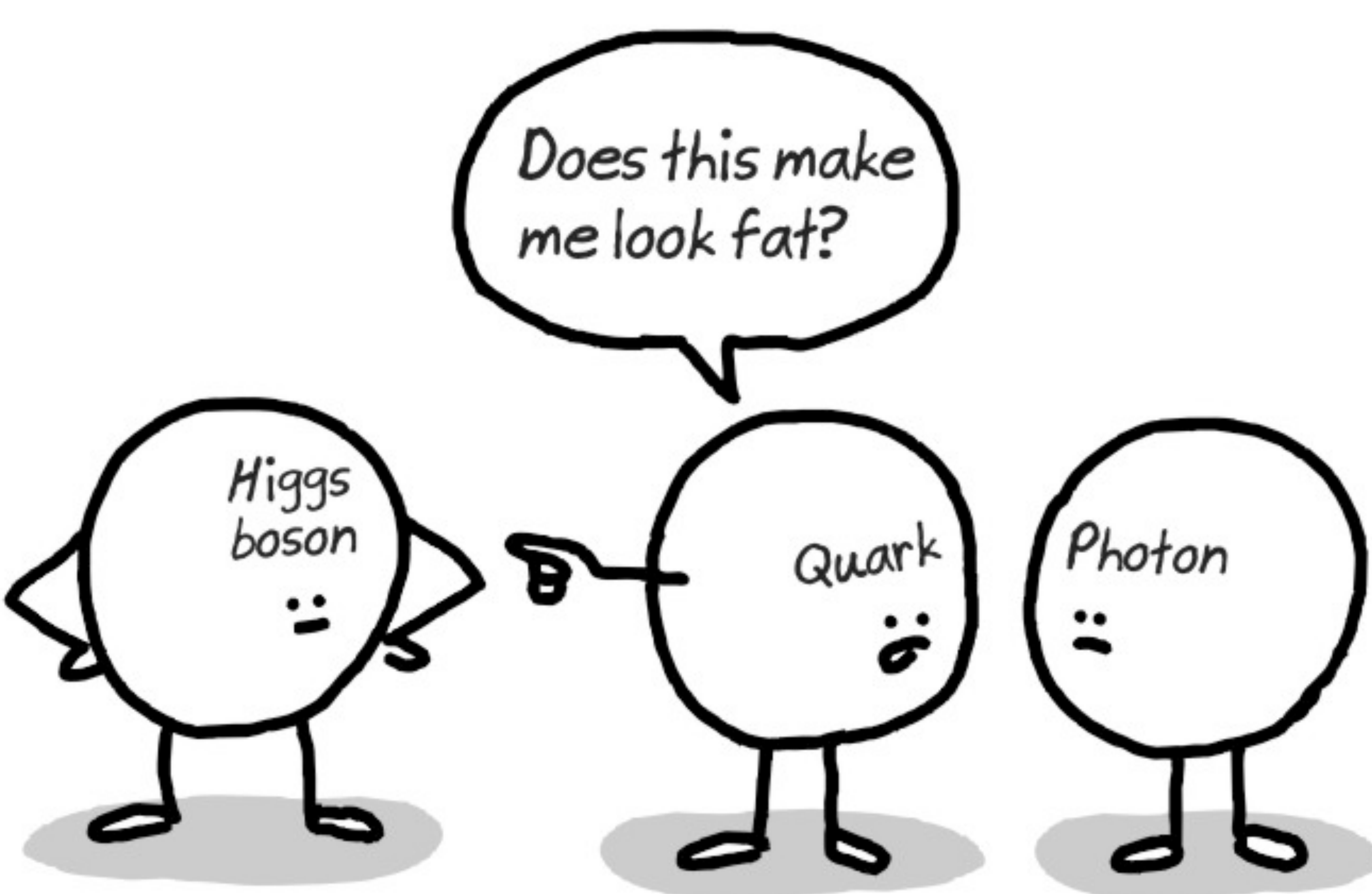


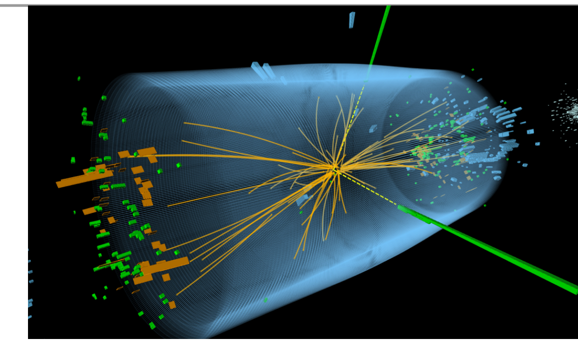
Higgs physics: what do we need to know?

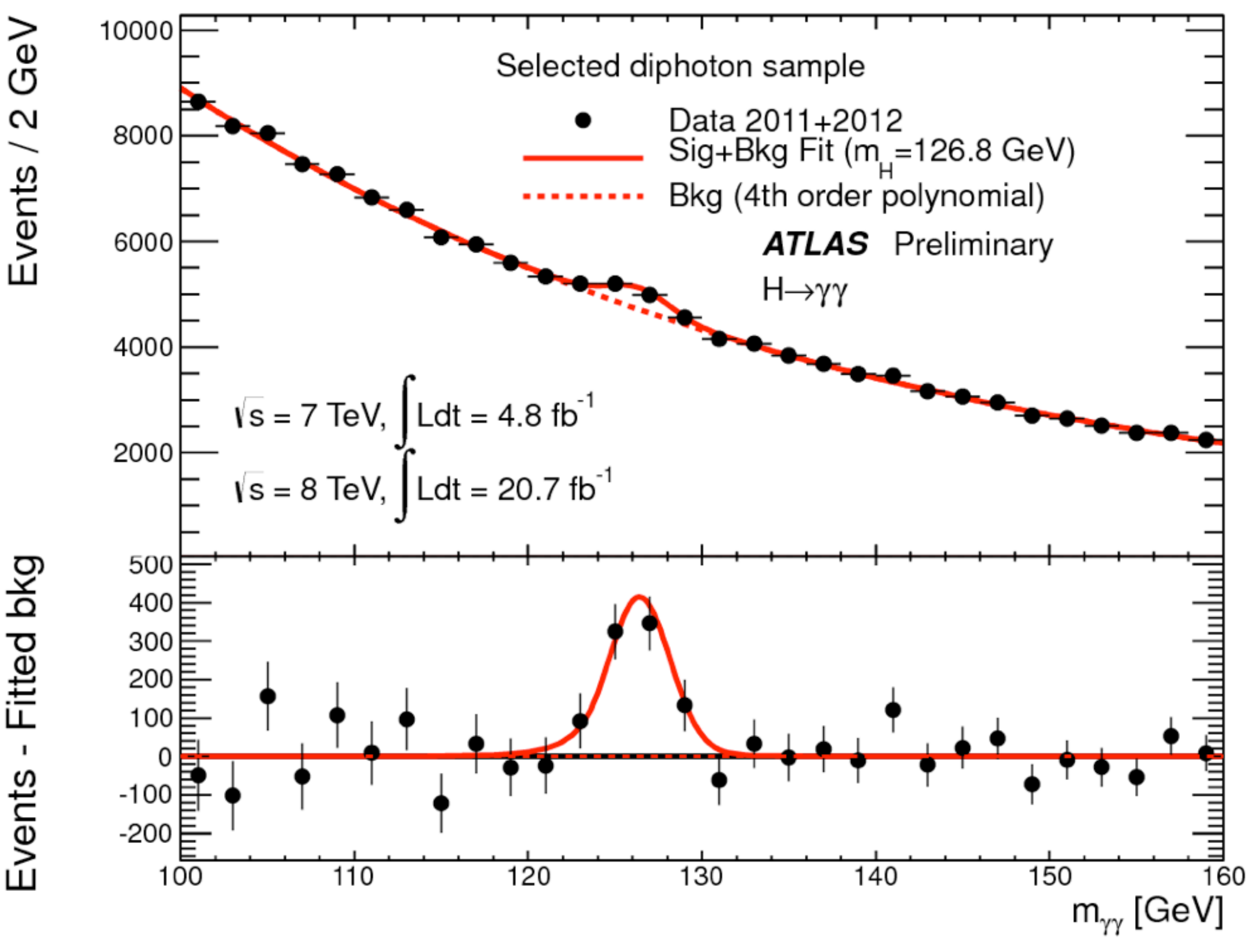
Georg Weiglein, DESY

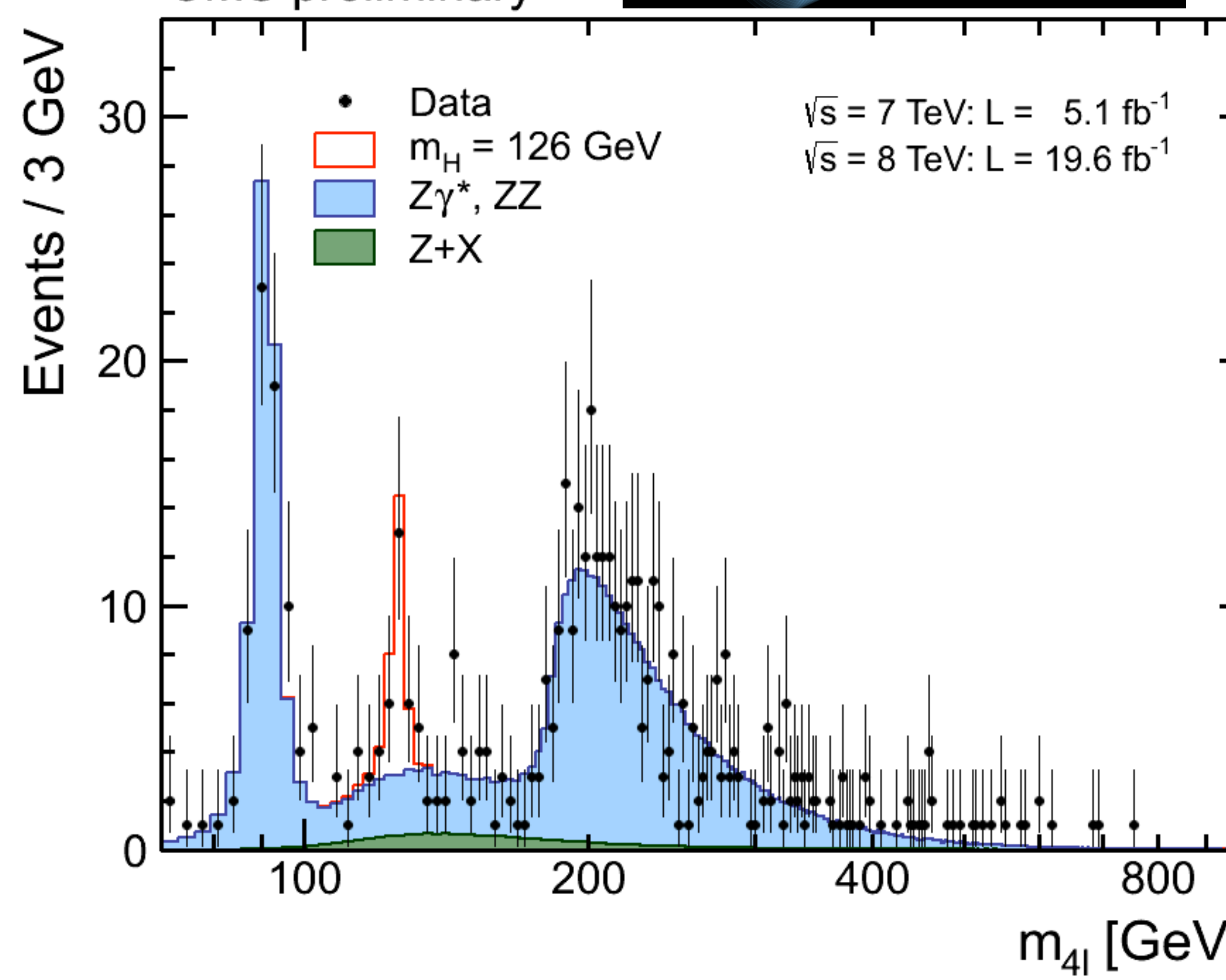
121st ILC@DESY Project Meeting, DESY, Hamburg, 04 / 2015

Higgs physics after the discovery

Discovery of a signal at about 125 GeV in the Higgs searches at ATLAS and CMS:







⇒ The spectacular discovery of a signal at ~125 GeV in the Higgs searches at the LHC marks the start of a new era of particle physics

What's so special about a Higgs boson? How do elementary particles get mass?

- The fundamental interactions of elementary particles are described very successfully by quantum field theories that follow an underlying symmetry principle:
  "gauge invariance"

- This fundamental symmetry principle requires that all the elementary particles and force carriers should be massless

- However: W, Z, top, bottom, . . . , electron are massive, have widely differing masses

  explicit mass terms $\Leftrightarrow$ breaking of gauge invariance

How can elementary particles acquire mass without spoiling the fundamental symmetries of nature?

The Brout-Englert-Higgs (BEH) mechanism

$\Rightarrow$ Need additional concept:

Higgs mechanism, spontaneous electroweak symmetry breaking:

New field postulated that fills all of the space: the Higgs field

Higgs potential
$\Rightarrow$ non-trivial structure of the vacuum postulated!

Gauge-invariant mass terms from interaction with Higgs field

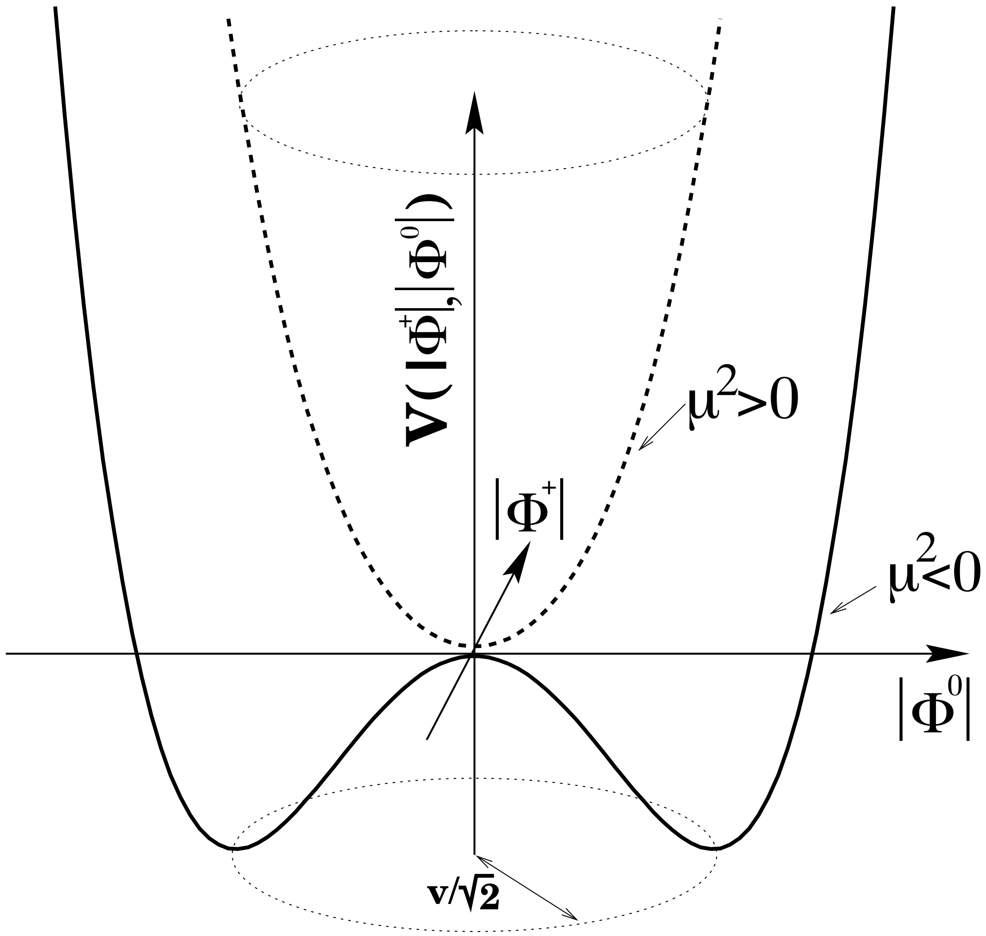
Spontaneous symmetry breaking: the interaction obeys the symmetry principle, but not the state of lowest energy

