Constraining extended Higgs sectors with HiggsSignals

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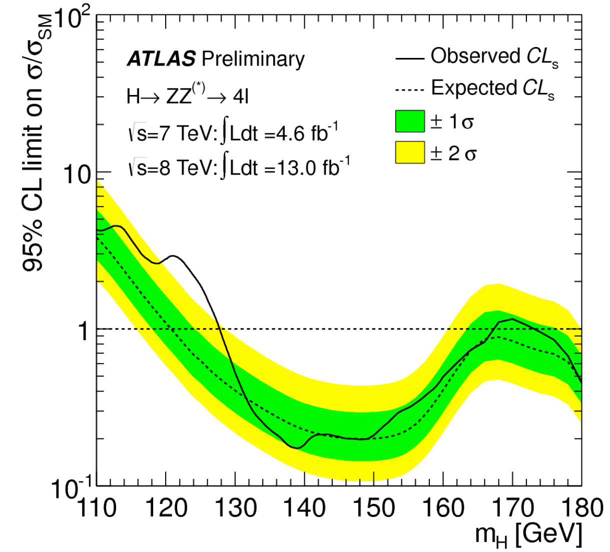
Work done in collaboration with P. Bechtle, S. Heinemeyer, T. Stefaniak, and G. Weiglein

Constraining new physics using LHC Higgs results

- *Exclusion Limits*

  Remains an important handle to constrain extended Higgs sectors even after discovery

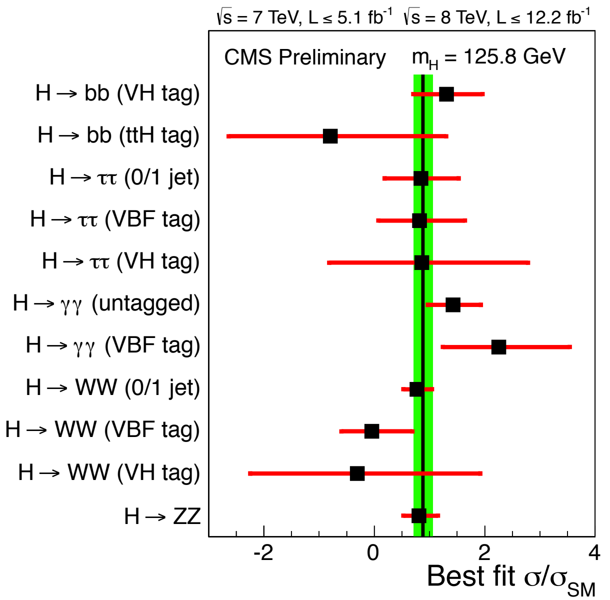
  → HiggsBounds



- *Mass/rate measurements*

  Additional information from the observed signal mass(es) and rates can also be used to constrain BSM theories

  → HiggsSignals



HiggsSignals

- Companion program to HiggsBounds.
  Uses the same input structure -> Easy to get started

  http://higgsbounds.hepforge.org

  Tests compatibility of arbitrary models to observed and future *measurements* of signals in Higgs searches

- Currently limited to hadron collider physics, but can easily be extended to e^+e^- if there is an interest

- Current version: 1.0.0 (released May 9, 2013)

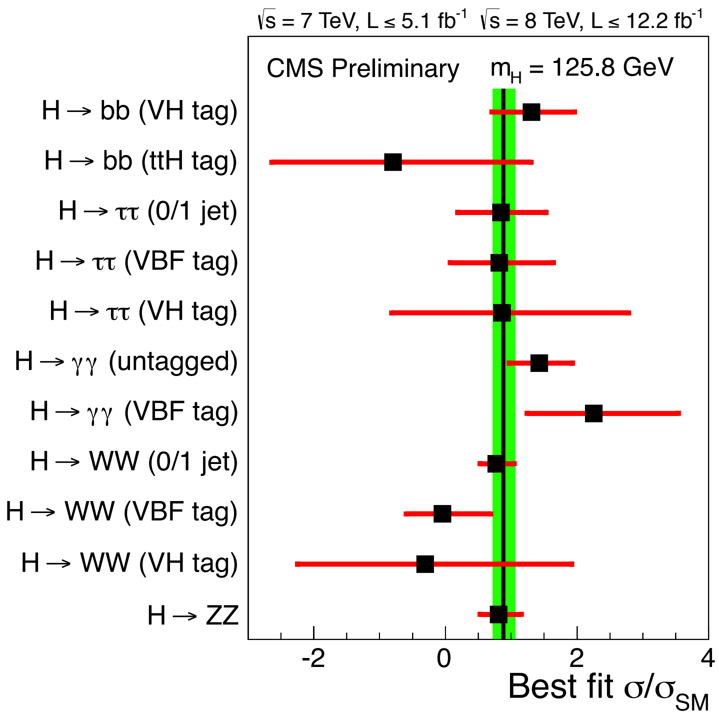
- Physics description and user manual published

