SUSY interpretations of the H signal: Implications for the LC

- *Higgs signal: what does it not tell us?*
- *Impact for H@LC in the MSSM*
- *Impact for H@LC in the NMSSM*
- *Prospects for extended SUSY Models@LC*
- *Conclusions*

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Status Higgs @ LHC

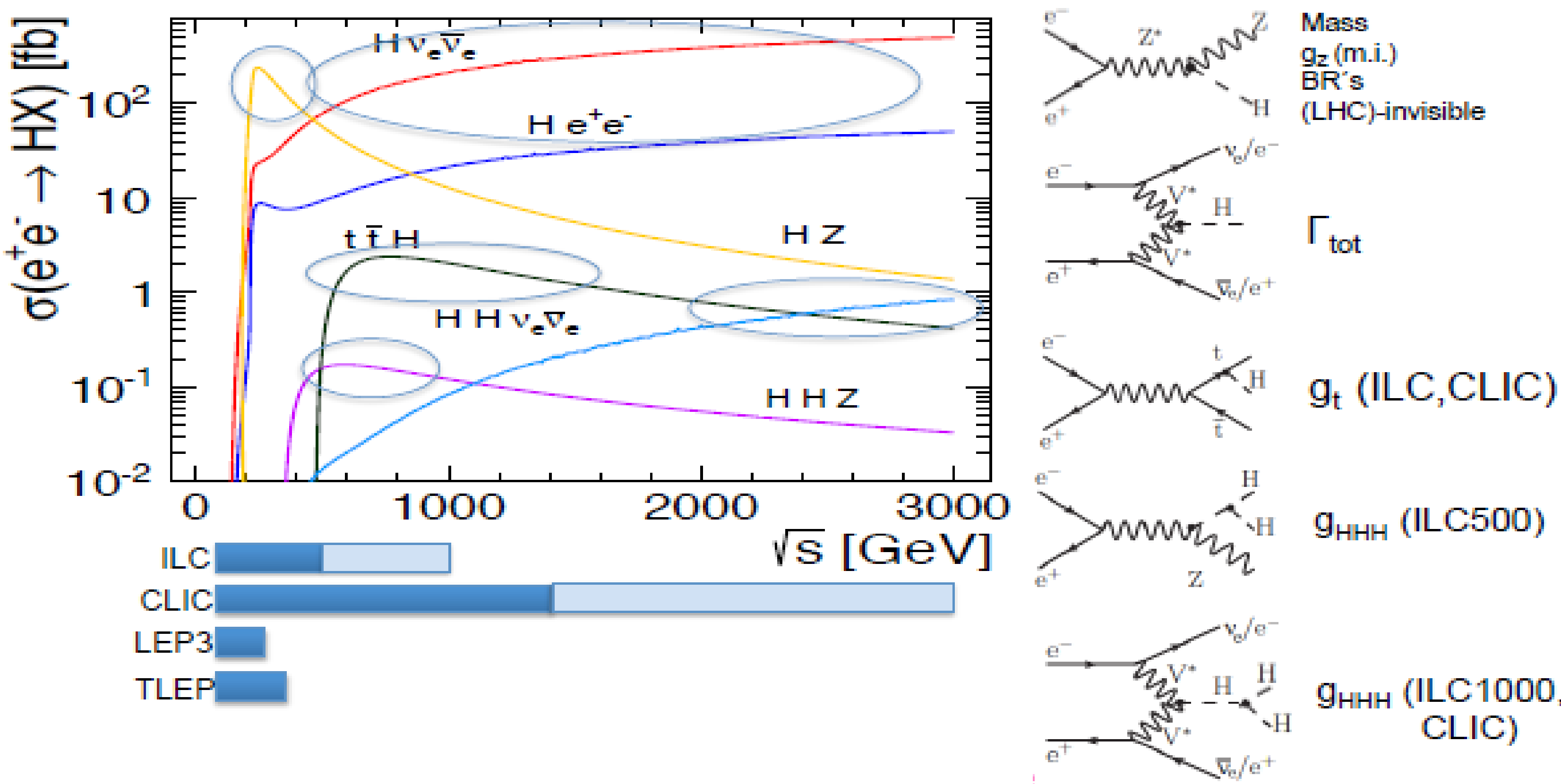
What does the discovered signal tell us?

- The discovered signal is so far compatible with a SM-like Higgs, but a variety of interpretations is possible, corresponding to very different underlying physics
- On the one hand: it is impressive how much we believe to know about the new state so short after its discovery
- On the other hand, there is still some way to go in exploring the properties and unravelling the underlying structure
  - Higher precision is required
  - Underlying assumptions being made so far have to be reduced

➡ **The Linear Collider is crucial in this regard!**

Higgs @ LC

Many processes at different √s needed & accessible



The Linear Collider is crucial in this regard!

Higgs mass: 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*), .etc.. to test BSM physics !**

CP Properties

- CP properties: more difficult than spin!
  - *Observed state : any admixture CP-even and CP-odd components*
- Observables mainly used to analyze CP-properties
  - $H \rightarrow ZZ^*, WW^*$ and H production in weak boson fusion

  involve HVV coupling
- General structure of HVV coupling (from Lorentz invariance):

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

  SM, pure CP-even state: $a_1 = 1$, $a_2 = 0$, $a_3 = 0$

  Pure 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

- **Problem:** *Observables involving the HVV coupling provide only limited sensitivity to effects of CP-odd components; even a rather large CP-admixture would not lead to observable effects in angular distributions of $H \rightarrow ZZ^* \rightarrow 4\,l$, etc. because of smallness of a_3!*
- **Hypothesis of a pure CP-odd state: experimentally disfavoured!**

  However, there are only very weak bounds so far on an admixture of CP-even and CP-odd components
- **Channels involving Higgs couplings to fermions mandatory**

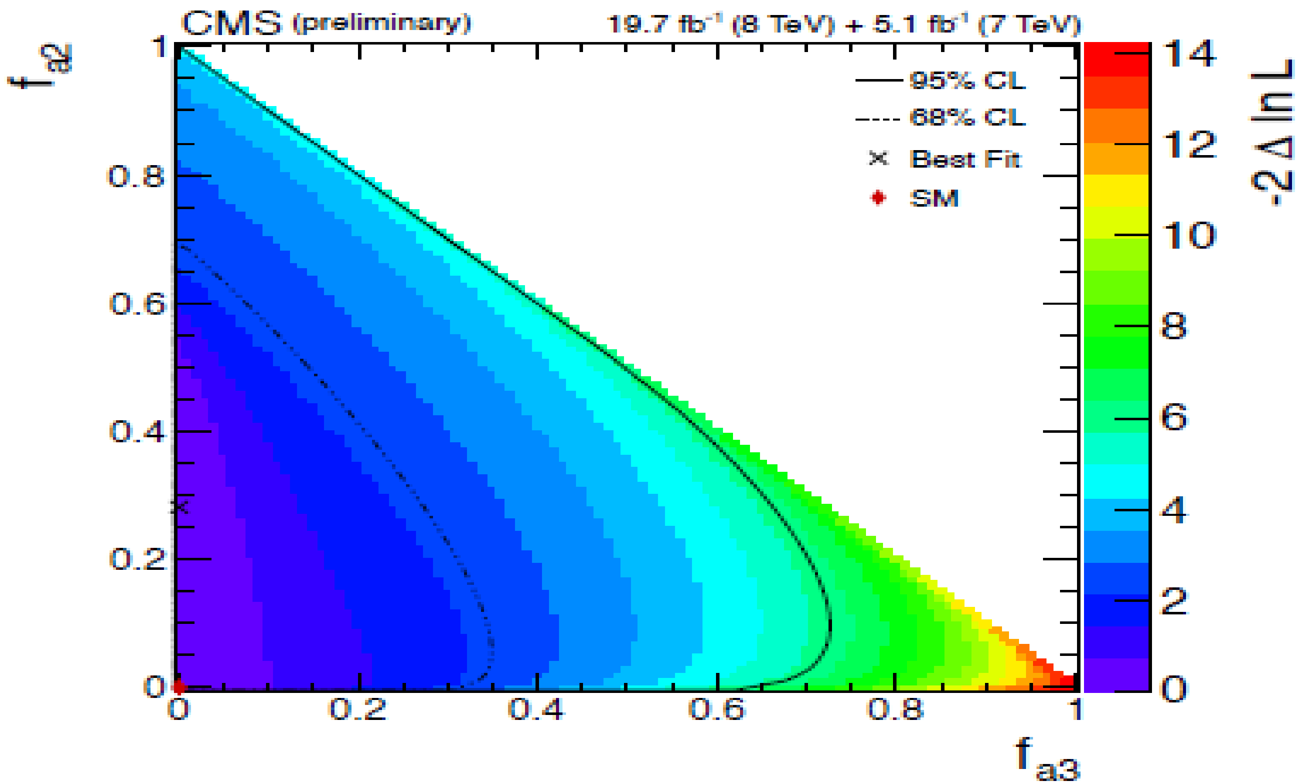
➢ ***Crucial input from ILC: exploitation of t and τ polarization!***

Beyond hypotheses of pure CP-even/odd

- **Experimental analyses:**

CMS Collaboration '14

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



Beyond hypotheses of pure CP-even/odd

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

- **At the LC:**
  - **Use angular distributions in $\tau\ \tau$ decays, exploit τ polarization, extract CP-violating phase up to 6^0** — Desch, Imhof, Was, Worek '04
  - **Other approach: top polarization**

Total Higgs width: recent LHC analyses

cf. talk S. Liebler!