Very common in nature, e.g. ferromagnet

The BEH mechanism in the Standard Model (SM)

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

The state of the lowest energy of the Higgs field (vacuum state) does not obey the underlying symmetry principle (gauge invariance)

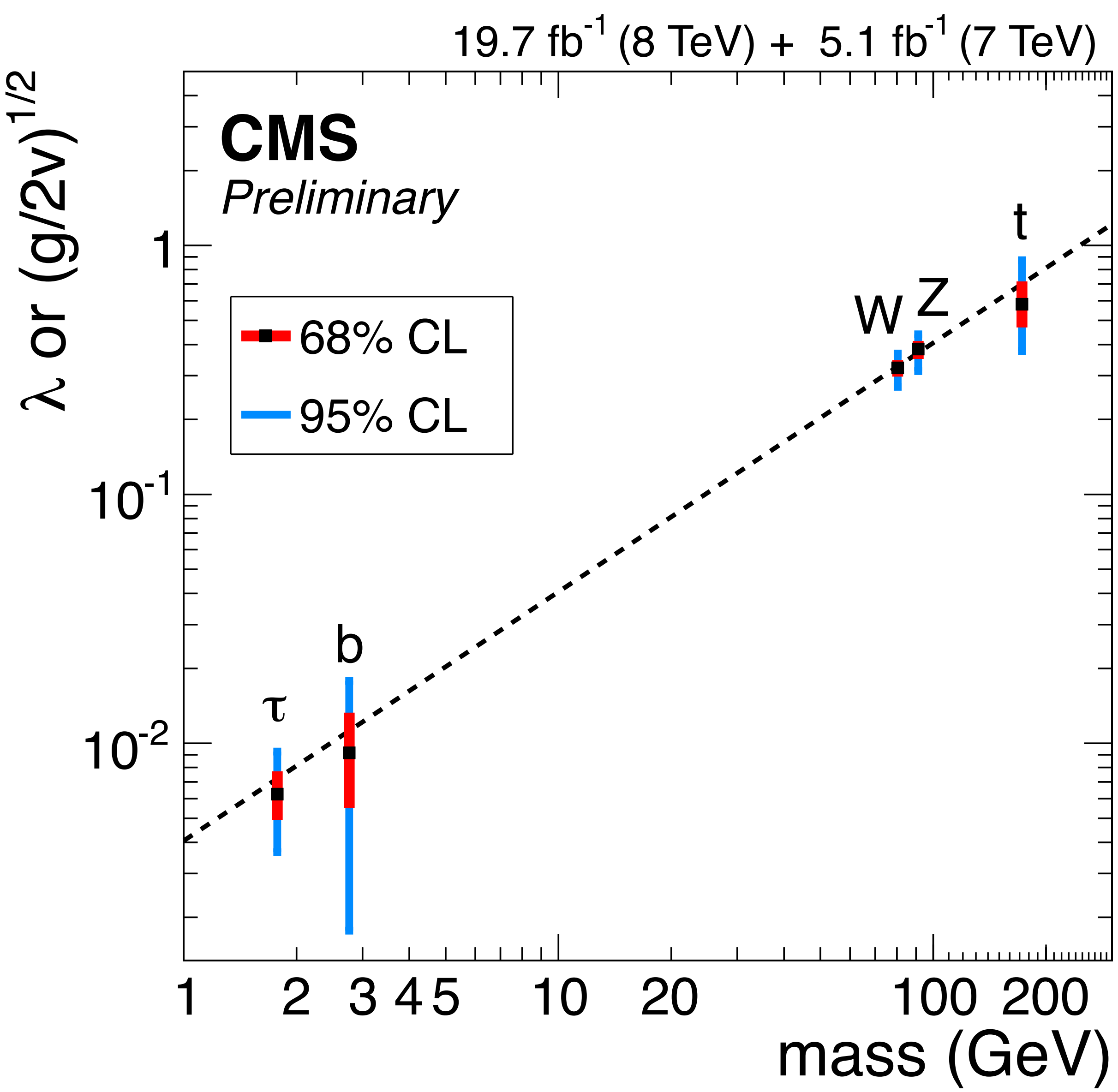


⇒ Spontaneous breaking of the gauge symmetry

BEH mechanism ⇔ non-trivial structure of the vacuum

Properties of the signal

Couplings to bosons and fermions scale with particle masses in accordance with BEH mechanism
⇒ Distinction from gauge interactions (generation universality)



[CMS Collaboration ’14]

⇒ Strong evidence for interpretation as a Higgs boson

Higgs discovery: the ultimate triumph for the SM?

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Or rather the beginning of the end of the SM?

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The SM is incomplete (in particular, it describes only three of the four fundamental interactions, i.e. it does not contain gravity) and cannot be the ultimate theory

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In fact: from what we know so far, we cannot understand how a Higgs boson could be as light as the one that was discovered
The 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)
⇒The mass should have been driven up to high scales

How can a Higgs boson be as light as 125 GeV?

- A new symmetry of nature $\longrightarrow$ Supersymmetry?
- A new fundamental interaction of nature $\longrightarrow$ composite Higgs?
- Extra dimensions of space $\longrightarrow$ impact on gravity on small scales?
- Multiverses $\longrightarrow$ anthropic principle?

What is the quantum structure of the universe?

Higgs particle provides access to the non-trivial structure of the vacuum

$\Rightarrow$ Answers to those questions are among the prime goals of the upcoming runs of the LHC and a future e^+e^- collider

Higgs physics: what do we want to know?

- What is the underlying nature of the observed signal and which role does it play in the physics of electroweak symmetry breaking?
  Fundamental / composite? Extended Higgs sector? ...

- Are there additional Higgs states?
  Could be heavier but also lighter than the state at 125 GeV

- Does the observed state unitarise WW scattering?
  Are there signs of a new strong interaction? Resonances? ...

- Higgs self-coupling: the ``holy grail” of Higgs physics
  Quantum structure of the vacuum? ...

- Does the observed signal provide access to further new physics?
  Decay into a pair of dark matter particles? ...

Higgs physics: how do we find out?

- High-precision studies of the properties of the observed signal
- Search for additional Higgs states above but also below 125 GeV
- Test unitarisation in different processes
- Explore Higgs self-coupling in different ways: different processes have different sensitivities to new physics, $H \to h(125)\, h(125)$, ...
- Explore interplay of Higgs physics and other new physics: h(125) as a final state in new physics processes, $h(125) \to \chi\chi$, ...
- ...

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 $M_{\mathrm{H}^\pm}$)

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

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

Including higher-order corrections: $M_\mathrm{h} \lesssim 135\,\mathrm{GeV}$
(for TeV-scale stop masses)

Interpretation of the signal at 125 GeV within the MSSM?

Interpretation of the signal in extended Higgs sectors (SUSY), 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.

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

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

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

⇒ Need very high precision for the couplings

⇒ ILC physics programme

Can h(125) decay into dark matter particles?

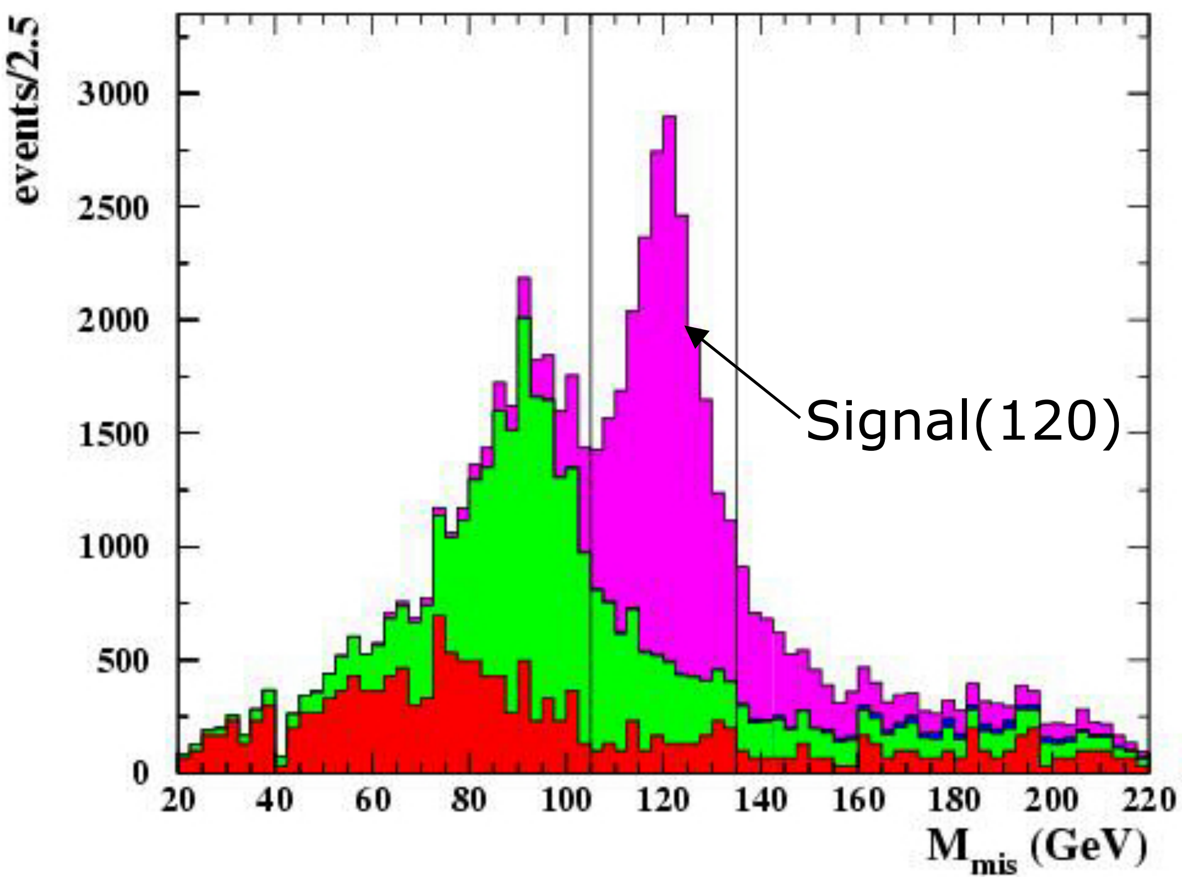
- If dark matter consists of one or more particles with a mass below about 63 GeV, then the decay of the state at 125 GeV into a pair of dark matter particles is kinematically open

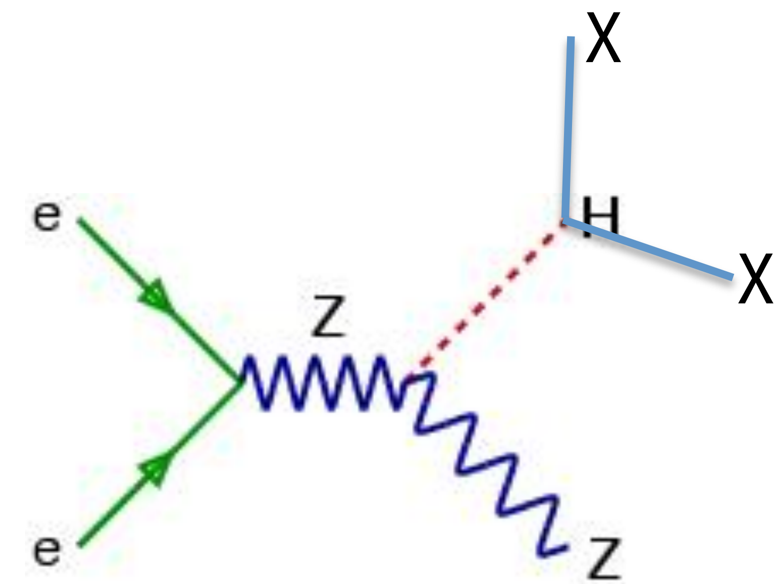
- The detection of an invisible decay mode of the state at 125 GeV could be a manifestation of BSM physics

  - Direct search for $H \to$ invisible

  - Suppression of all other branching ratios

Invisible decays





⇒ Unique sensitivity at the ILC!

Properties of the other Higgs states: sum rule for coupling to gauge bosons

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

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

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

•$\varkappa_V \leqq 1$

•The more SM-like the couplings of the state at 125 GeV turn out to be, the more suppressed are the couplings of the other Higgses to gauge bosons

•Heavy Higgses have a much smaller width than a SM-like Higgs of the same mass

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 → 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 → $\tau\tau$

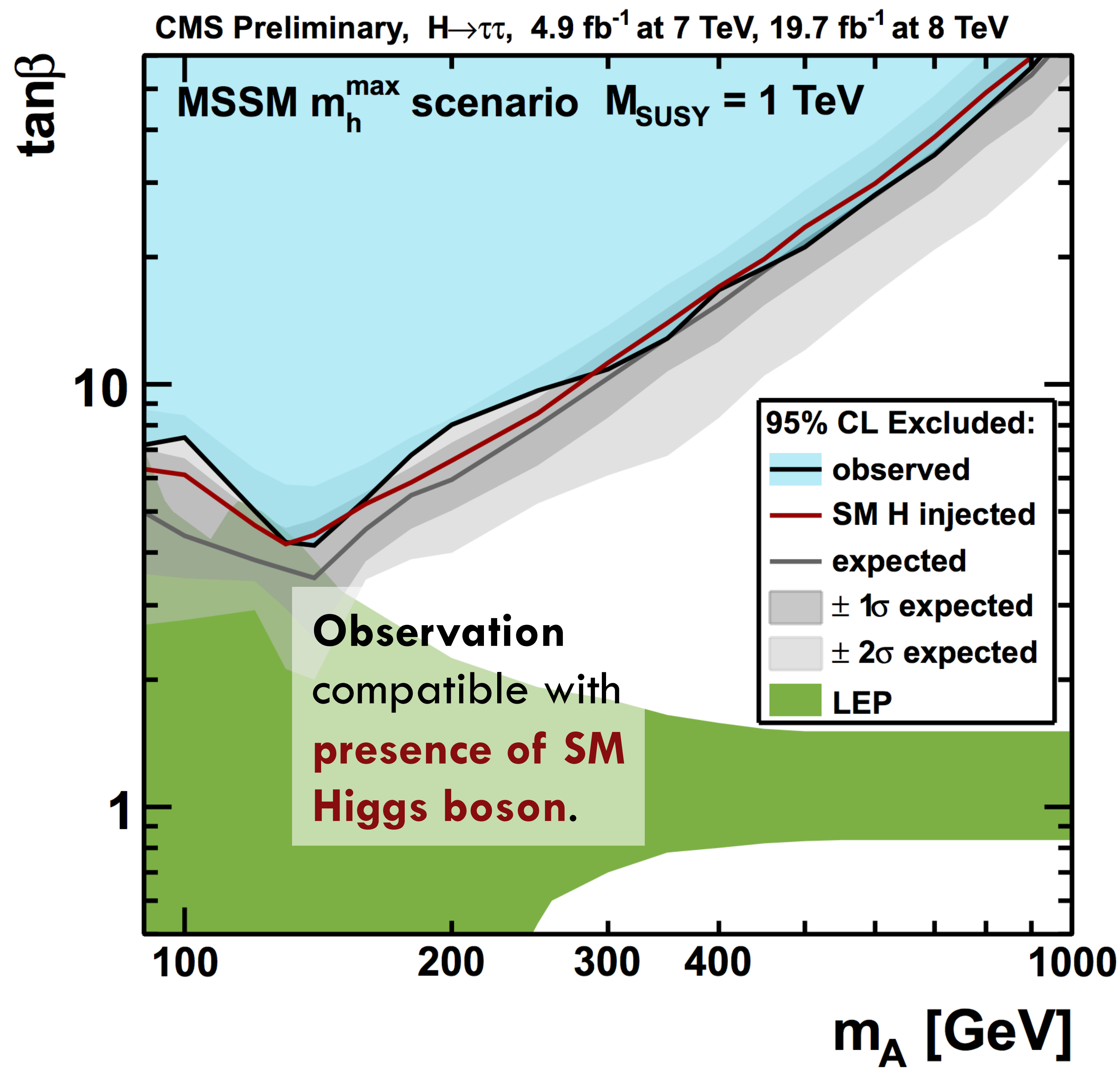
• Non-standard search channels can play an important role: H → hh, H, A → $\chi\chi$, ...