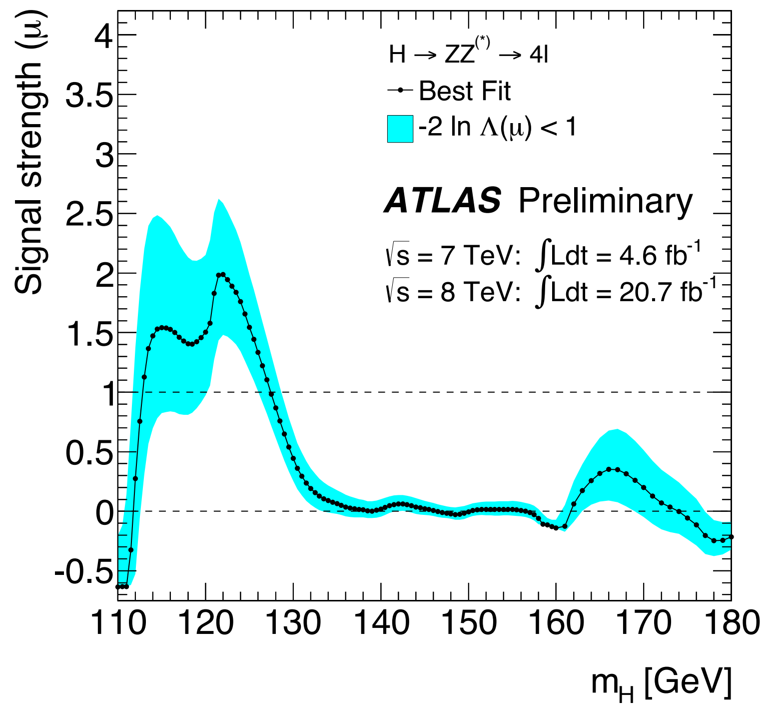
P. Bechtle, S. Heinemeyer, OS, T. Stefaniak, G. Weiglein, [arXiv:1305.1933]