- Exploit different dependence of on-peak and off-peak contributions on the total width in Higgs decays to ZZ(*)
- CMS quote upper bound of Γ/Γ_{SM}<5.4 at 95% c.l., where 8.0 was expected, ATLAS: Γ/Γ_{SM}<5.7 at 95% c.l., 8.5 expected

CMS Collaboration '14, ATLAS Collaboration'14

- Problem: assumed equality beyond on-shell and 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. Spannowsk '14

➢ SM consistency test rather than model-independent bound

Destructive interference between Higgs- and gauge-boson contr. (unitarity cancellations) ⟶ difficult to reach $\Gamma/\Gamma_{SM} \sim 1$ even for high statistics

Extended Higgs sectors: possible deviations from SM

- **SUSY as prototype: well motivated, theory predictions worked out up to high level of sophistication**
  - **`Simplest' extension of minimal Higgs sector: Minimal Supersymmetric Standard Model (MSSM)**
  - **Two doublets to give masses to up- and down-type fermions (extra symmetry forbids to use the same doublet)**
  - **SUSY imposes relations between the parameters**

    Two parameters instead of one: $\tan\beta = v_u/v_d$, M_A (or $M_{H\pm}$)

    Upper bound on lightest Higgs mass, M_h:

    Lowest order: $M_h < M_Z$

    Including higher order corrections: $M_h \approx 135$ GeV (for TeV m_{stop})

- ***Interpretation of signal at 125 GeV within the MSSM?***

Signal interpretation in extended Higgs sectors (SUSY), case 1: signal=light state h

- **Most obvious interpretation: 125 GeV is lightest Higgs in the spectrum**

➢ **Additional Higgs states at higher masses**

➢ **Differences from SM could be detected via:**

- **Properties of h(125): precision measurements of couplings, width, branching ratio, CP properties ….ILC needed!**
- **Detection of additional Higgs states: H,A $\rightarrow \tau\tau$, H $\rightarrow$ hh,**
  H,A $\rightarrow \chi\chi$, …

Discovery potential at LC for heavy Higgs!

Signal interpretation as light MSSM Higgs boson

- Detection of SM-like Higgs with M_H>135 GeV would have ruled out the MSSM (with TeV scale m_{stop})
- Signal at 125 GeV is well compatible with MSSM predictions
- Observed mass value of signal gives rise to lower bound on the mass of the CP-odd Higgs: M_A>200 GeV

➢ MA» MZ: `Decoupling region' of the MSSM, where the light Higgs h behaves SM-like

➢ *Would not expect observable deviations from the SM at the current level of accuracy …… but at the LC!*

Quest for identifying the underlying physics

- **In general 2HDM-type models one expects % level deviations from SM couplings for BSM particles in the TeV range, for instance:**

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

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

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

➢ ***Precision potential of the LC crucial!***

Unique sensitivity at a LC: H→invisible

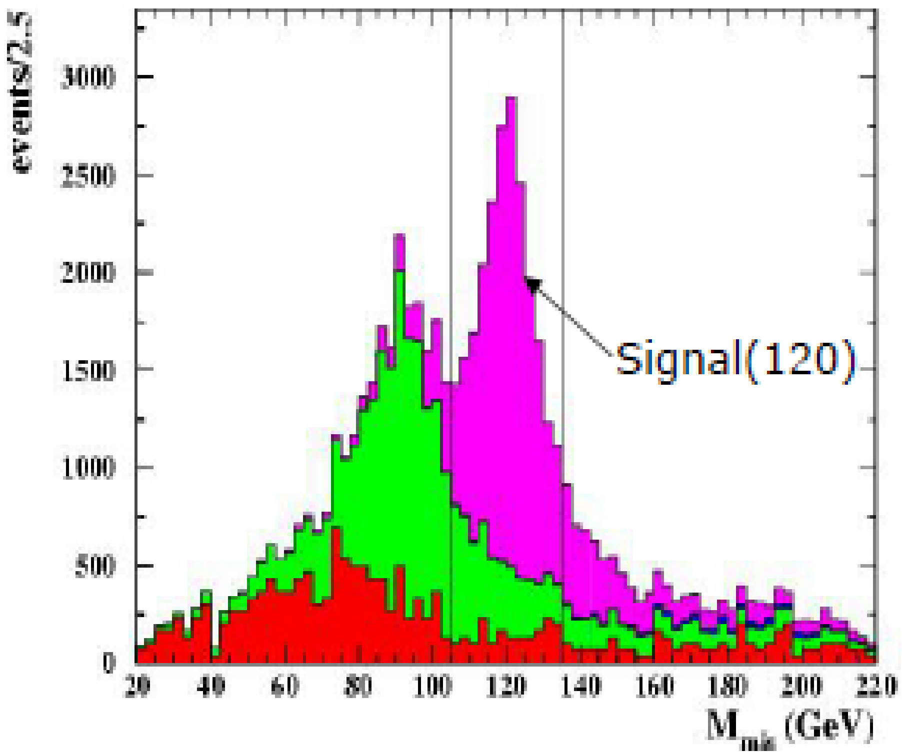
Possibility for a sizeable deviation even if couplings to gauge bosons and SM fermions are very close to SM case

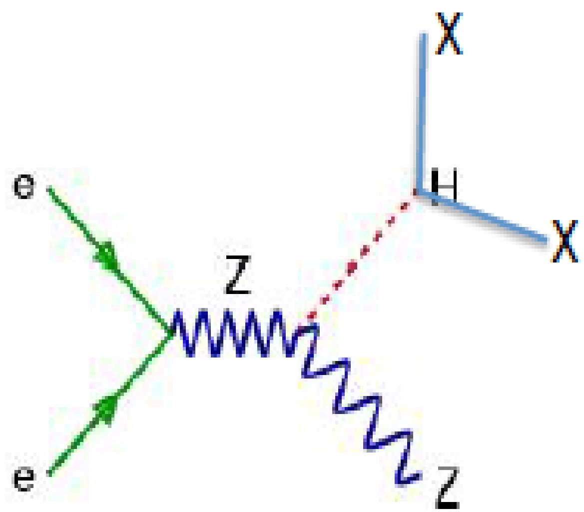
- If dark matter consists of one or more particles with a mass below about 63 GeV, then the decay of the state at 125 GeV into a dark matter pair is kinematically open

- Crucial: detection of an invisible decay mode of the 125 GeV-state could be manifestation of BSM physics
  - Direct search for H → invisible
  - Suppression of all other branching ratios