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

[CMS Collaboration '14]

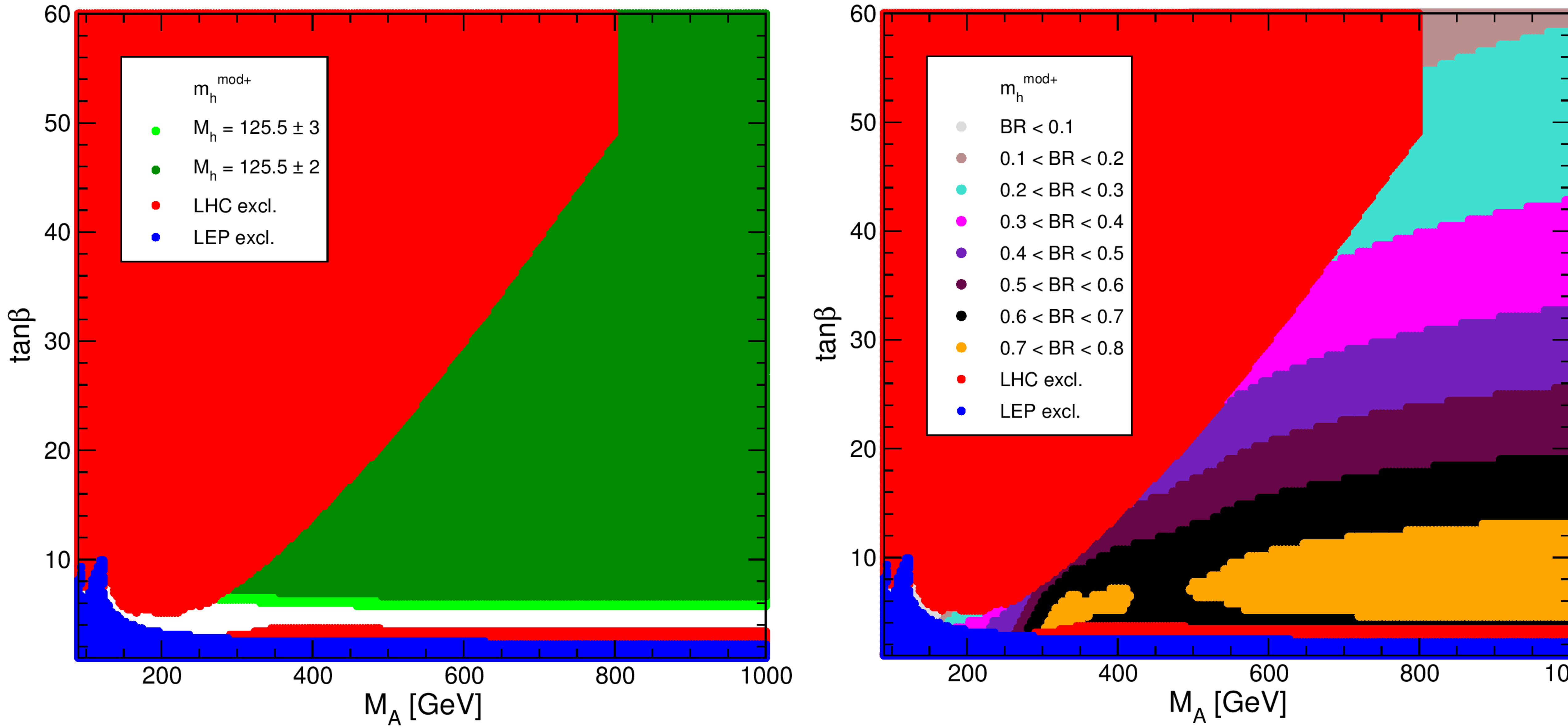
Analysis starts to become sensitive to the presence of the signal at 125 GeV

⇒ 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



m_h^{mod} benchmark scenario

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



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

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

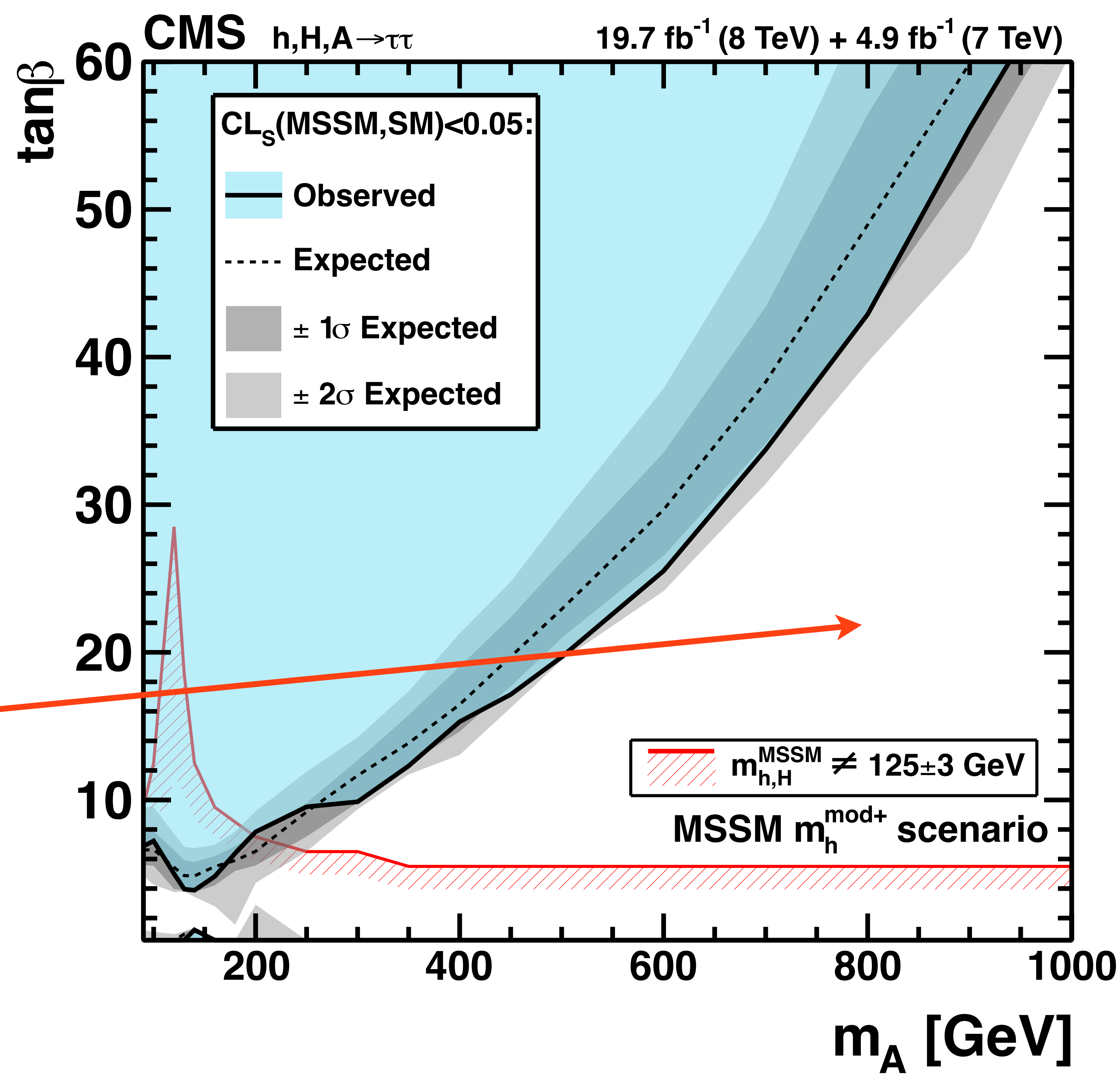
CMS result for h, H, A → ττ search

[CMS Collaboration ’14]

m_h^{mod} benchmark scenario

Test of compatibility of the data to the signal of h, H, A (MSSM) compared to SM Higgs boson hypothesis

⇒ ``Wedge region”, where only h(125) can be detected; difficult to cover also with more luminosity



General case with non-zero CP violation

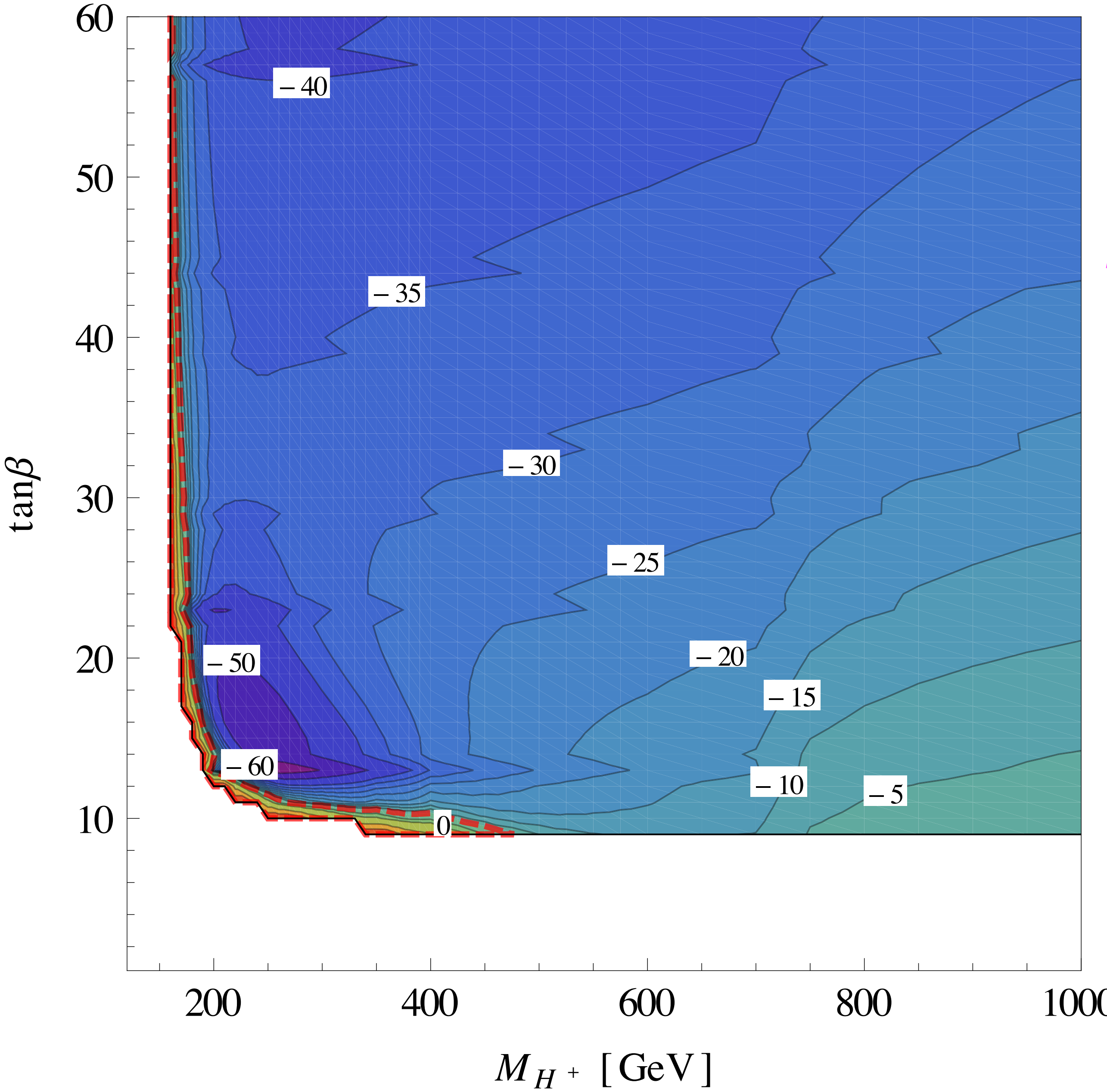
Mixing of the three neutral Higgs states: h, H, A → h_1, h_2, h_3
Heavy Higgs search: h_2, h_3, are nearly mass-degenerate, large mixing possible *[A. Fowler, G. W. '10]*

⇒ Large interference effects (constructive / destructive) possible

Effect of non-zero phase ϕ_{A_t}:
$\delta = (\sigma_\phi - \sigma_0)/\sigma_0$

m_h^{mod+} scenario

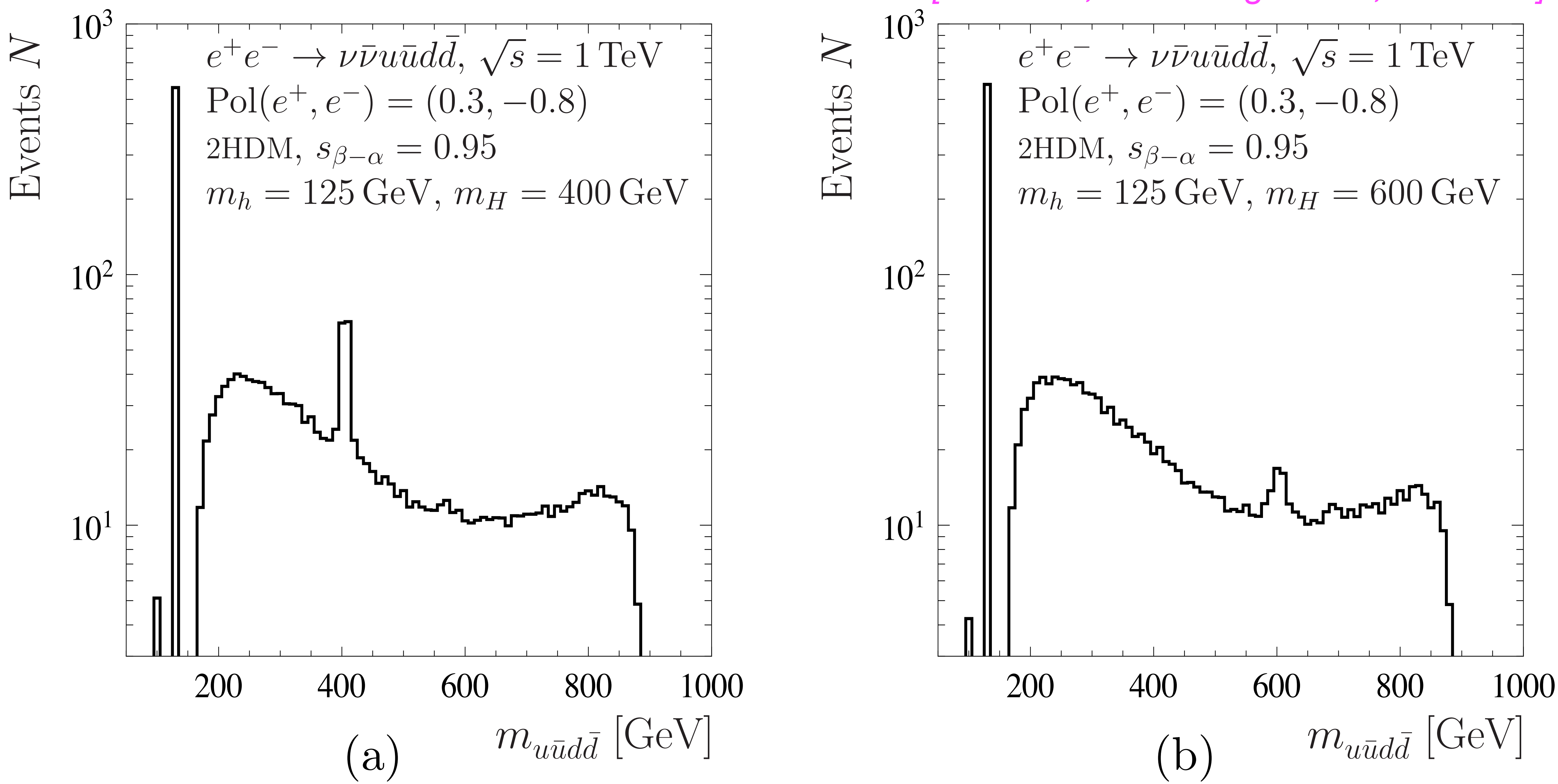
μ = +500 GeV



[E. Fuchs, G. W. '14]

ILC: sensitivity to a heavy Higgs from off-shell effects

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



⇒ Potential sensitivity beyond the kinematic reach of Higgs pair production

Could it be a composite Higgs?