Experimental data

- Basic quantity used in HiggsSignals is the signal strength modifiers

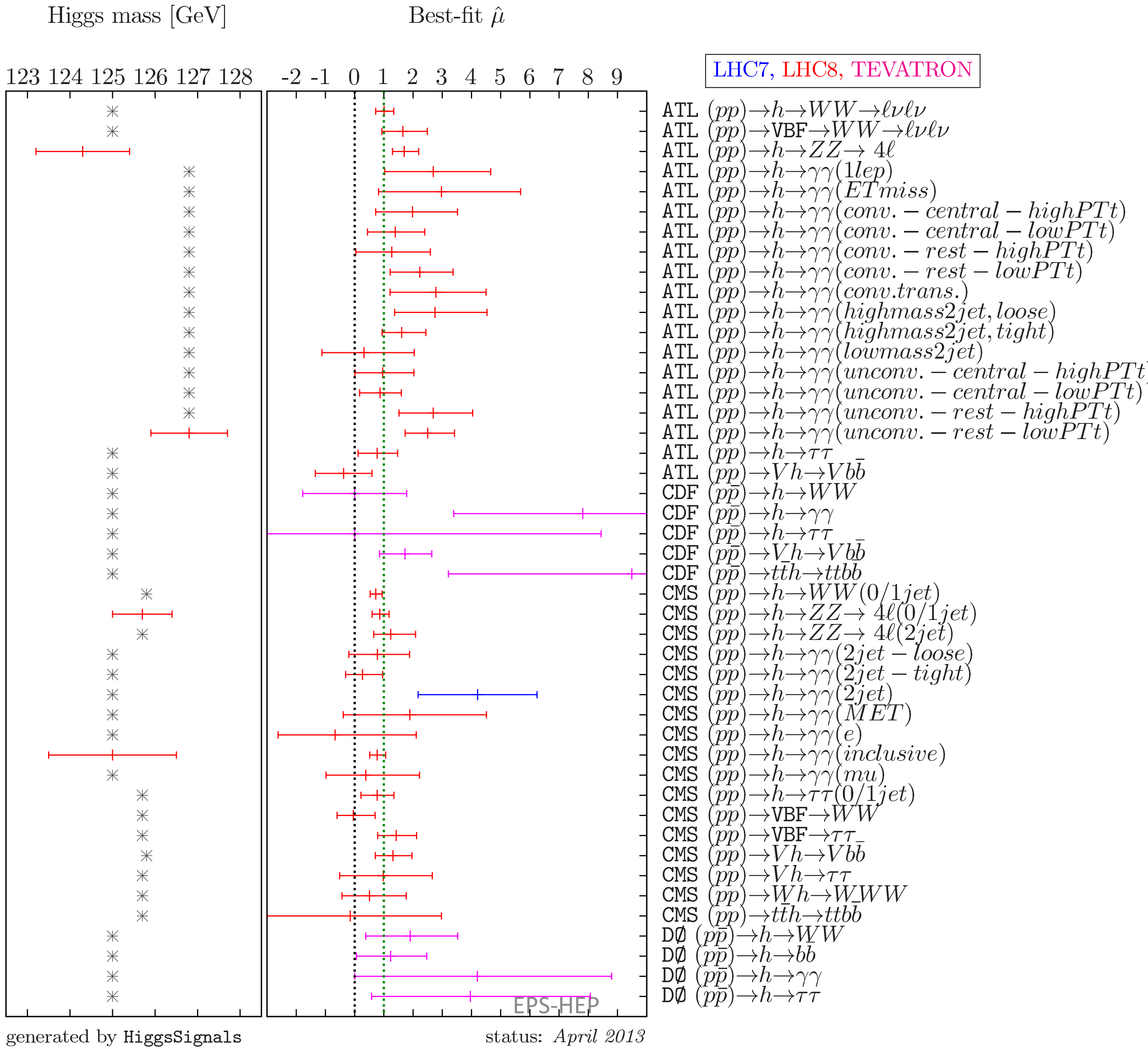
$$\mu_{xx}^{i} = \frac{[\sigma_i(pp \to H) \times \mathrm{BR}(H \to xx)]_{\mathrm{model}}}{[\sigma_i(pp \to H) \times \mathrm{BR}(H \to xx)]_{\mathrm{SM}}}$$





- Both historic, present and future (also toy) data can be used. User-accessible data format (text files)

Observables included for the LHC 125 GeV signal



Theory input

- To test a model, the user has to provide HiggsSignals with input:

  - Number of neutral (and charged) Higgs bosons
  - Higgs masses
  - Production cross sections
  - Total decay widths (narrow width approximation must be valid)
  - Decay branching ratios

- There are a number of physics options to give these predictions: hadronic cross sections, partonic cross sections, effective couplings

- And a number of technical interfaces to do it: data files, SLHA (for MSSM/NMSSM), library of subroutines
  … all documented in the manual and example programs provided

Rate predictions

- Signal rate prediction for a single Higgs boson in one analysis:

$$\mu = \sum_i c_i \omega_i$$

- Individual channel signal rate $c_i = \frac{[\sigma \times \mathrm{BR}]_i}{[\sigma_{\mathrm{SM}} \times \mathrm{BR}_{\mathrm{SM}}]_i}$