➢ *Unique potential of the LC via high precision recoil method !*

Unique sensitivity at a LC: H→invisible





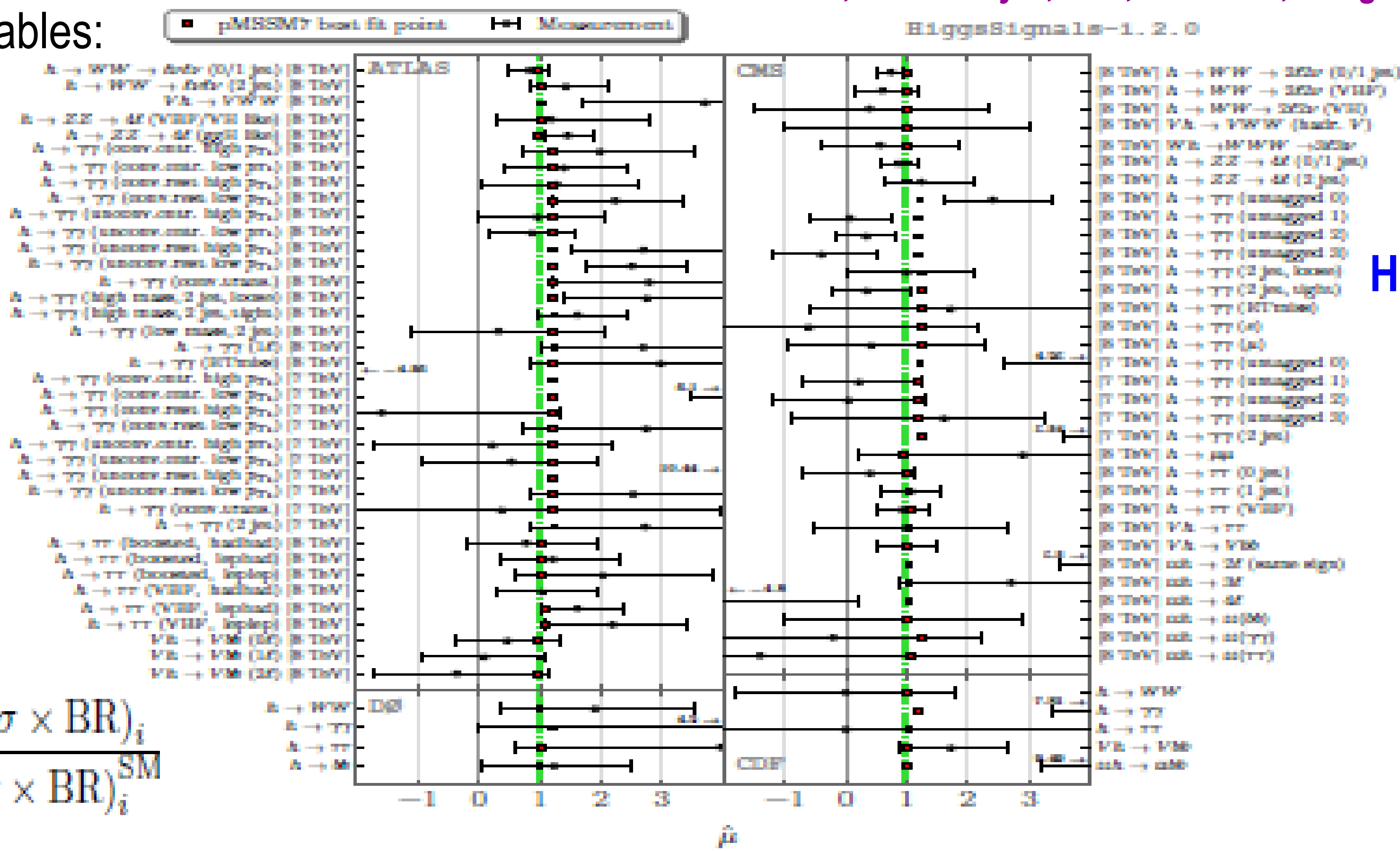
- ***Unique potential of the LC via high precision recoil method !***

SUSY interpretation of signal: light Higgs h

- **Fit to LHC data, Tevatron, prec. observ.: SM vs. MSSM**

Bechtle, Heinemeyer, Stal,Stefaniak, Weiglein, Zeune '14

Observables:



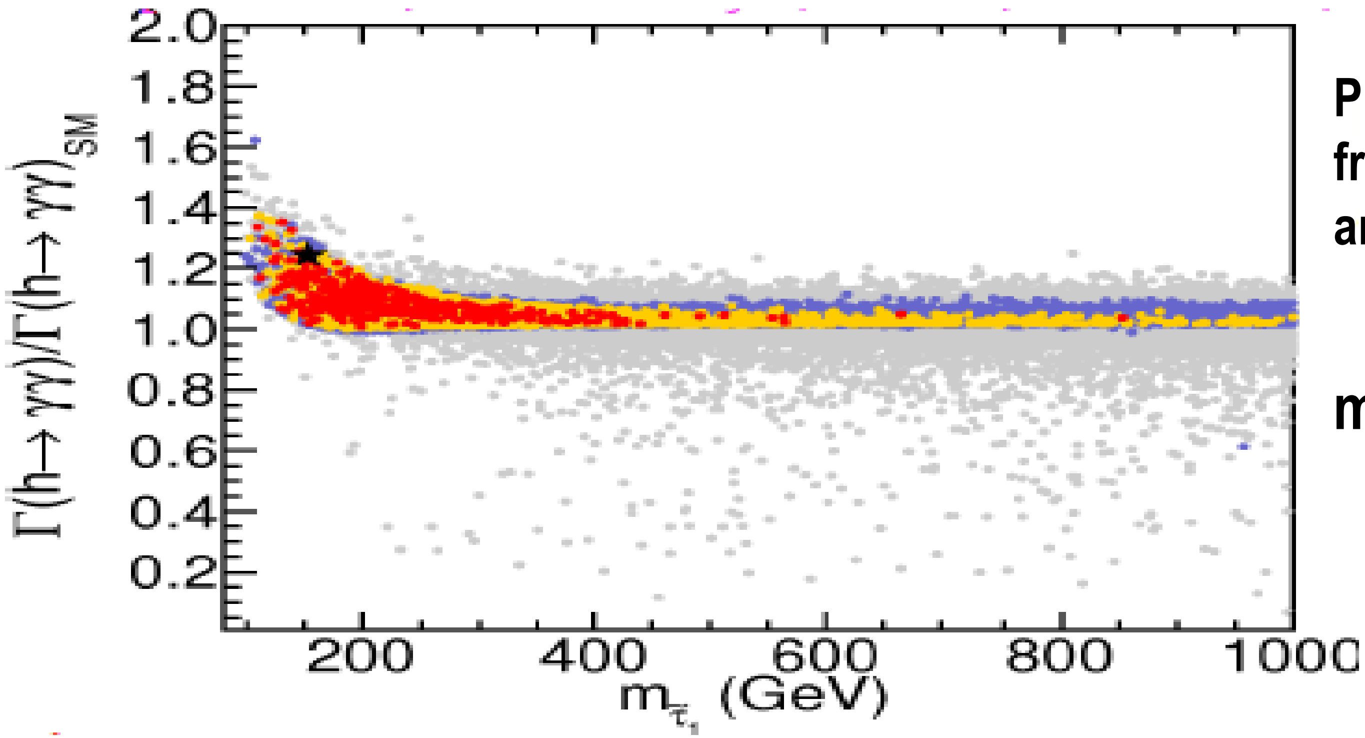
HiggsSignals

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

➢ ***X^2 reduced compared to the SM, (slightly) improved fit quality***

Best fit prefers enhanced γγ rate from light $\tilde{\tau}$'s

Bechtle, Heinemeyer, Stal,Stefaniak, Weiglein, Zeune '14



Pre-ICHEP data from ATLAS and CMS

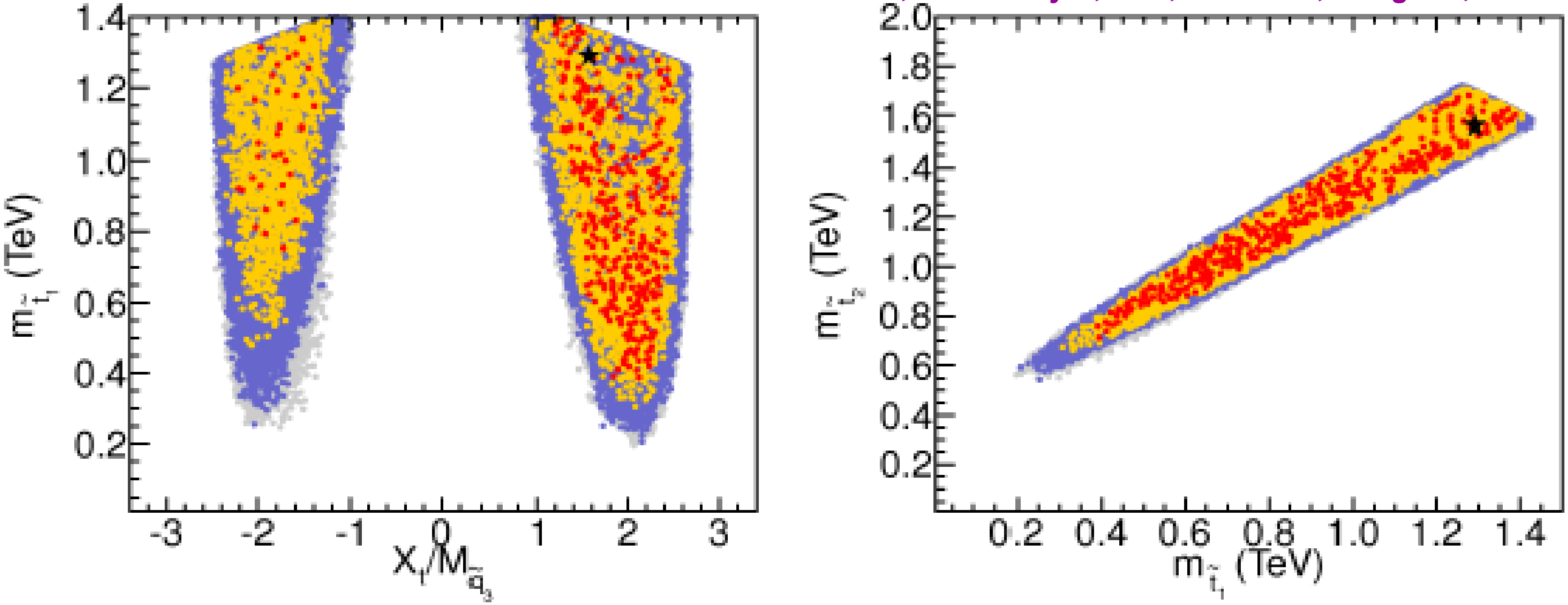
m_{τ}~200 GeV

- **≈20% enhancement of partial width**
- **Fit assumes slepton mass universality: $M_{E1,2}$= $M_{L1,2}$=M_{l3}**
- **Also impact from g_{μ}-2**
- ***Light staus: high discovery potential for 500 GeV LC!!!***