Composite "pseudo-Goldstone boson", like the pion in QCD $\Rightarrow$ Would imply new kind of strong interaction

Relation to weakly-coupled 5-dimensional model (AdS/CFT correspondence)

Discrimination from fundamental scalar

- Precision measurements of couplings ($\Rightarrow$ high sensitivity to compositeness scale), $\mathcal{CP}$ properties, ...
  Does the new state have the right properties to unitarize $W_L W_L$ scattering?
- Search for resonances
  (light Higgs $\Leftrightarrow$ light resonances?)

Interpretation of the signal in extended Higgs sectors (SUSY), case II: 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)

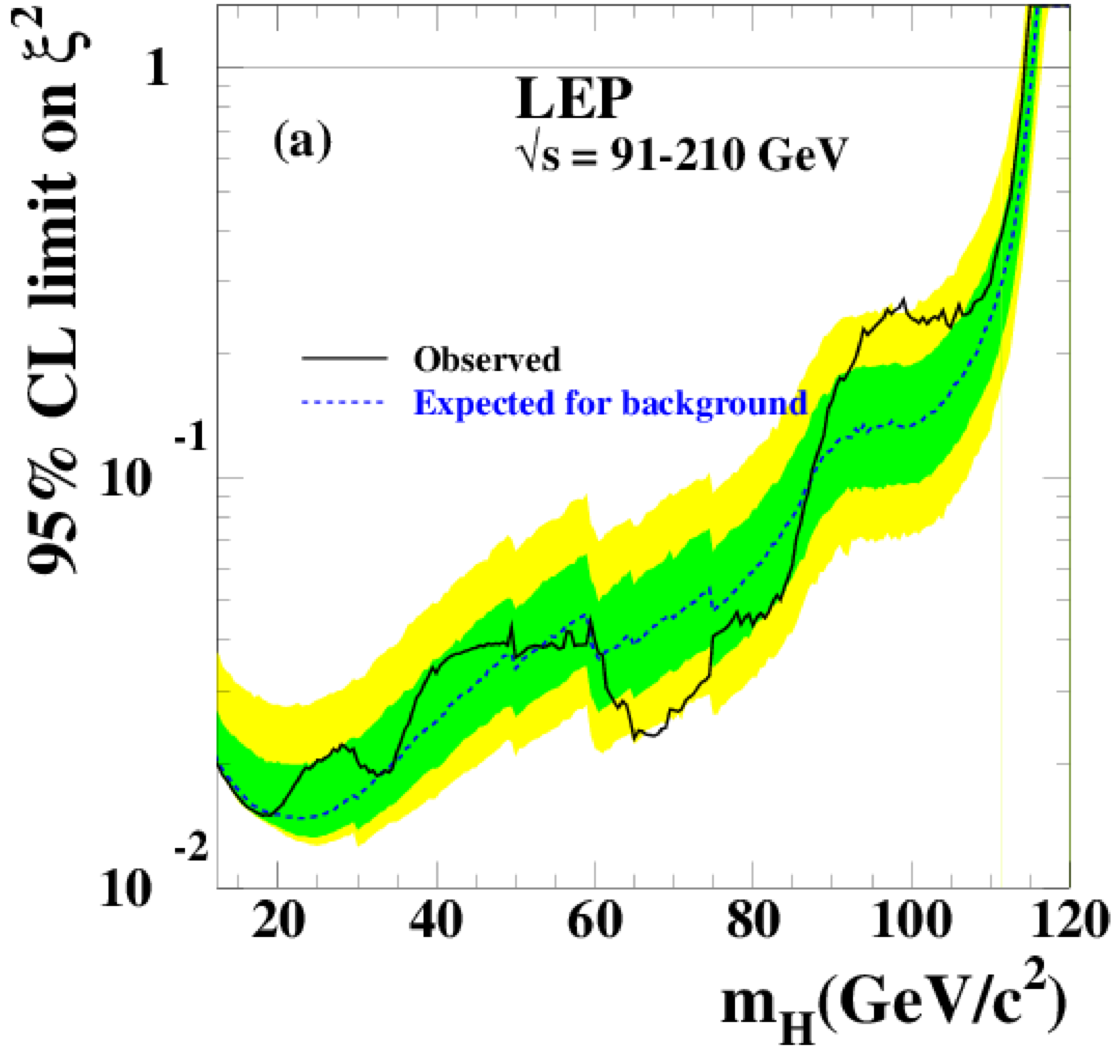
Possible realisations: 2HDM, MSSM, NMSSM, ...

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.

LEP limits on low-mass Higgs bosons

Limits from the LEP Higgs searches: $e^+e^- \to ZH, H \to b\bar{b}$

$$\left(\frac{g_{\mathrm{HZZ}}}{g_{\mathrm{HZZ}}^{\mathrm{SM}}}\right)^2$$



⇒ Limit for SM Higgs (ξ = 1): $M_{\mathrm{H}} > 114.4$ GeV at 95% CL

No limit if the HZZ coupling is below 10% of the SM value

⇒ Unique sensitivity at the ILC

How much can the ILC improve over LEP?

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]*

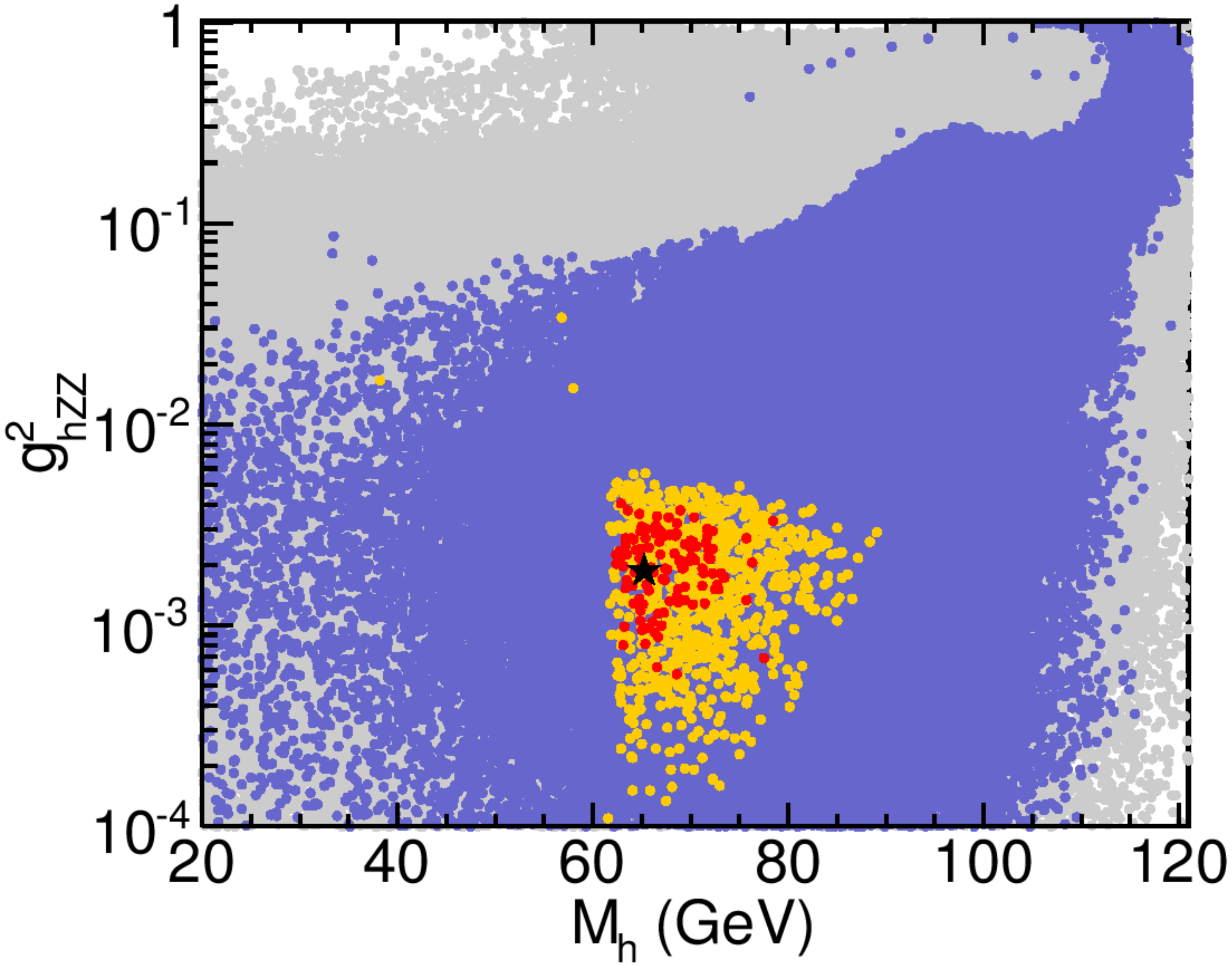
  - Test of Higgs sector predictions in arbitrary models against measured signal rates and masses

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

MSSM realisation: very exotic scenario, where all five Higgs states are light, h, H(125), A, H^{+-}

Lightest Higgs: mass and couplings to gauge bosons (blue: *HiggsBounds*-allowed)

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

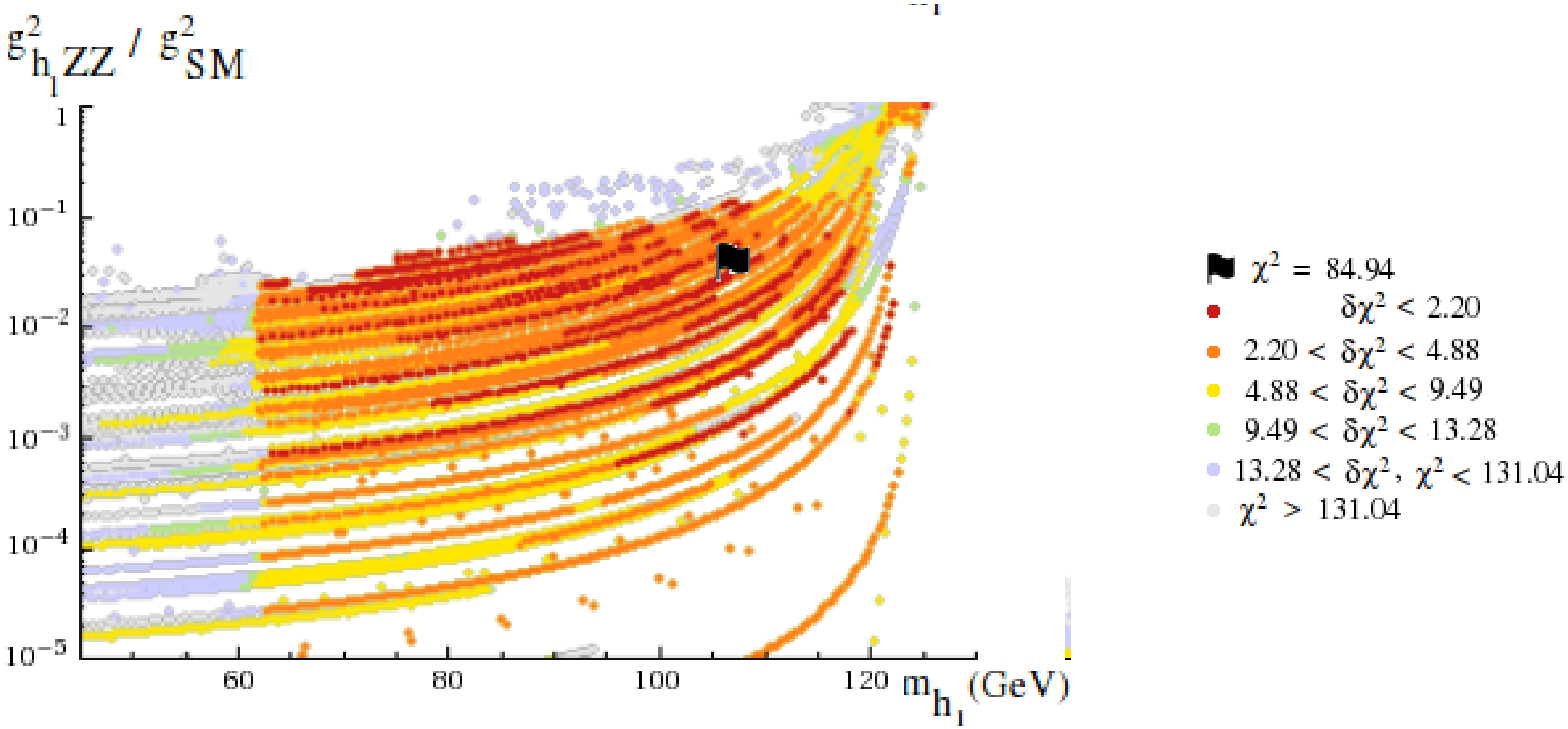


⇒ Light Higgs with $M_\mathrm{h} \approx 70~\mathrm{GeV}$, in agreement with LEP limits