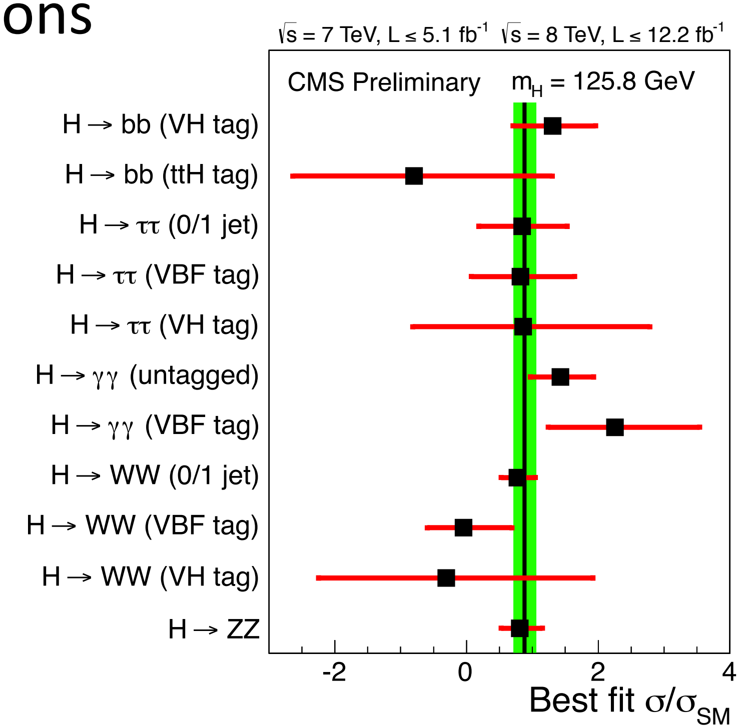
- Channel weights (evaluated in the SM) $\omega_i = \frac{\epsilon_i \, [\sigma_{\mathrm{SM}} \times \mathrm{BR}_{\mathrm{SM}}]_i}{\sum_j \epsilon_j \, [\sigma_{\mathrm{SM}} \times \mathrm{BR}_{\mathrm{SM}}]_j}$

- Narrow width approximation must be applicable

- Predictions for multiple Higgs bosons contributing to the same signal are added incoherently (interference effects neglected)

Peak-Centered χ^2 method

- Tests compatibility of data observed at specified signal mass values, “peaks”, against model predictions
- This determines if the model provides one (or more) Higgs bosons that can explain the observed signal(s)
- Example:
  Observed LHC signal around 125 GeV



- Most sane theories would now like to have a reasonably SM-like Higgs boson at this mass
- Test complementary to exclusion limits for multi-Higgs models

Details of peak-centered χ^2 method

- Global χ^2 function calculated from comparing model to experiment, using Gaussian approximation, including correlations of theory + luminosity unc. included

$$\chi^2_\mu = \sum_{\alpha=1}^{N} \chi^2_{\mu,\alpha} = (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})^T \mathbf{C}_\mu^{-1} (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})$$

- χ^2 for mass observables added: $\chi^2_{\text{tot}} = \chi^2_\mu + \chi^2_m$

- The theoretical prediction μ used for each particular signal is determined by *assigning* one or more Higgs bosons

Required assignment: $|m_i - \hat{m}_\alpha| \leq \Lambda \sqrt{(\Delta m_i)^2 + (\Delta \hat{m}_\alpha)^2}$

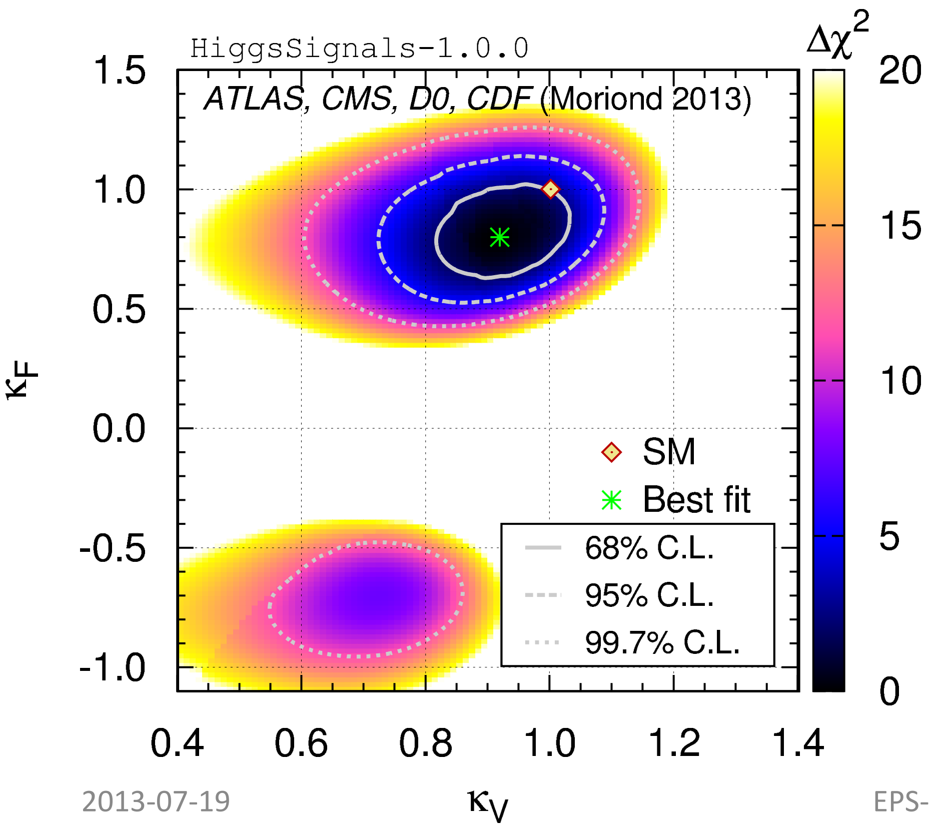
Allowed assignment outside this range only for observables with mass measurement if it improves the overall χ^2