Signal interpretation as light MSSM Higgs h

- **MSSM fit, preferred values for stop masses**

Bechtle, Heinemeyer, Stal,Stefaniak, Weiglein, Zeune '14



➢ **Large stop mixing required**

Best fit prefers heavy stops beyond 1 TeV

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

Sum rule: properties of other Higgs states

- **Squared couplings to gauge bosons fulfill 'sum rule'** (in large variety of models with extended Higgs sectors):

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

- ➢ **SM couplings strength is `shared' between all Higgs states of an extended Higgs sector**
  - **$\kappa_V \leq 1$**
- **The more SM-like the couplings of the 125 GeV-state turn out to be, the more suppressed are couplings of other Higgs to gauge bosons**
- ➢ ***Heavy Higgs: much smaller width than SM Higgs of same mass !***

Search for non-standard heavy Higgs

- `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 gauge bosons

➢ A signal could show up in $H \longrightarrow ZZ \longrightarrow 4l$ as small bump, very far below expectations for a SM-like Higgs (and with much smaller width!)

- High Relevance for LC physics potential:
  - *Particularly important search channel: $H,A \longrightarrow \tau\,\tau$*
  - *Non-standard search channels can play an important role:*

    $H \longrightarrow hh$, $H,A \longrightarrow \chi\chi$, …..

Signal interpretation in extended Higgs sectors (SUSY), case 2: signal=NTL state H

- **Extended Higgs sector where 2nd lightest (or higher) Higgs has SM-like couplings to gauge bosons**

➢ **Lightest h 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 realizations: 2HDM, MSSM, NMSSM,…**

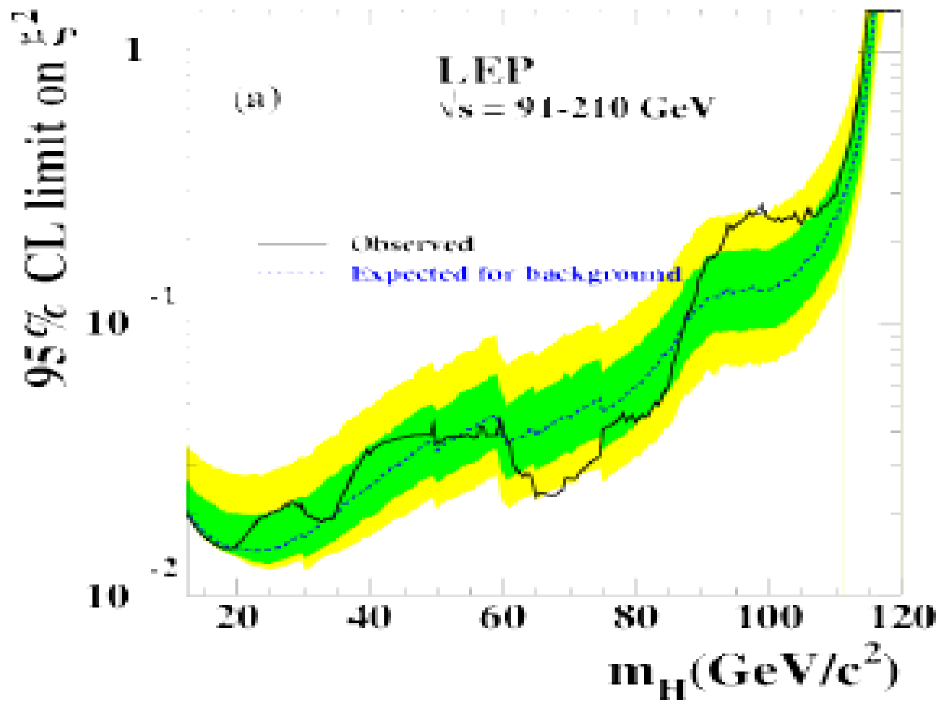
A light neutral Higgs in the mass range of about 60-100 GeV is a generic feature of such a scenario. Search for Higgs in this range has recently started at LHC. Such a state could copiously be produced in SUSY cascades!

Great opportunity for the LC…..but not many studies so far!

LEP limits on low-mass Higgs bosons

- **Limits from the LEP Higgs searches: $e^+e^- \longrightarrow ZH,\ H \longrightarrow bb$**

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

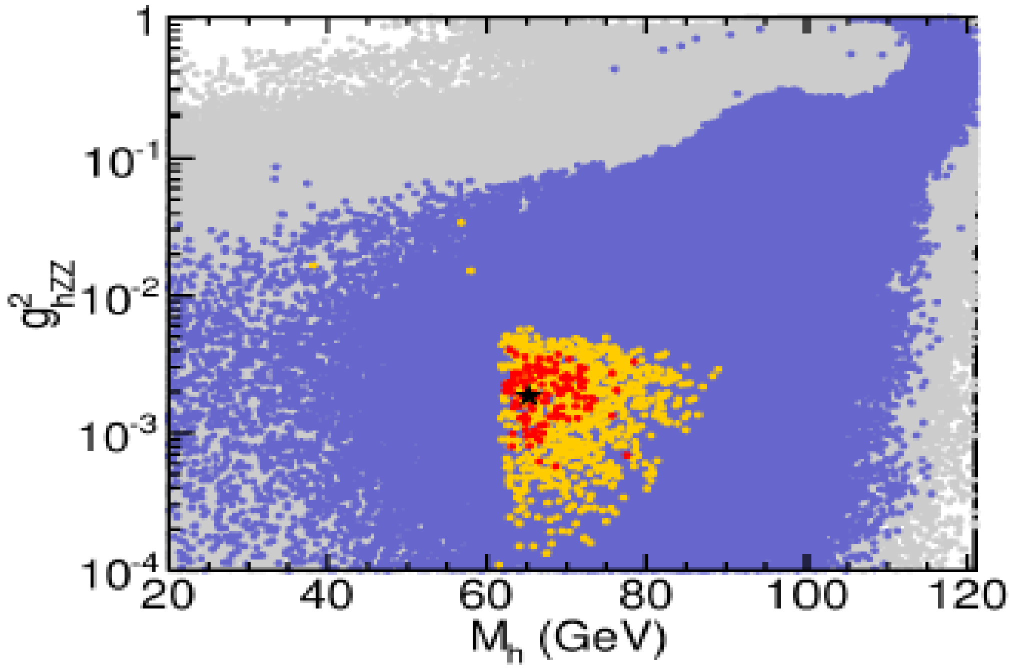


➢ **Limit for SM Higgs (ε=1): M_H>114.4 GeV at 95% c.l.**
No limit if HZZ couplings is below 10% of the SM value

MSSM realization: very exotic scenario
all five Higgs states light: h, H(125), A, $H^{\pm}$

- **Lightest Higgs: mass and couplings to gauge bosons**

(in blue: HiggsBounds allowed) *Bechtle, Heinemeyer, Stal,Stefaniak, Weiglein, Zeune '12*