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

In the NMSSM such a situation arises generically if the Higgs singlet is light

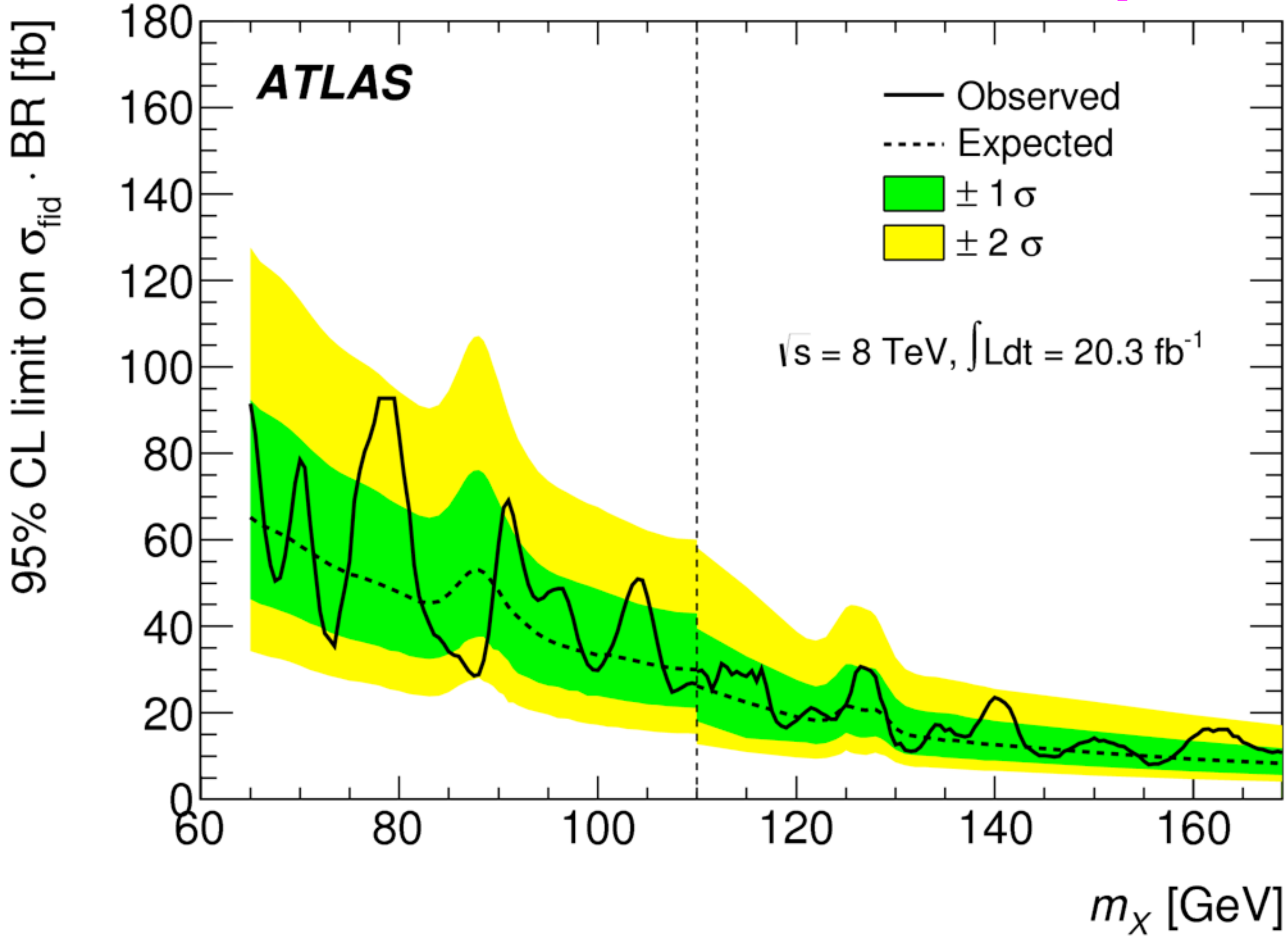
[F. Domingo, G. W. '14]



⇒ SM-like Higgs at 125 GeV + singlet-like Higgs at lower mass
Large singlet component leads to strong suppression of the coupling to gauge bosons

Are LHC searches sensitive to a low-mass Higgs with suppressed couplings to gauge bosons?

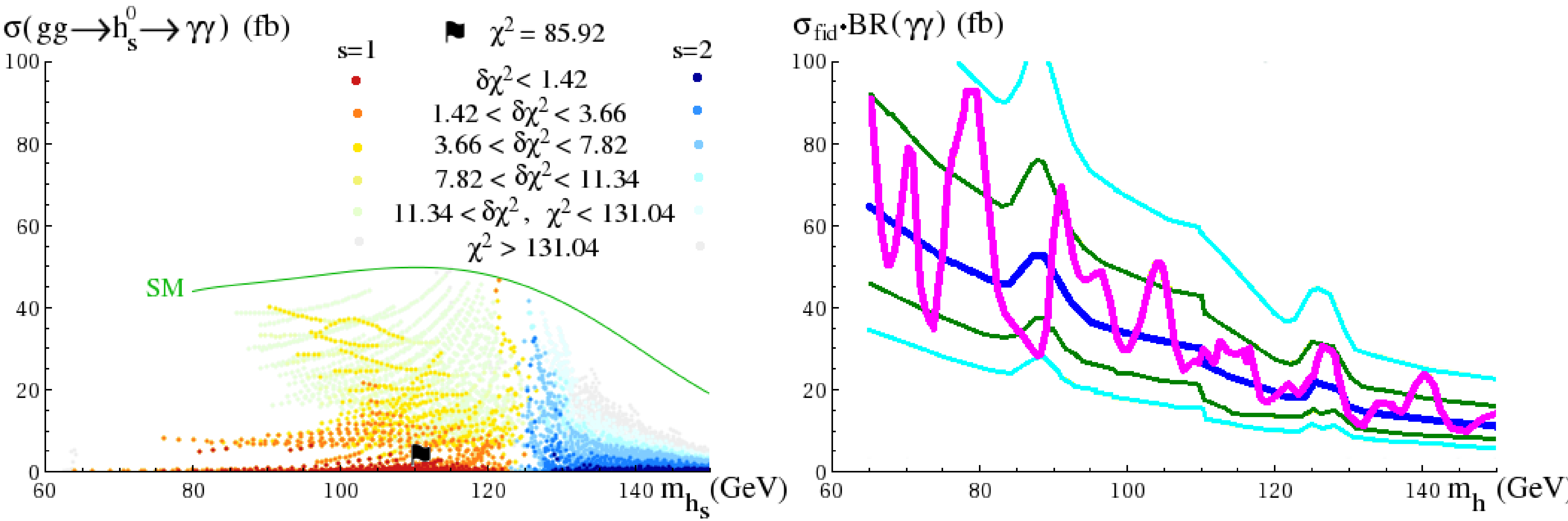
ATLAS h → $\gamma\gamma$ searches in the low-mass region: [ATLAS Collaboration '14]



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

Light NMSSM Higgs: comparison of gg $\rightarrow h_1 \rightarrow \gamma\gamma$ with the SM case and the ATLAS limit on fiducial σ

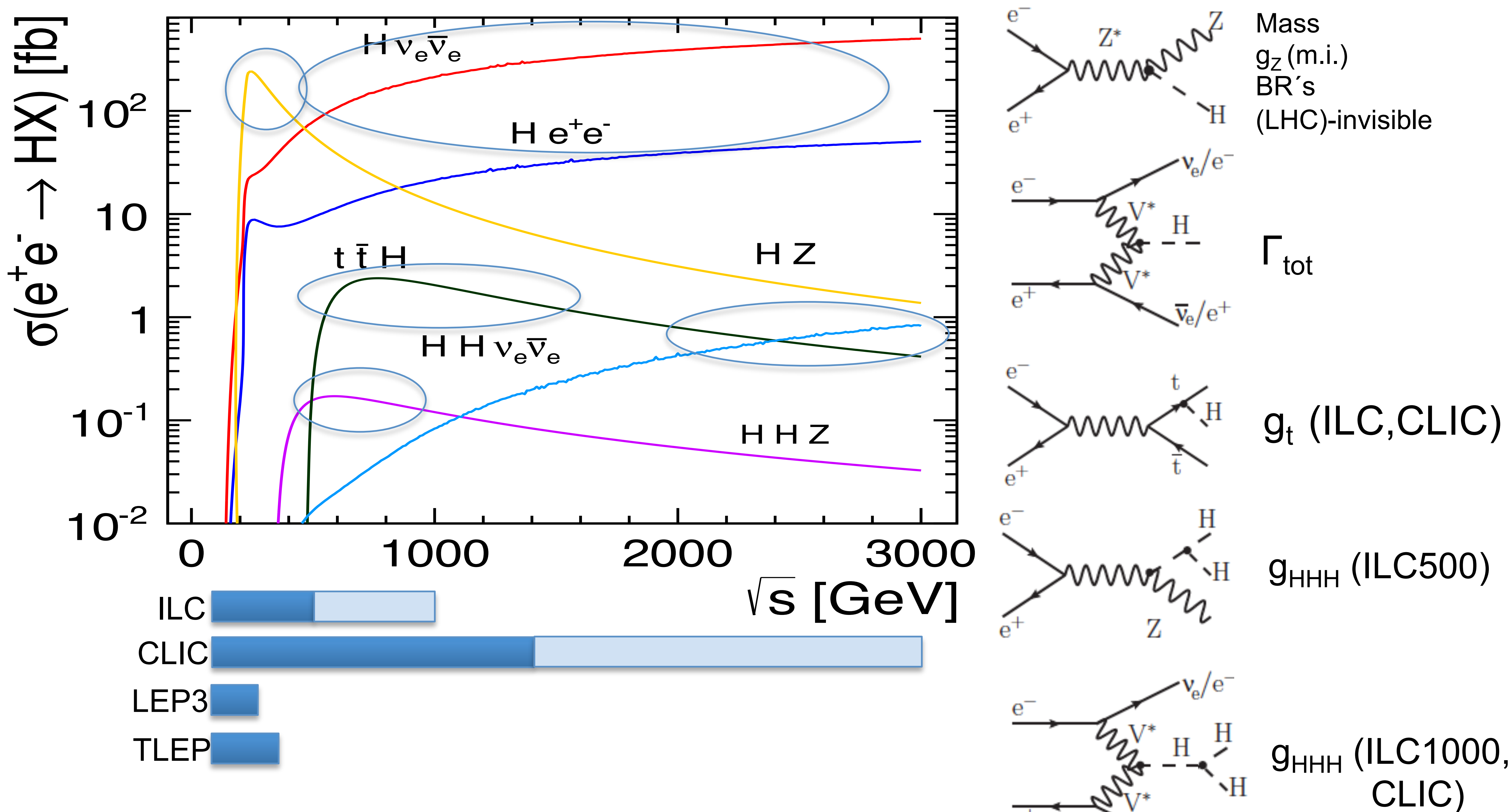
[F. Domingo, G. W. ’14]



⇒ Limit starts to probe the NMSSM parameter space

But: best fit region is far below the present sensitivity

Higgs production at e^+e^- colliders



- Many processes at different $\sqrt{s}$ needed & accessible

What do we know about the properties of the discovered signal?

- Mass: ATLAS + CMS ⇒ M_H = 125.09 ± 0.24 GeV : already a precision observable (0.19%)

- 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

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

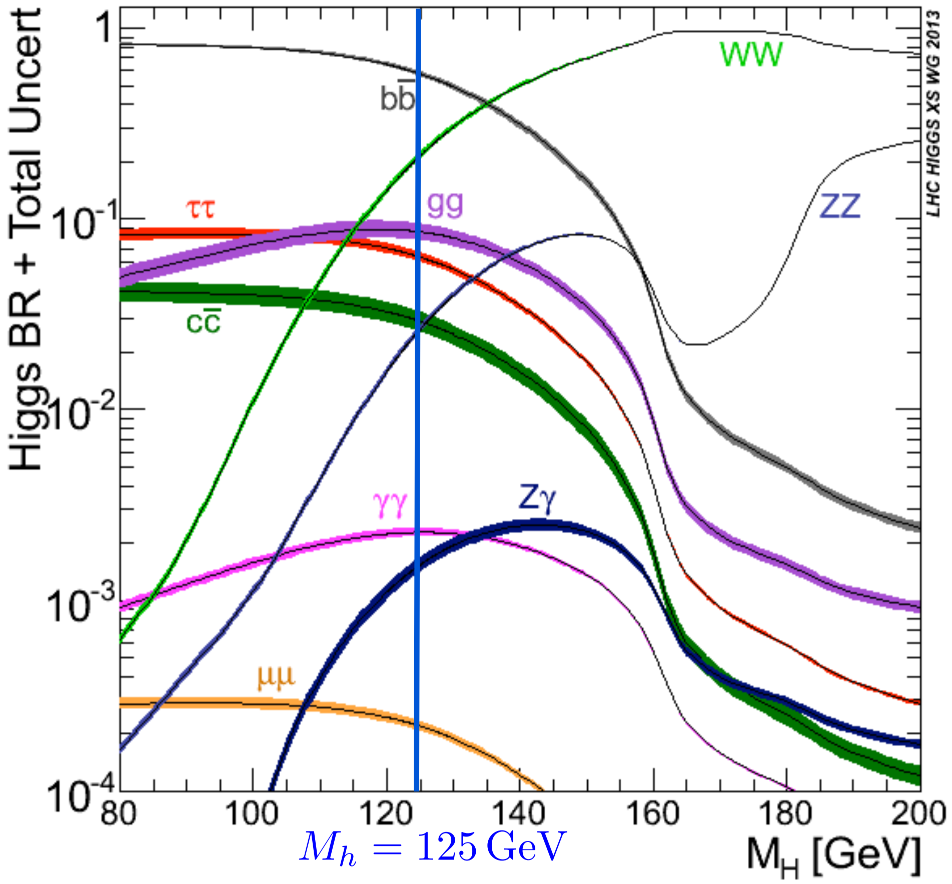
A change in M_H of 0.2 GeV shifts $BR(H \to ZZ^*)$ by 2.5%!

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

Mass dependence and off-shell effects

High sensitivity on mass value and importance of off-shell effects for BR(H → ZZ*), BR(H → WW*) have same physical origin:

SM Higgs branching fractions:



[LHC Higgs XS WG '14]

For a 125 GeV Higgs boson the branching ratios into BR(H → ZZ*), BR(H → WW*) are far below threshold
⇒ Strong phase-space suppression, steep rise with M_H

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

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 $H \to ZZ^* \to 4\, l$, etc. because of the smallness of a_3

Hypothesis of a pure CP-odd state is experimentally disfavoured

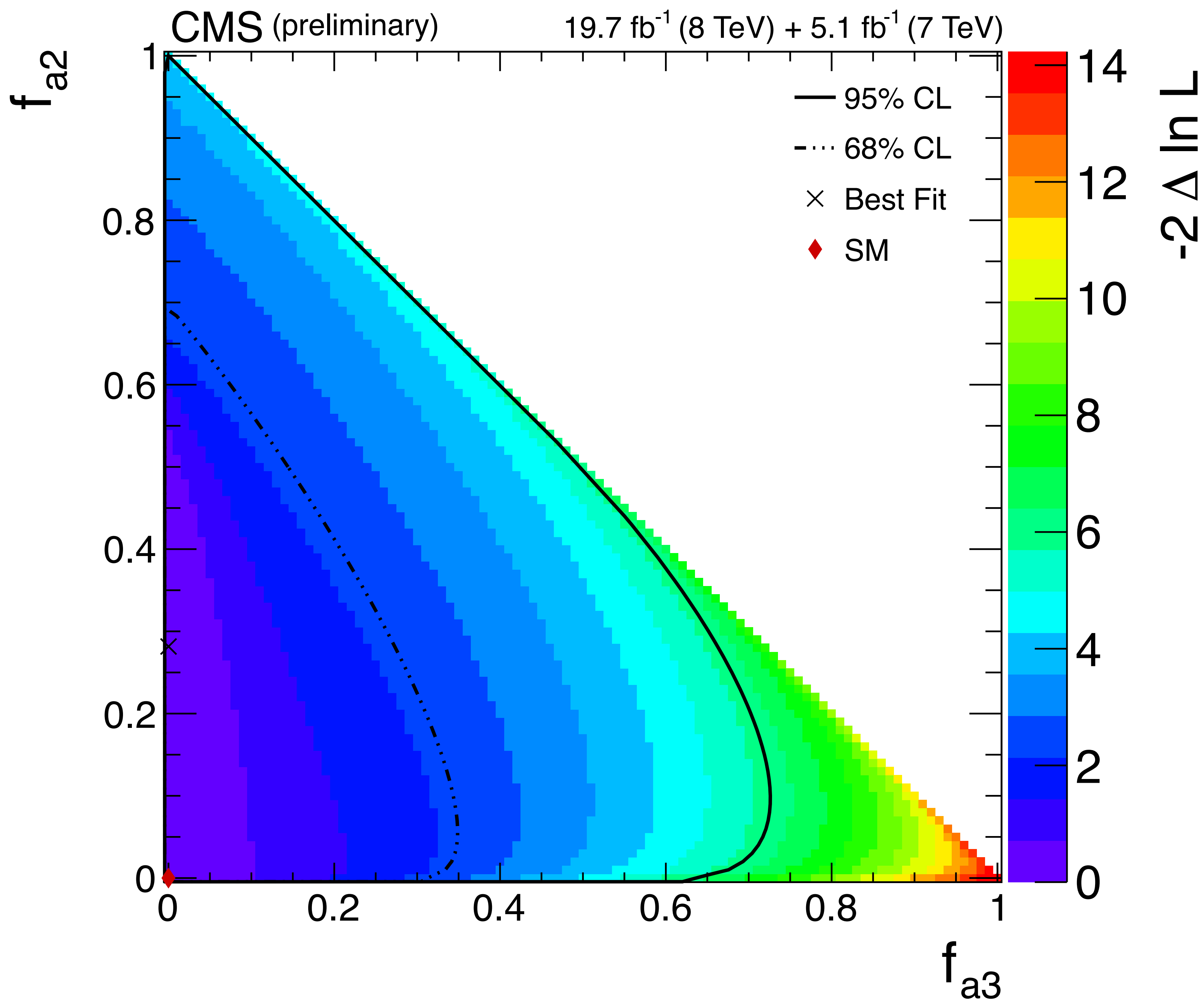
However, there are only very weak bounds so far on an admixture of CP-even and CP-odd components

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

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}!