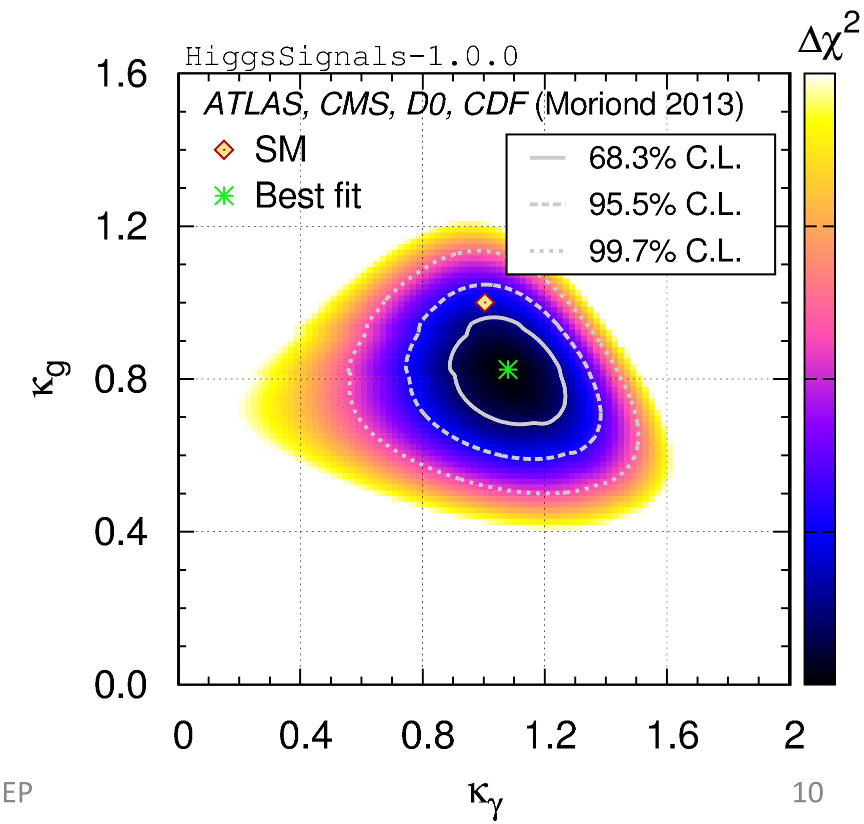
Fit of coupling scale factors

- Fit to universal coupling scale factors κ (SM: $\kappa_i = 1$)
  Assumes structure of couplings unchanged wrt SM

[1209.0040]

- HiggsSignals procedure validated against official ATLAS/CMS fits
  Here: Full Moriond data from LHC/Tevatron included