➢ **Light Higgs with $M_h \approx$ 70 GeV, in agreement with LEP limits**

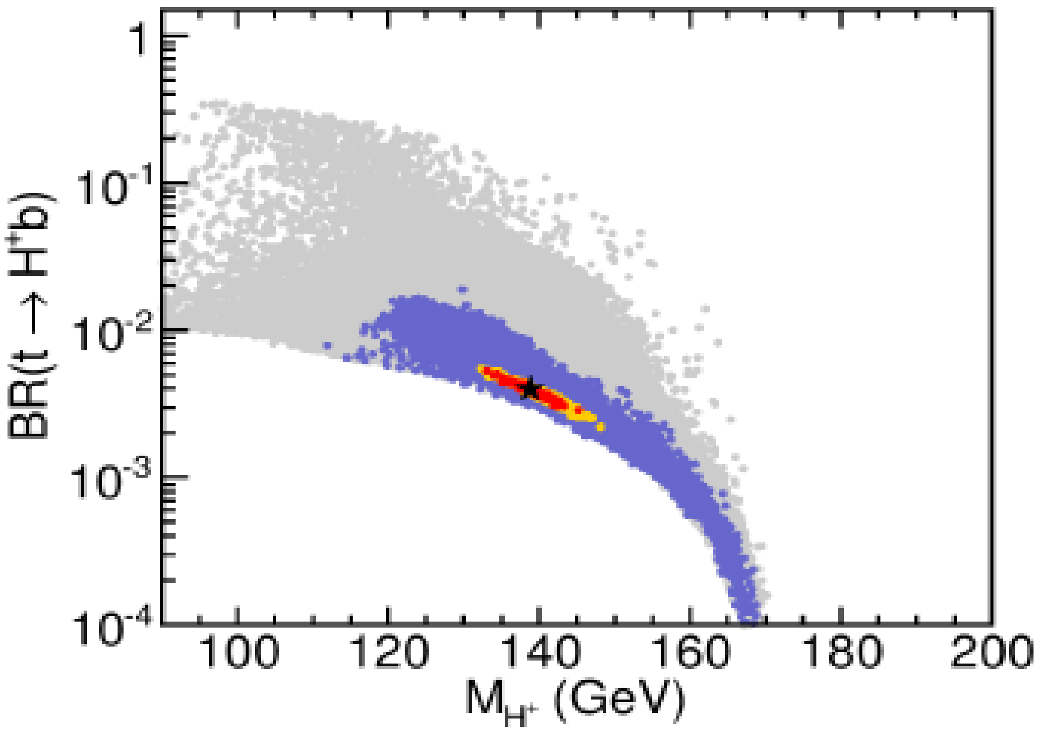
Before charged Higgs results from ATLAS: global fit yielded acceptable fit probability

MSSM scenario directly probed with charged Higgs searches

Bechtle, Heinemeyer, Stal,Stefaniak, Weiglein, Zeune '12

Low M_H scenario: benchmark scenario for demonstrating the impact of charged Higgs searches

- ***So far not explored by ATLAS and CMS***



NMSSM

= **Extension of the MSSM by a Higgs singlet + superpartner**

Interpretation of observed signal in terms if NTL Higgs boson

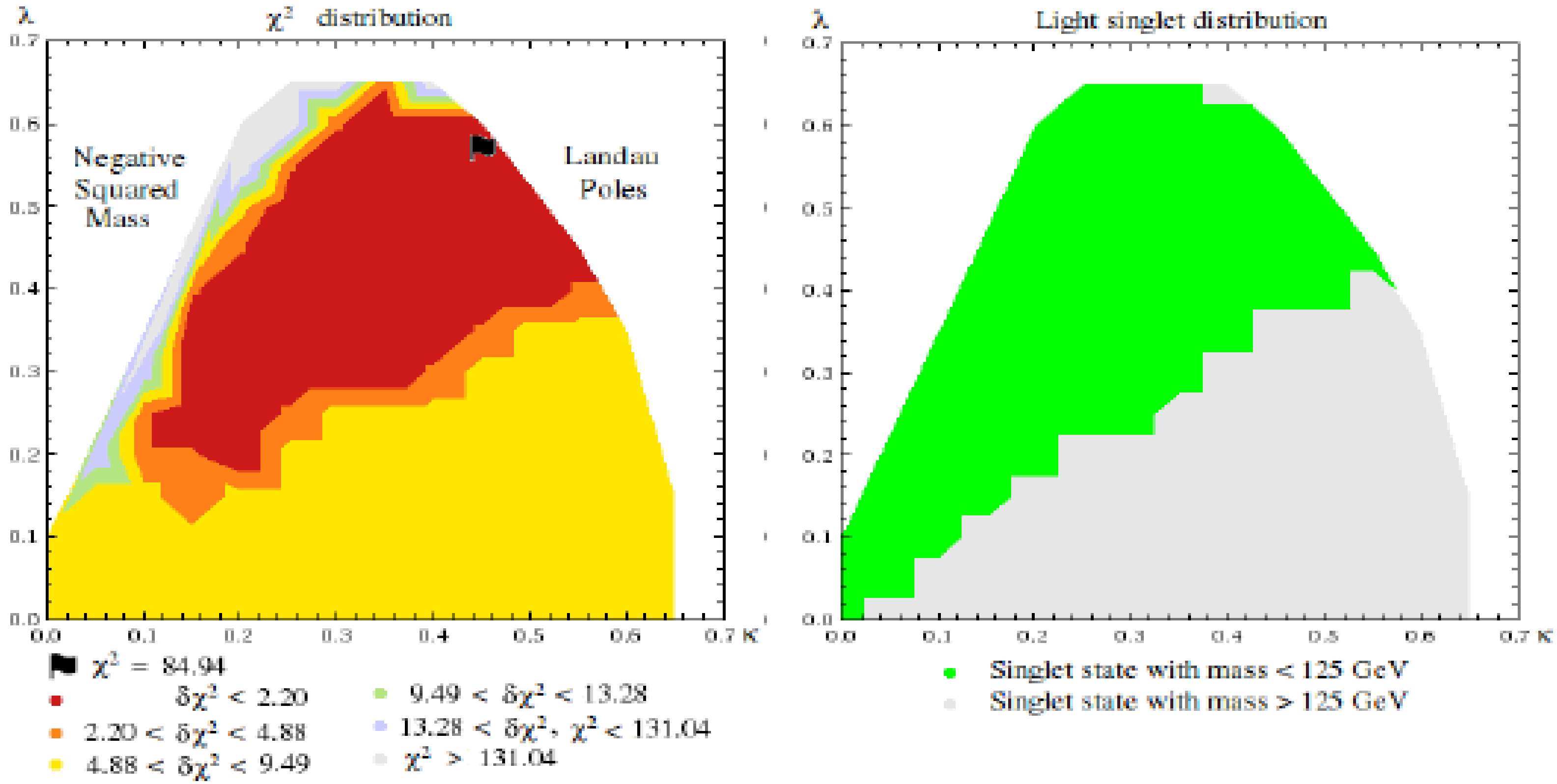
- **Quite generically in the NMSSM: Case that signal at 125 GeV corresponds to a Higgs that is not the lightest in the spectrum if singlet is light (singlet-doublet mixing ⟶ upward shift of the SM-like Higgs)**
- **Analysis of possible NMSSM phenomenology in view of existing limits from the Higgs searches and the properties of the signal at 125 GeV (implemented via HiggsBounds and HiggsSignals)** *(F. Domingo, G. Weiglein '14)*

- **Other work in this context:**

  (Belanger, Ellwanger, Gunion, Jiang, Kraml, Schwarz '13), (Badziak, Olechowski, Pokorski '13), (Gunion, Jiang, Kraml '12), (Christensen, Han, Su '13), (King, Muehlleitner, Nevzorov,Walz'14)