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

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

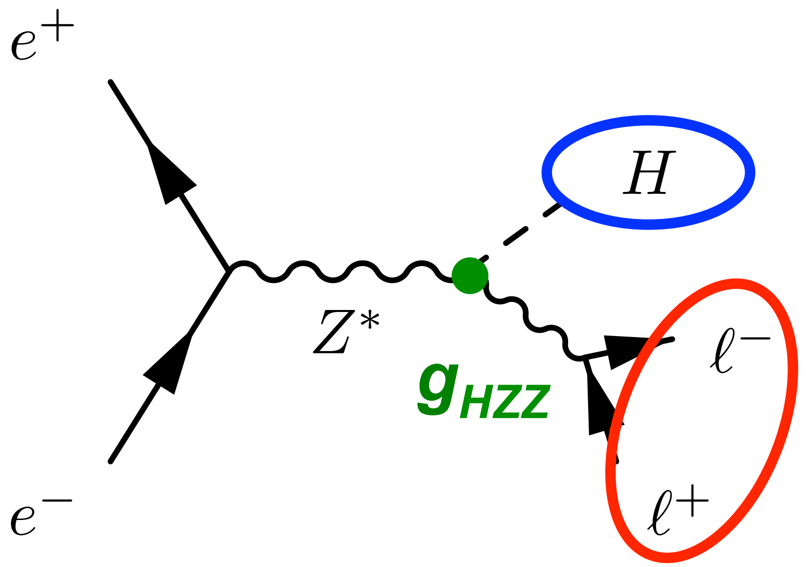
"Golden channel" at the ILC: $e^+e^- \to ZH, Z \to e^+e^-, \mu^+\mu^-$

Recoil method: absolute measurement of *ZH* cross section and branching ratios

Reconstruct $Z \to l^+l^-$

independent of Higgs decay

sensitive to invisible Higgs decays



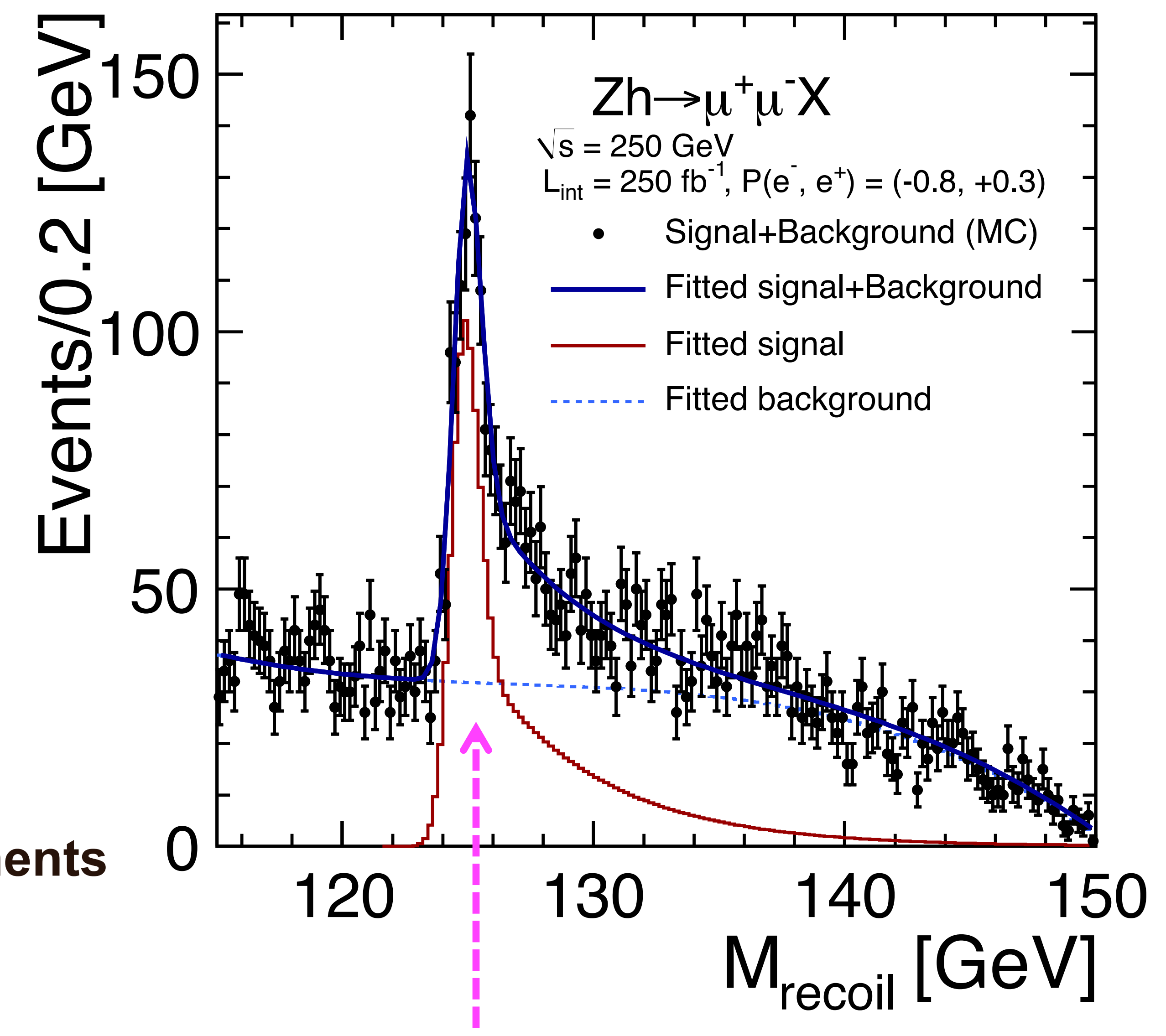
$$m^2_{\text{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

Model-independent, absolute measurements

$Z \to e^+e^-, \mu^+\mu^-$, $\sqrt{s}$=250 GeV, L=250 fb-1

- $\sigma_{ZH} \leq 2.6\%$
- $\Delta m_H \leq 30$ MeV
- BR(invisible) < 0.7% (95% C.L.)

ILC Higgs WG Input to Snowmass



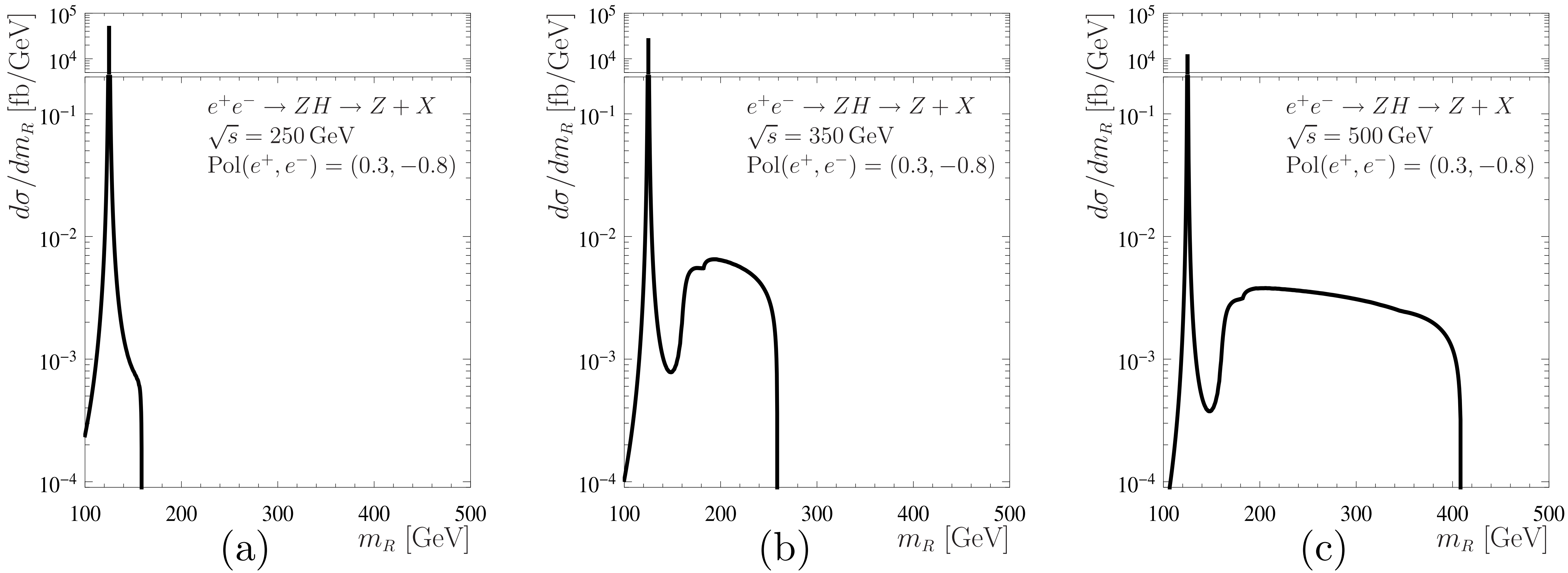
Gauss. width ≈ 650 MeV = 560 MeV ⊕ 330 MeV

beam energy spread

detector resolution

Recoil method: impact of off-shell effects

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



$\sqrt{s}$	250 GeV	300 GeV	350 GeV	500 GeV	1 TeV
Δ_{off}	0.02 %	0.12 %	0.30 %	0.91 %	1.84 %

$\Rightarrow$ Relatively small overall effect, grows with increasing c.m. energy

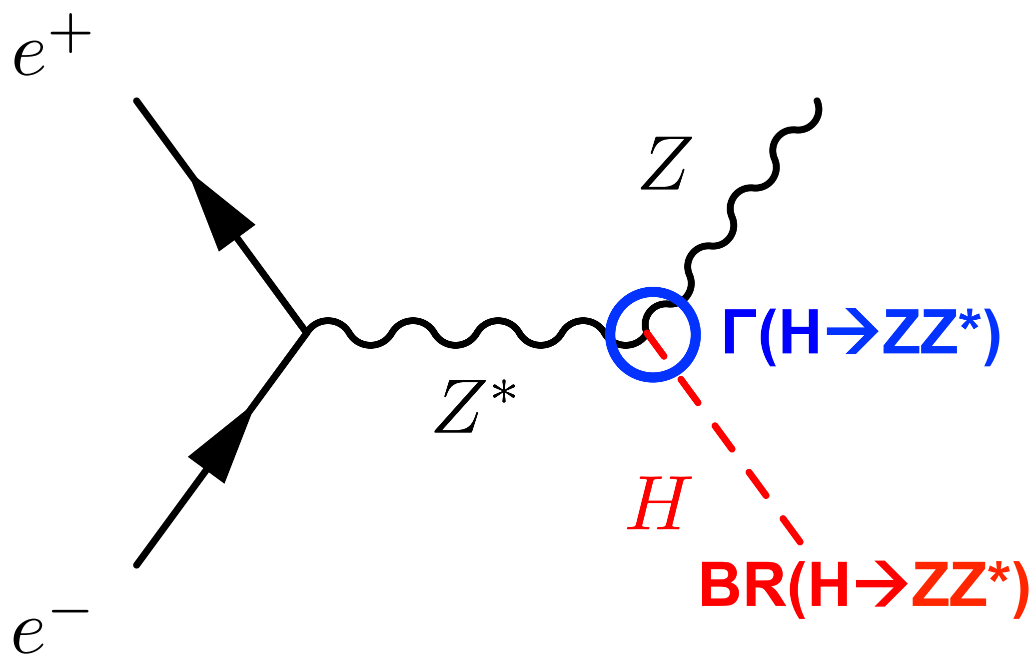
Total width

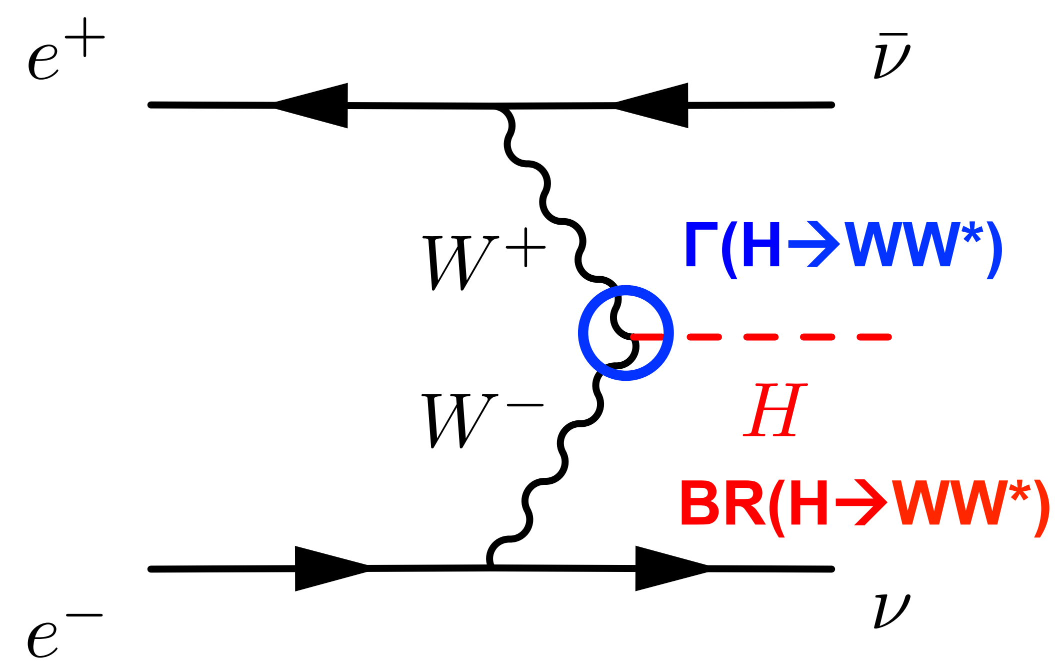
To extract couplings from BRs, we need the total width:

$$g_{HXX}^2 \propto \Gamma(H \to XX) = \Gamma_H \cdot BR(H \to XX)$$

To determine the total width, we need at least one pair of partial width and BR:

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





Combining 250 GeV (250 fb-1) + 500 GeV (500 fb-1) measurements

$$\Delta\Gamma_H/\Gamma_H \simeq 5\%$$

Total Higgs width: recent analyses from CMS and ATLAS

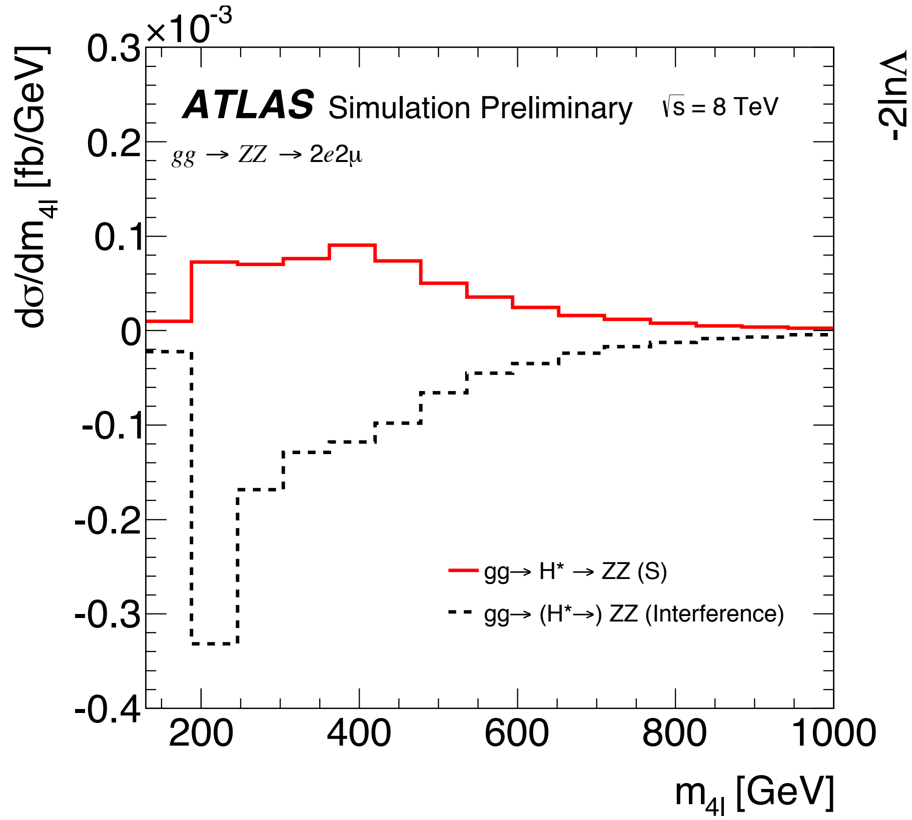
- Exploit different dependence of on-peak and off-peak contributions on the total width in Higgs decays to $ZZ^{(*)}$
- CMS quote an upper bound of $\Gamma/\Gamma_{\mathrm{SM}} < 5.4$ at 95% C.L., where 8.0 was expected, ATLAS: $\Gamma/\Gamma_{\mathrm{SM}} < 5.7$ at 95% C.L., 8.5 expect.
  [CMS Collaboration '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

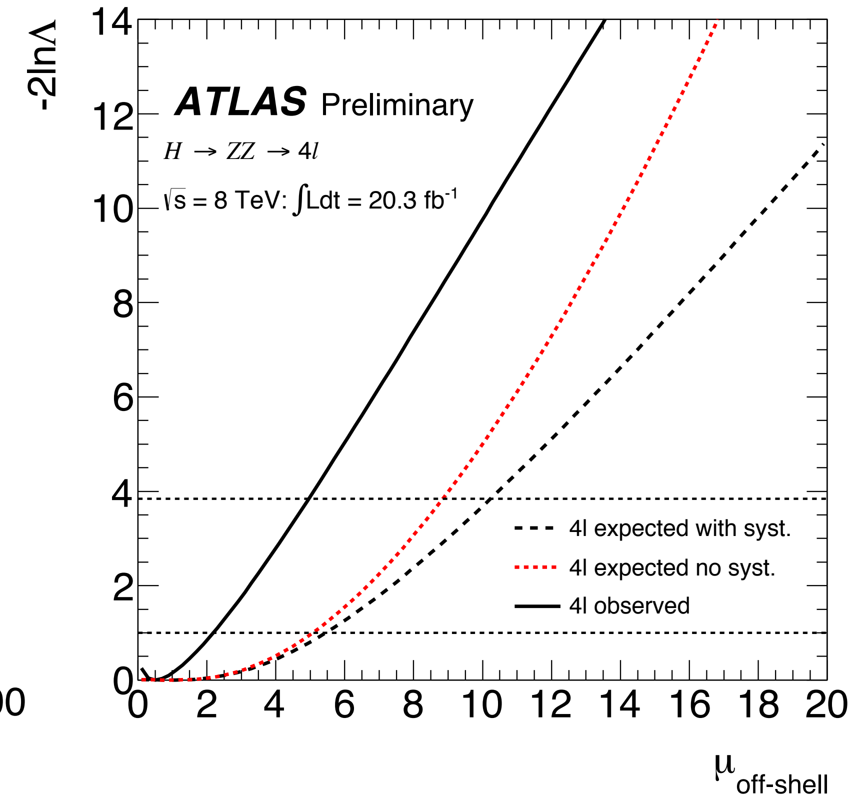
Destructive interference between Higgs- and gauge-boson contributions (unitarity cancellations) ⇒ difficult to reach $\Gamma/\Gamma_{\mathrm{SM}} \approx 1$ even for high statistics

Destructive interference in $gg \to$ 4 leptons

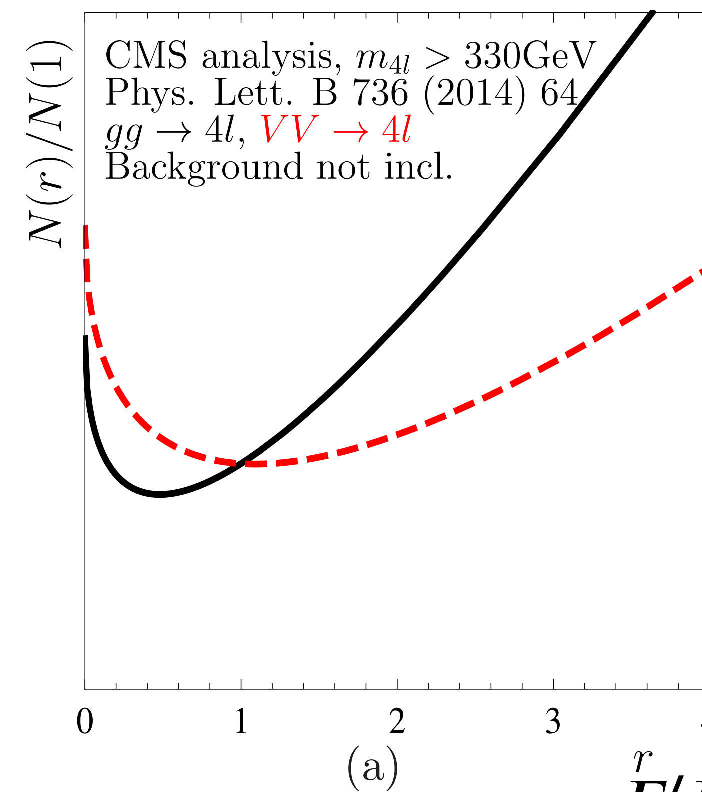
[ATLAS Collaboration ’14]



[ATLAS Collaboration ’14]



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



r = Γ/Γ_{SM}

Destructive interference between Higgs- and gauge-boson contributions (caused by unitarity cancellations)

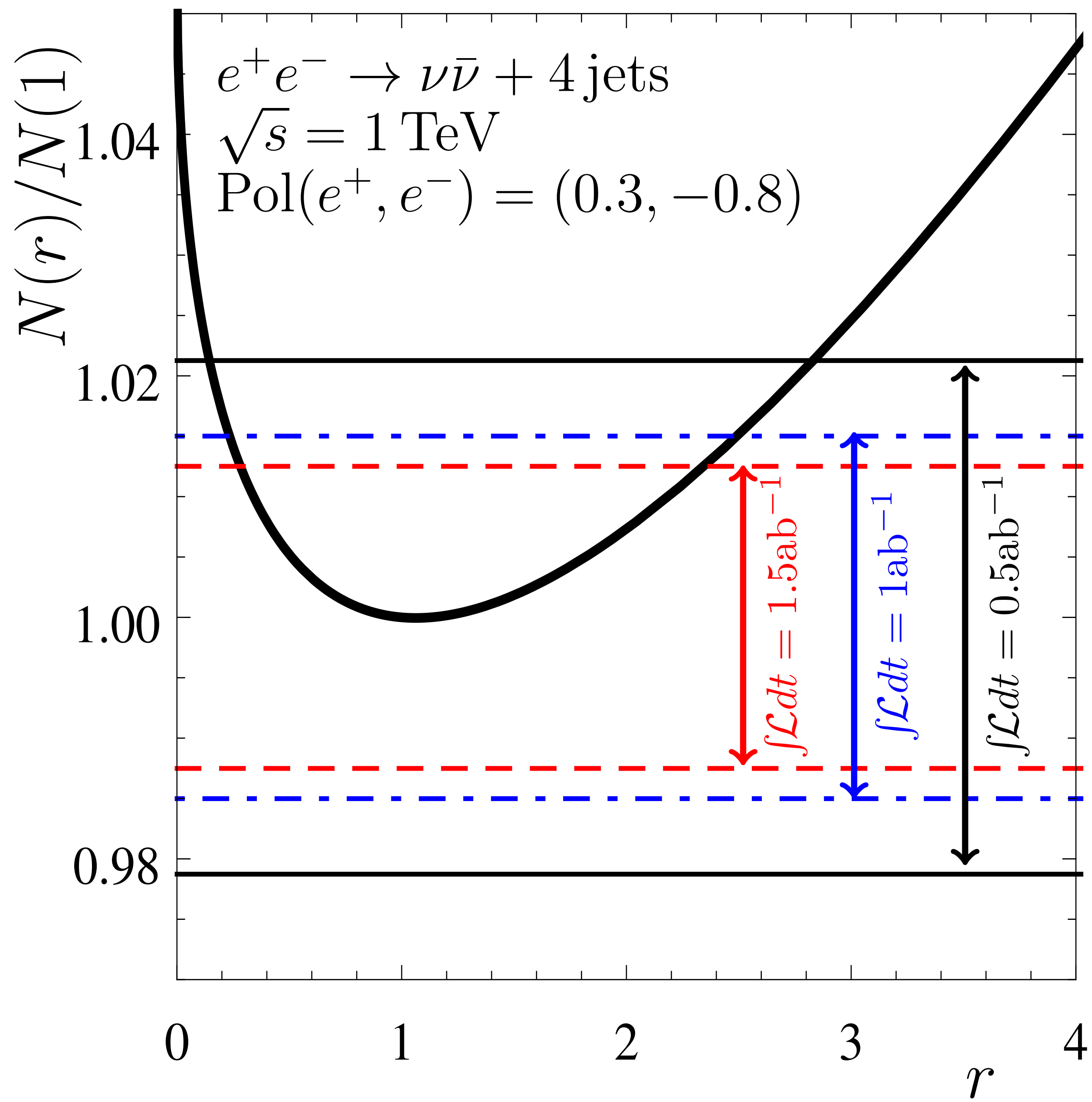
Large negative s - b interference

⇒ Sensitivity to Higgs width flattens out near $\Gamma/\Gamma_{SM} \approx 1$; $N(r) = N_0(1 + R_1\sqrt{r} + R_2 r)$

⇒ It will be difficult to reach the level of the SM width, even with high statistics

ILC: constraints on the total width via off-shell effects

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



⇒ Limited sensitivity even with high integrated luminosity

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” $\varkappa_i$.

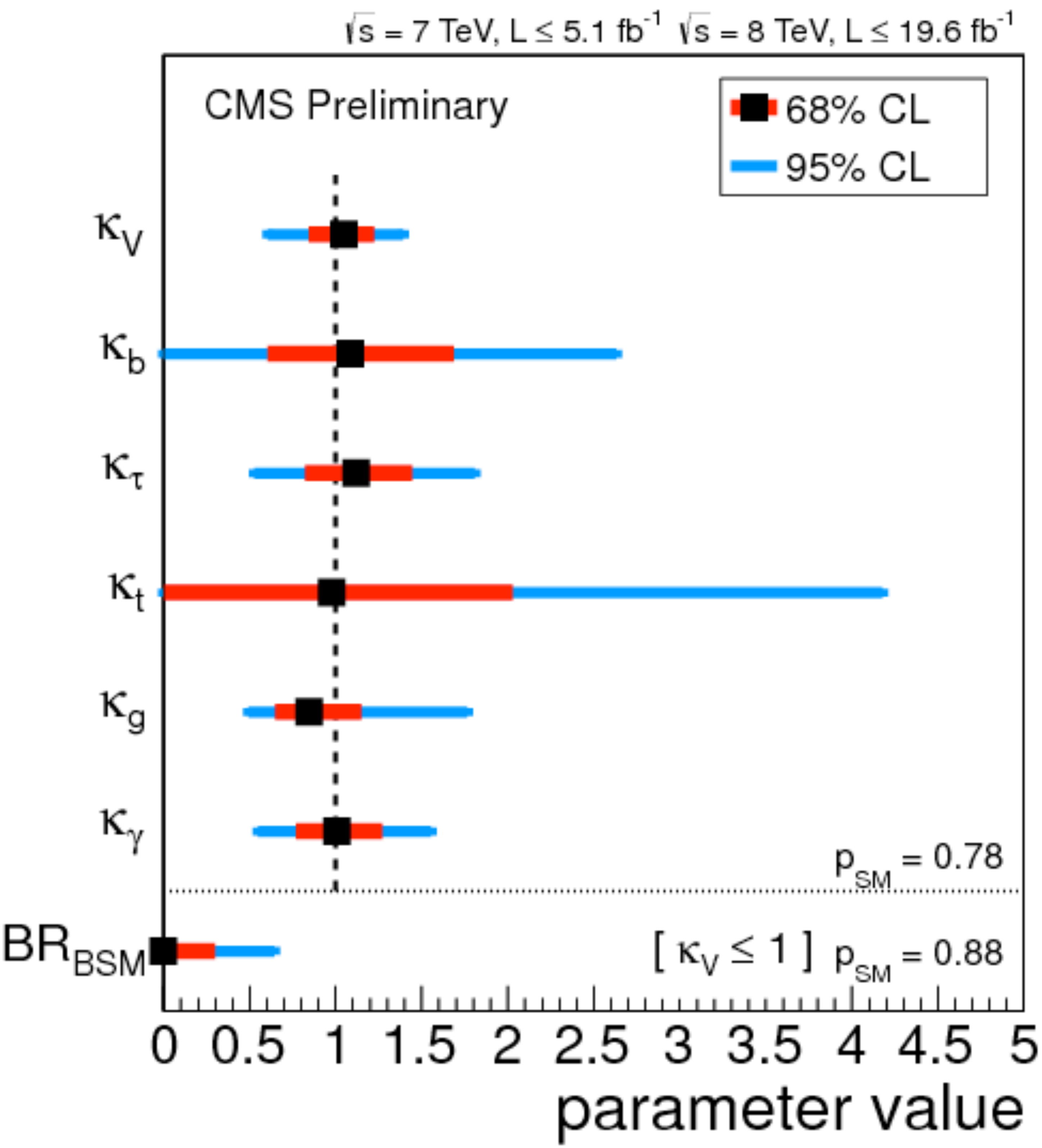
Assumptions:

- 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]