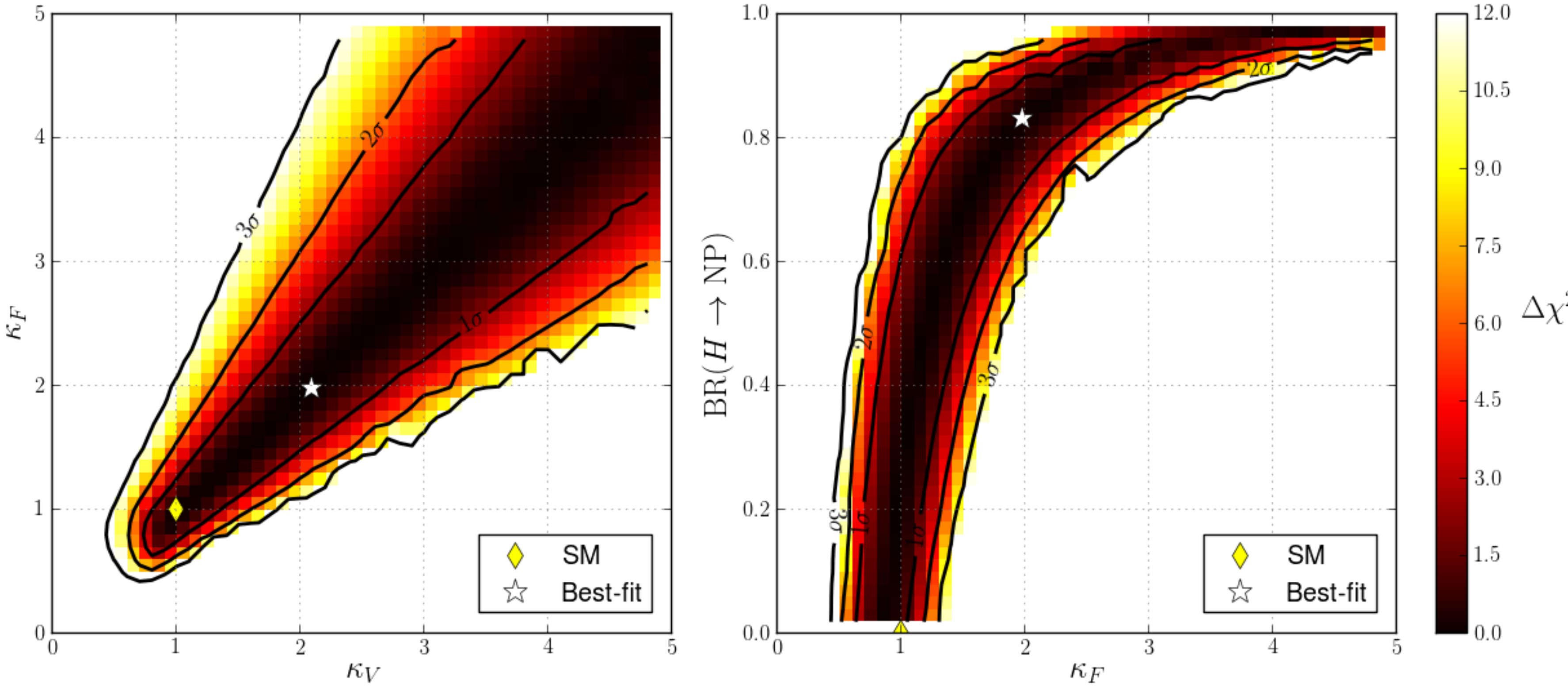


Allowing for new decay modes

$$\kappa_u = \kappa_d = \kappa_\ell = \kappa_F$$

$$\kappa_W = \kappa_Z = \kappa_V$$

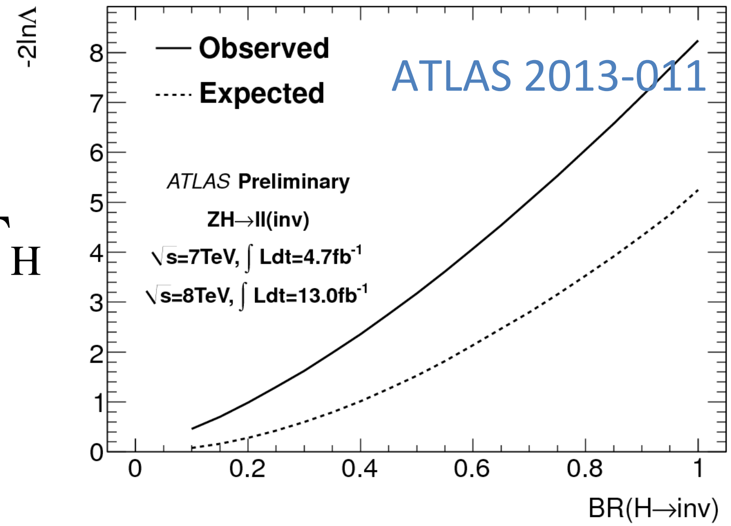
$$\mathrm{BR}(H \to \mathrm{NP})$$

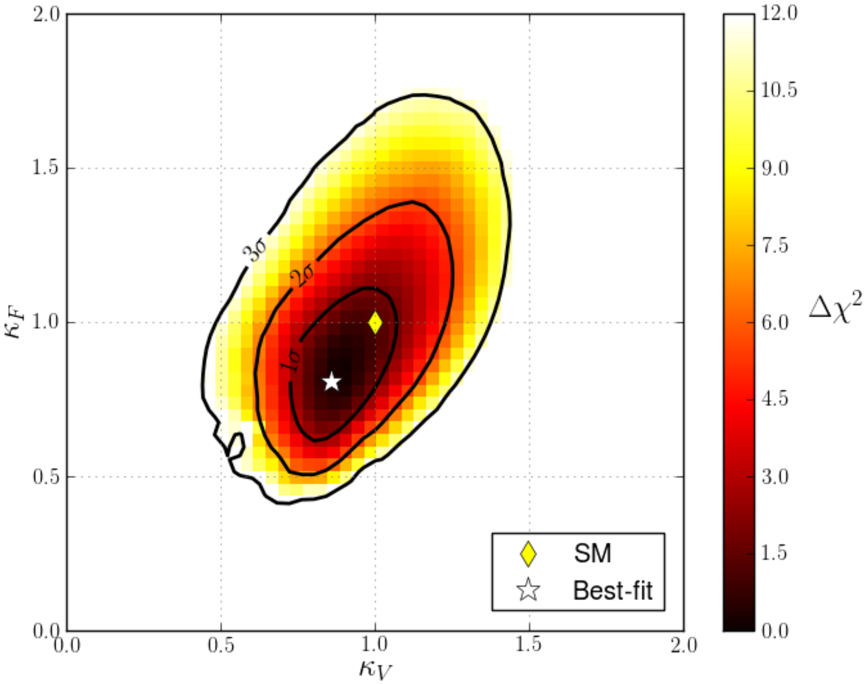