Best fit point and preferred region in κ-λ-plane

Domingo, Weiglein '14

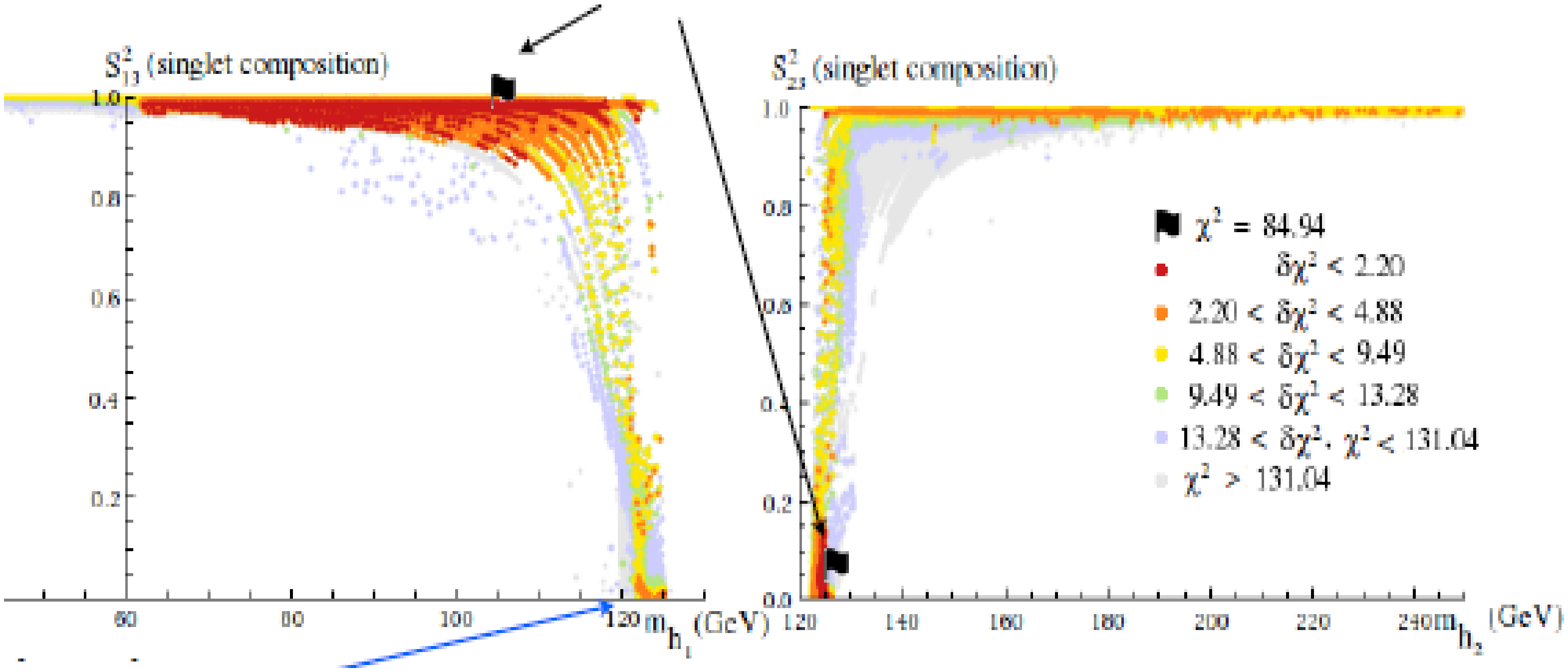


- Preferred region spans over wide range of κ and λ
- Coincidence largely with region, where singlet is below 125 GeV

Composition of the lightest CP-even state

Domingo, Weiglein '14

Best fit value

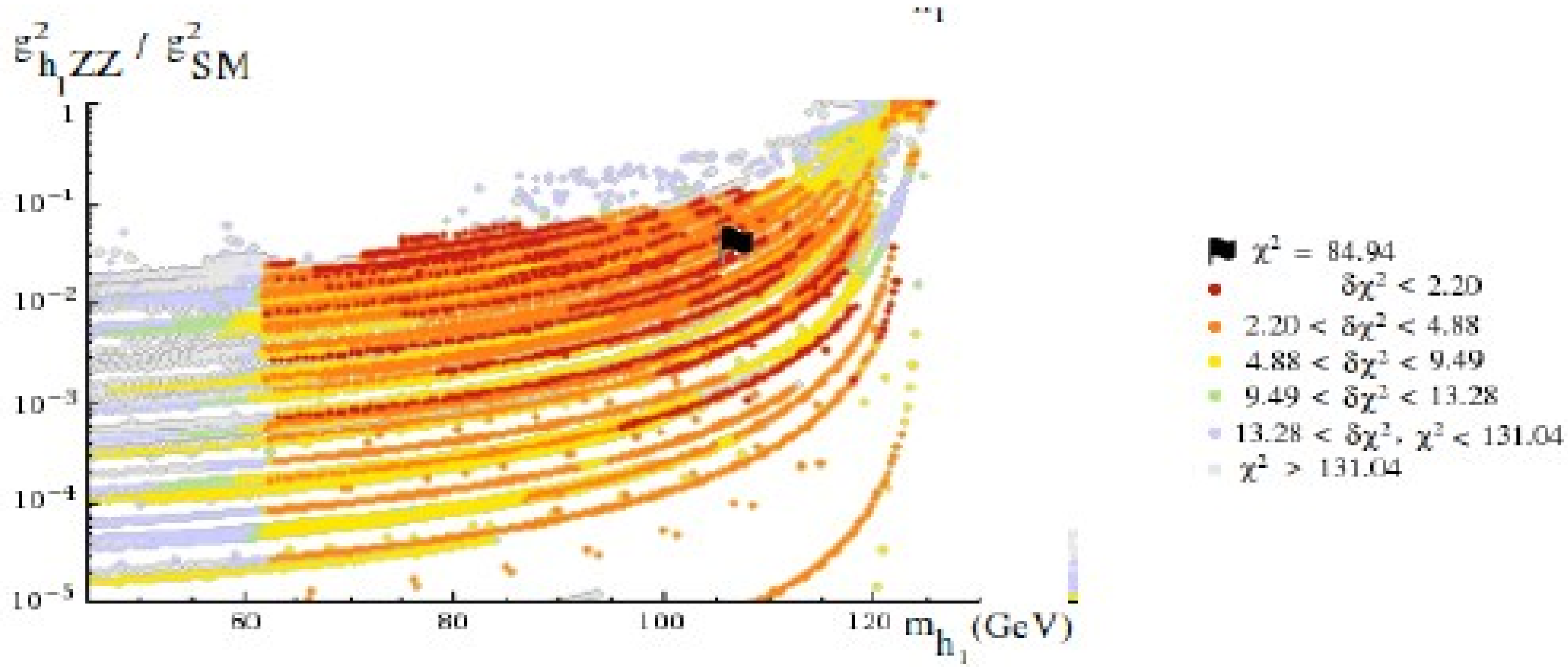


Case where lightest Higgs is doublet-like

- **In the preferred fit region the lightest Higgs is singlet-like Singlet-doublet mixing up to 20% possible**

Composition of the lightest CP-even state

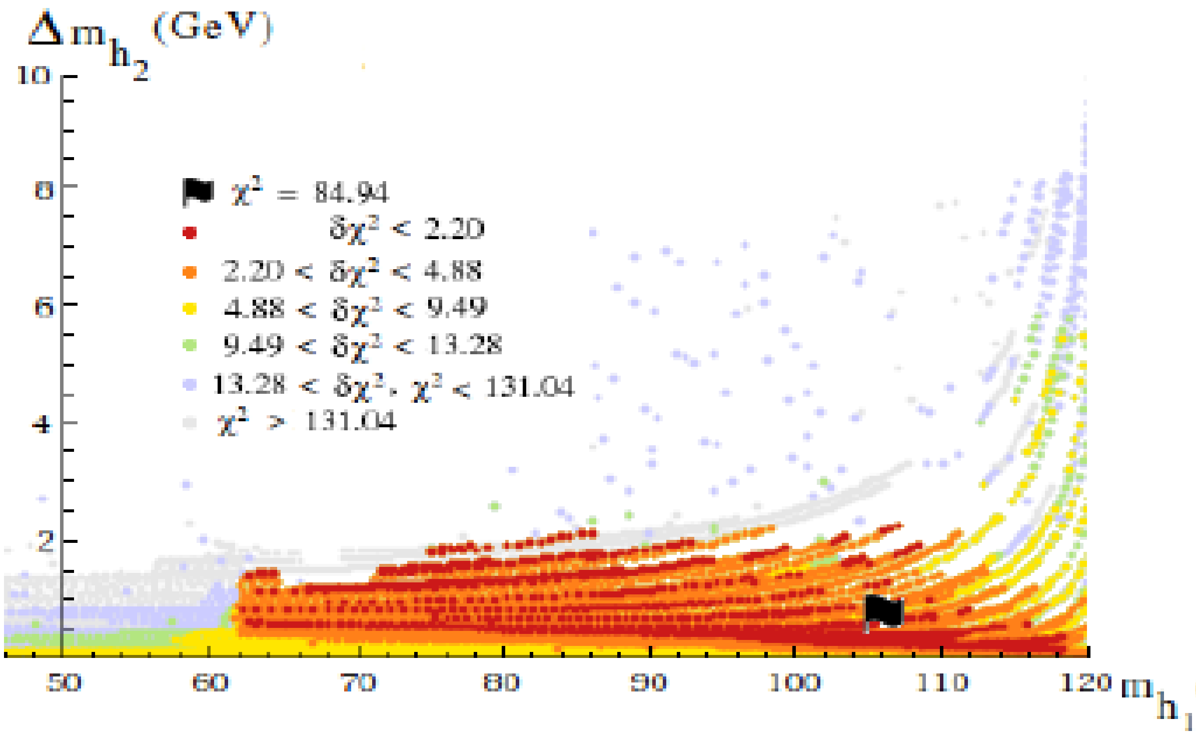
Domingo, Weiglein '14



- **Large singlet component leads to strong suppression of the coupling to gauge bosons**

Upward shift in mass of SM-like state from singlet-doublet mixing

Domingo, Weiglein '14



- **Upward shift by 1-2 GeV in preferred region** (shifts up to 8 GeV possible)
- **If doublet state has lower mass,** singlet-doublet mixing leads to **downward shift** of the mass of the SM-like state