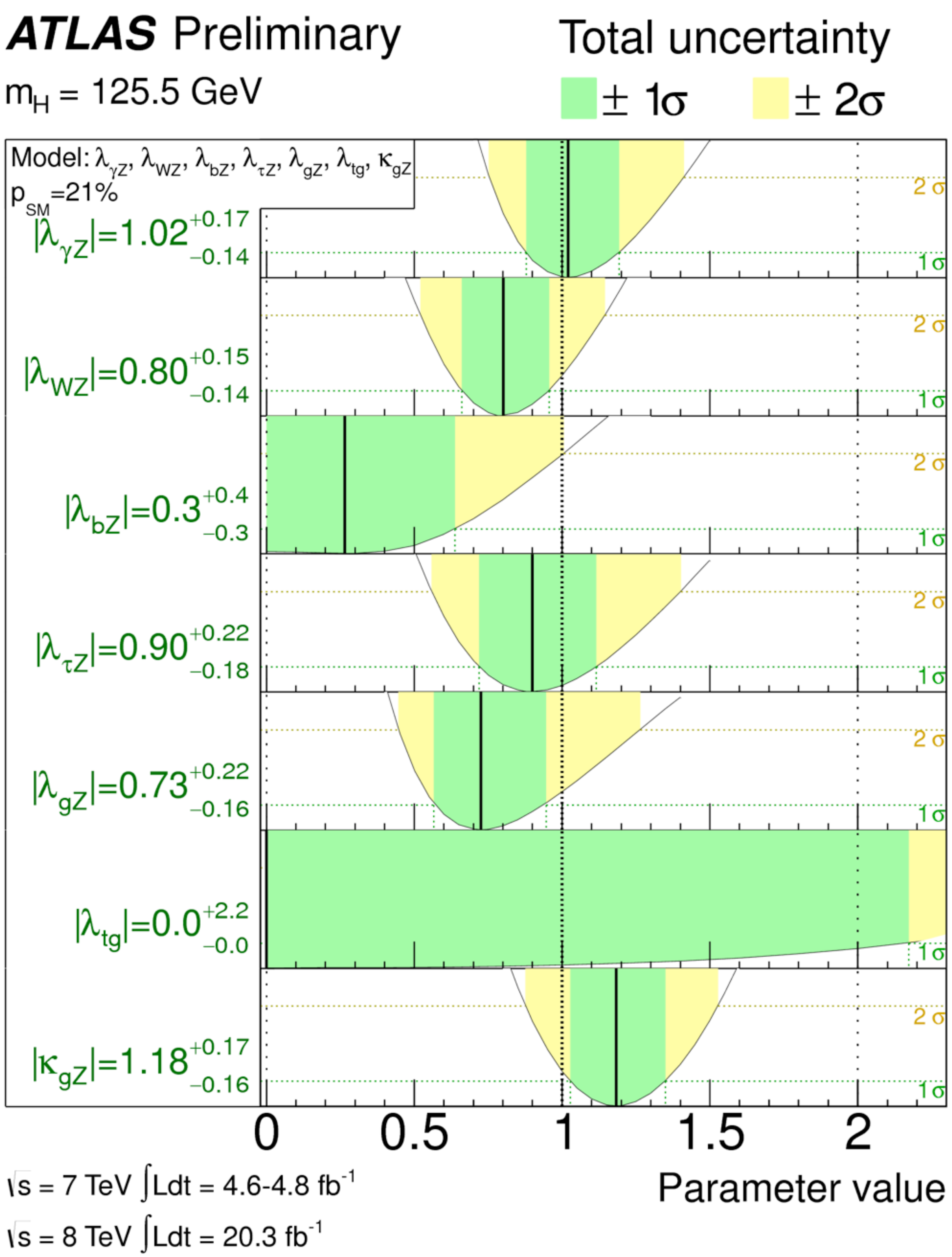
⇒ Compatible with the SM with rather large errors

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]

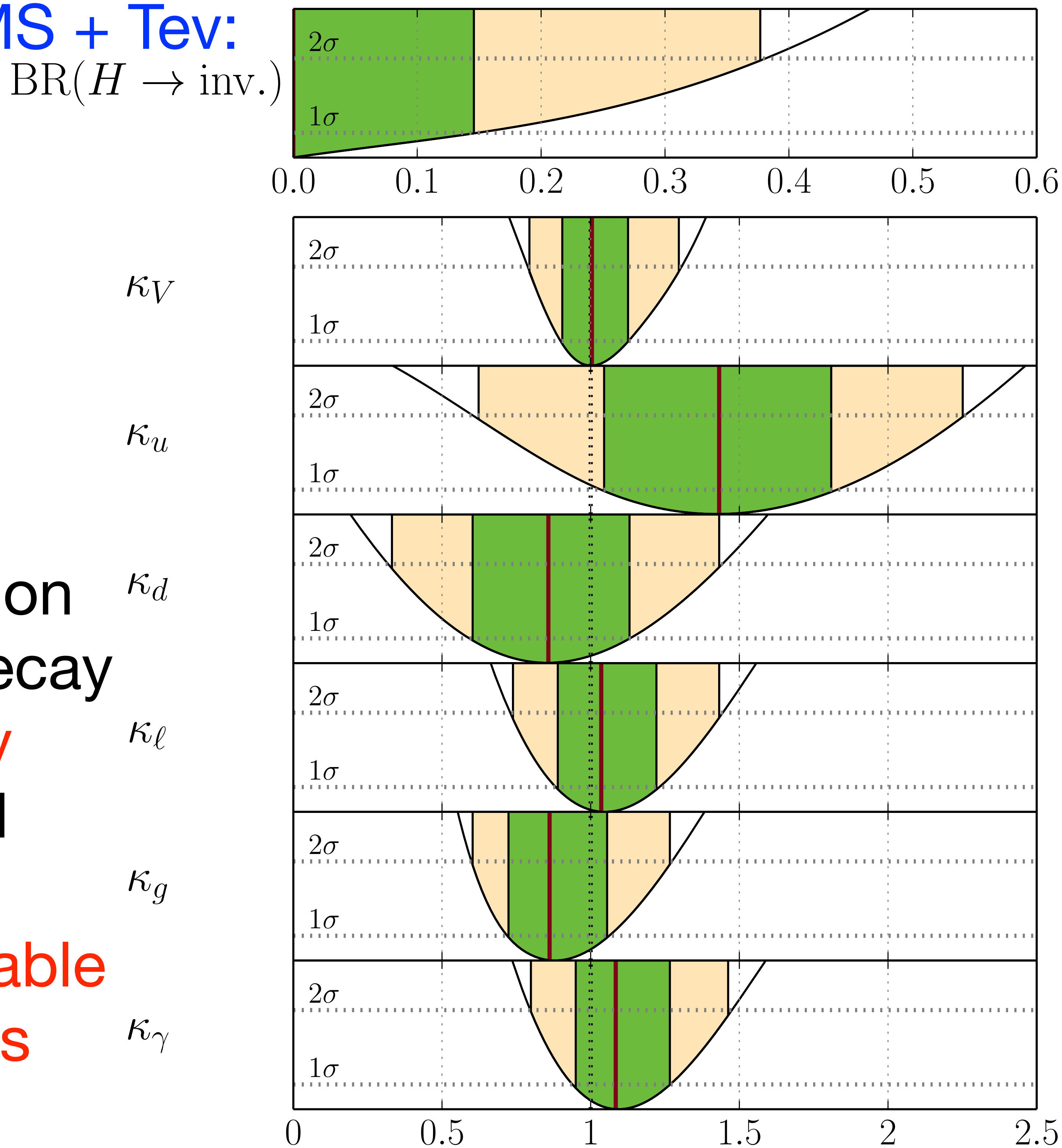


⇒ Determination of ratios of coupling scale factors

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

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

ATLAS + CMS + Tev:



HiggsSignals

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

Seven fit parameters

Assumption on additional decay modes: only invisible final states; no undetectable decay modes

⇒ Significantly improved precision compared to ATLAS or CMS results alone

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

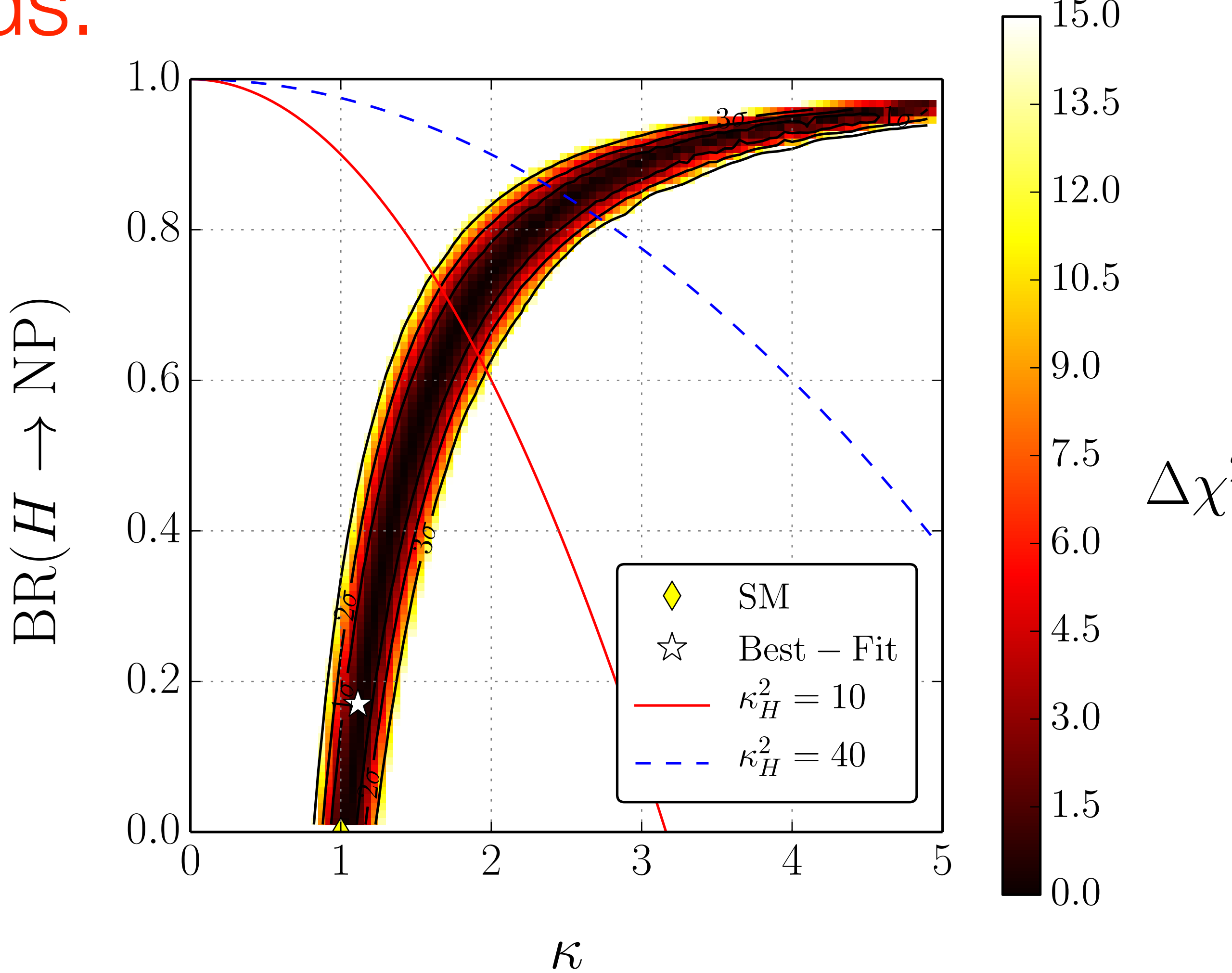
[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W. '14]

HiggsSignals

ATLAS + CMS bounds:

Common scale factor ϰ for all Higgs couplings

No assumptions on undetectable / invisible decays

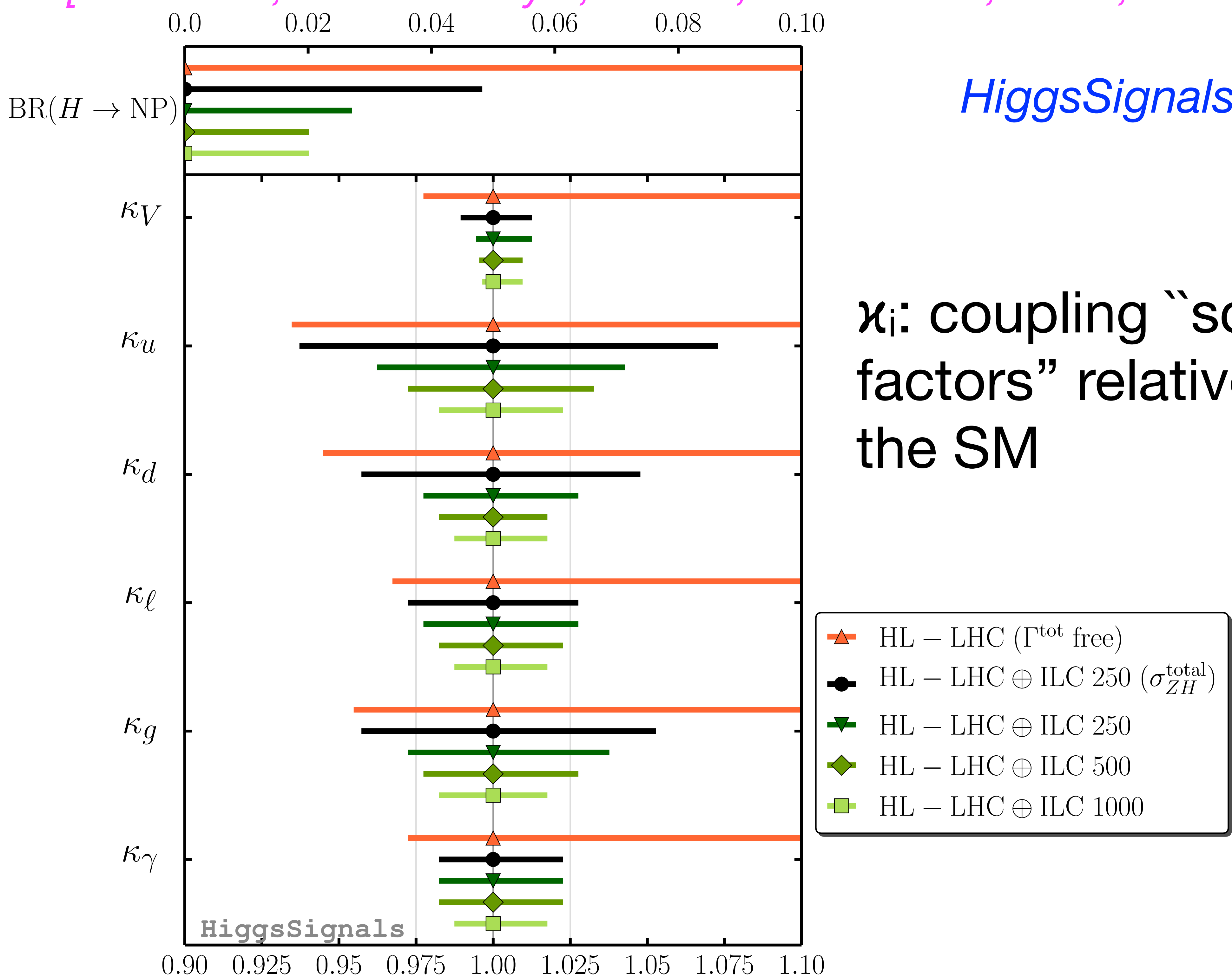


⇒ • Large range possible for scale factor ϰ and branching ratio into new physics final states without additional theoretical assumptions

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

Prospects for Higgs-coupling determinations at HL-LHC, ILC without theory assumption on total width

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



HiggsSignals

$\varkappa_i$: coupling ``scale factors" relative to the SM

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

Conclusions

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

Need high-precision measurements of the properties of the detected particle + precise theory predictions to reveal the nature of electroweak symmetry breaking
⇒ Close interaction between experiment and theory needed!

The best way to experimentally prove that the observed state at 125 GeV is not the SM Higgs would be to find in addition (at least one) non-SM like Higgs! Have to look above but also below 125 GeV!

⇒ Rich physics programme for Run 2 of the LHC and the ILC
⇒ Exciting prospects: Higgs physics may be the key to revealing the physics behind the Standard Model!