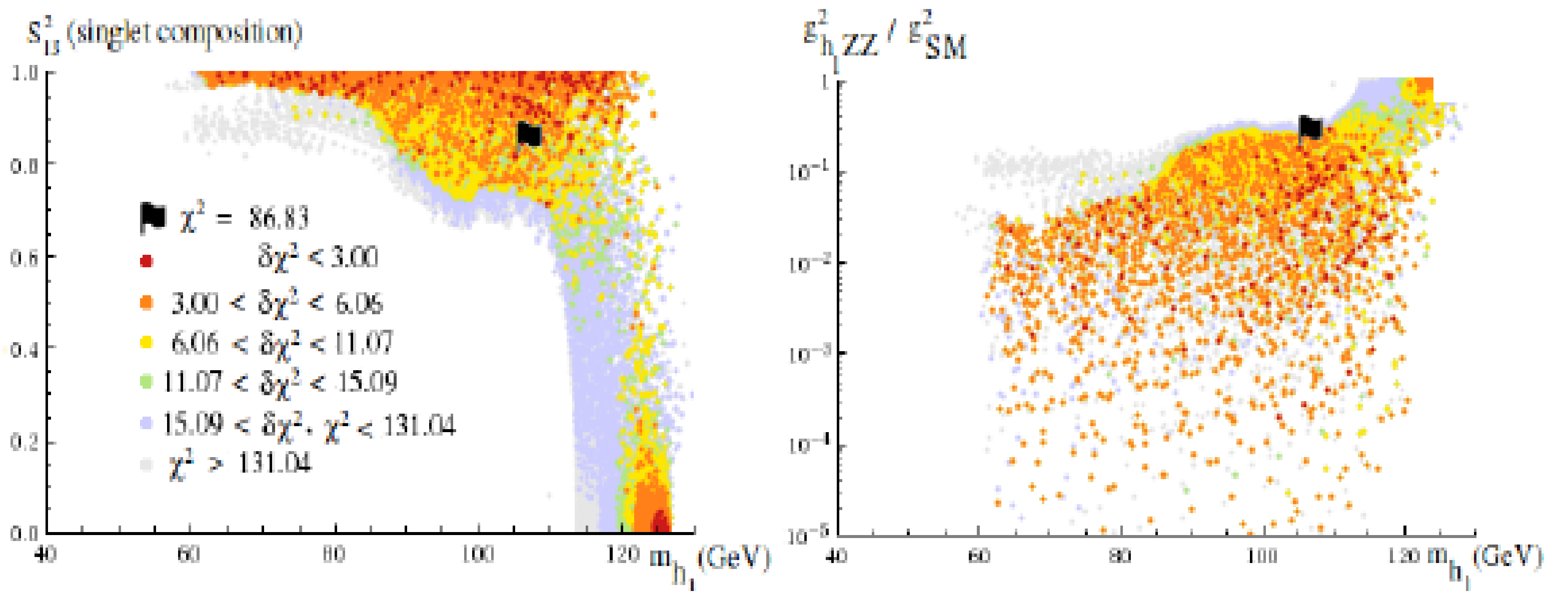
Particular focus in the NMSSM: region with low tan β, large λ / small κ

- **Additional tree-level contribution in the NMSSM**
  - **No large radiative corrections to Higgs mass required**
  - **Relatively low stop masses, small stop mixing possible**

  κ / λ « 1: `Peccei-Quinn' limit

Scenario with low tan β, large λ / small κ

Domingo, Weiglein '14



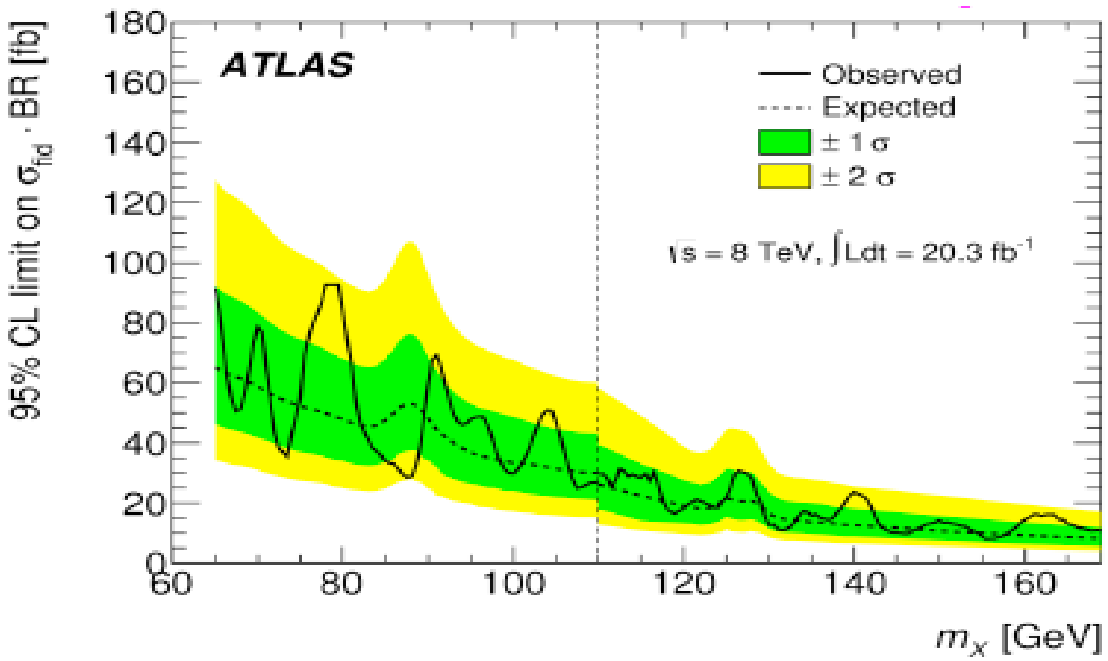
➢ **Sizable mixing**

Best fit value compatible with slight access observed at LEP

LHC searches sensitive to low –mass Higgs with suppressed couplings to gauge bosons

- **ATLAS h⟶γγ searches in the low mass region**

ATLAS Collaboration '14



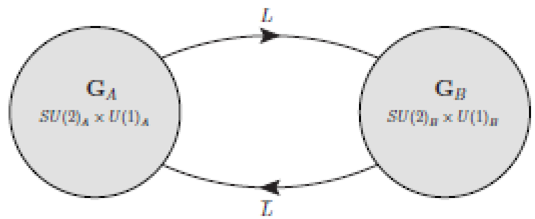
- **Example: MSSM, H(125) case: BR (h_1⟶γγ)=8.5x10^{-7}**

➢ **Three orders of magnitude below BR for a SM-like Higgs with 65GeV**

Higgs @ Gauge extended MSSM

- **Quiver models and non-decoupling D-terms**

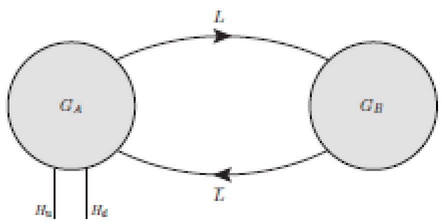
McGarrie, GMP, Porto '14



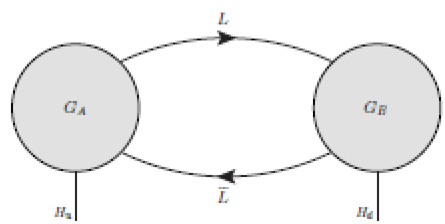
  - ➢ **Additional non-decoupling D-terms in the Higgs potential**

- **Features:**
  - **Higgs mass lifted at the tree-level, relaxing naturalness**
  - **Almost vanishing contributions to EW observables**

Vector Higgs case

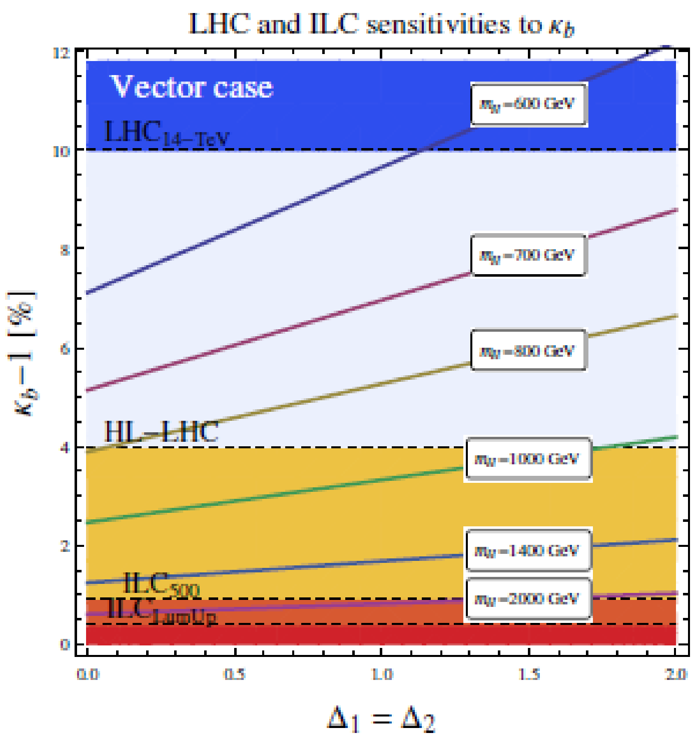


Chiral Higgs case

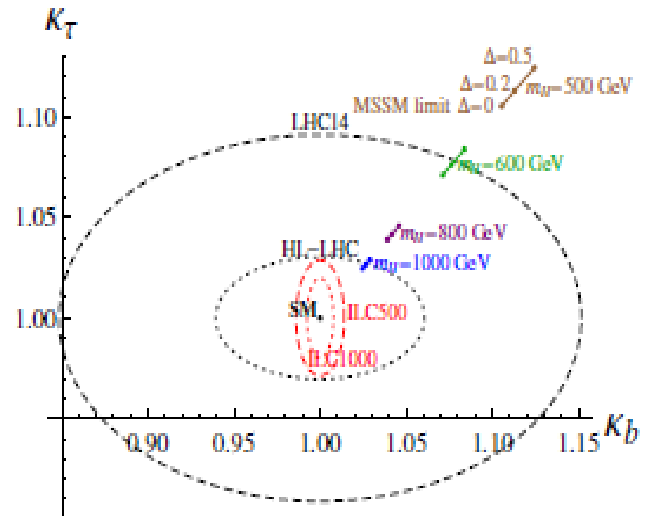


Prospects at LHC+ILC

Example Vector Higgs case: coupling enhancement



$$c_b^{\text{vector}} \simeq \left(1-\frac{m_h^2}{m_H^2}\right)^{-1}\left(1+\frac{[g_2^2(1+\Delta_2)+\frac{3}{5}g_1^2(1+\Delta_1)]v^2}{4(m_H^2-m_h^2)}\right)$$



- ILC precision: precise coupling measurements allows to distinguish the model up to masses for heavy Higgs m_H~2 TeV

Conclusions

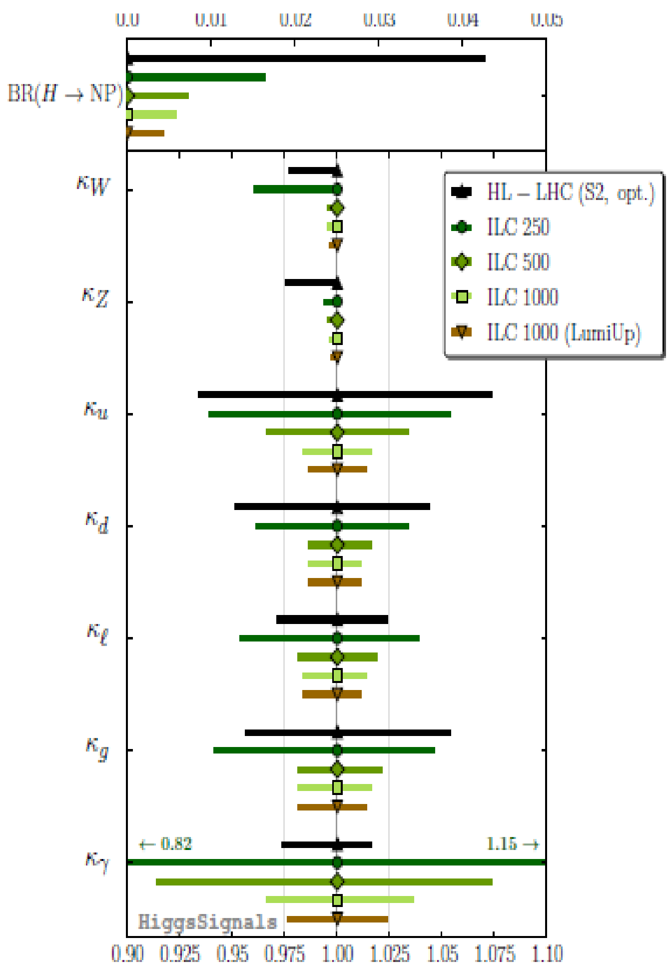
- Extended Higgs sectors of SUSY-type: well motivated alternative to SM
  - Search for Higgs states of extended Higgs sector: need to test compatbility with signal at 125 GeV
- Most obvious interpretation of signal, h(125): lightest Higgs state
- MSSM: M_h= 125 GeV (lightest Higgs) implies M_A» M_Z:
  - decoupling region, SM-like Higgs; MSSM provides good fit to the data, slightly improved fit quality w.r.t. SM
- 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 be realized generically in the NMSSM: NMSSM fit prefers singlet-like light Higgs

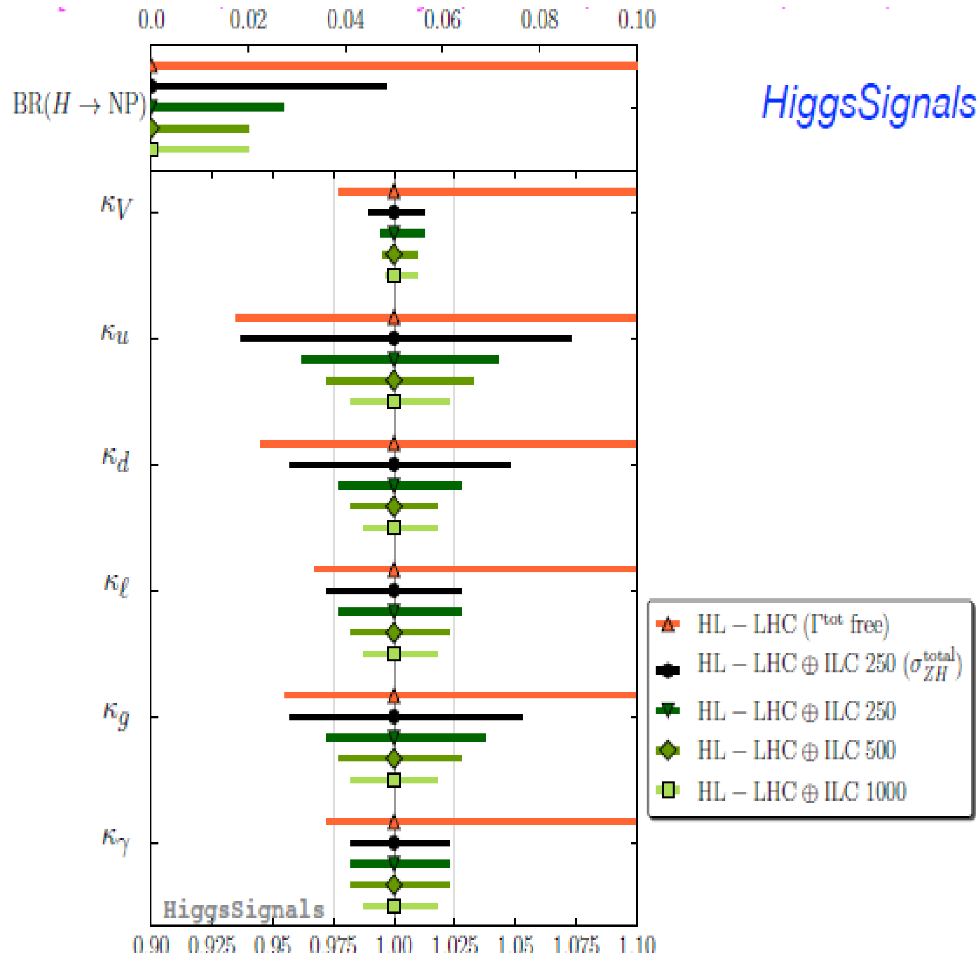
➢ Physics potential of the LC: high precision measurement of h(125) and searches for light/heavy Higgses!

Great thanks to LHC+ILC

Somewhen in ~2050 ?!

Assumed: $\kappa_V \leq 1$





HiggsSignals

Codes: HiggsBound and HiggsSignal

- **Incorporation of cross sections limits and properties of the signal at 125 GeV**
  - **Programs that use the experimental information on cross section limits (HiggsBounds) and observed signal strengths (HiggsSignal) for testing theory predictions** *(Bechtle, Brein,Heinemeyer, Stal, Stefaniak, Weiglein ,Williams 08,'12, '13)*
  - **HiggsSignal:** *(Bechtle, Heinemeyer, Stal, Stefaniak, 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**