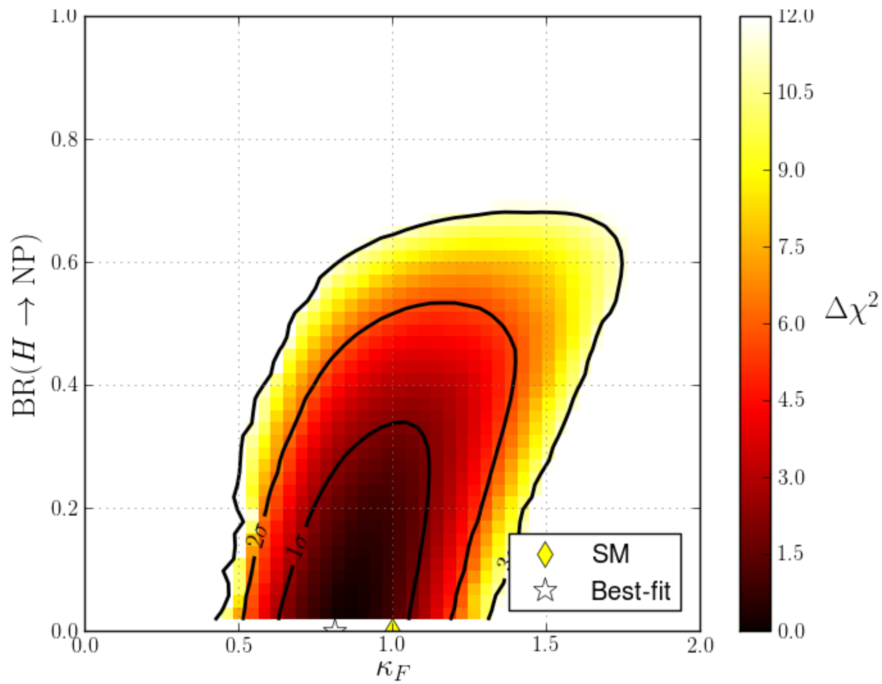
- Degeneracy between increased production and invisible decay
  The total Higgs width is not accessible at the LHC

Including constraint on invisible decays

- Assuming new decays are truly invisible (= generate E_T-miss) we can use ATLAS results to constrain Γ_H

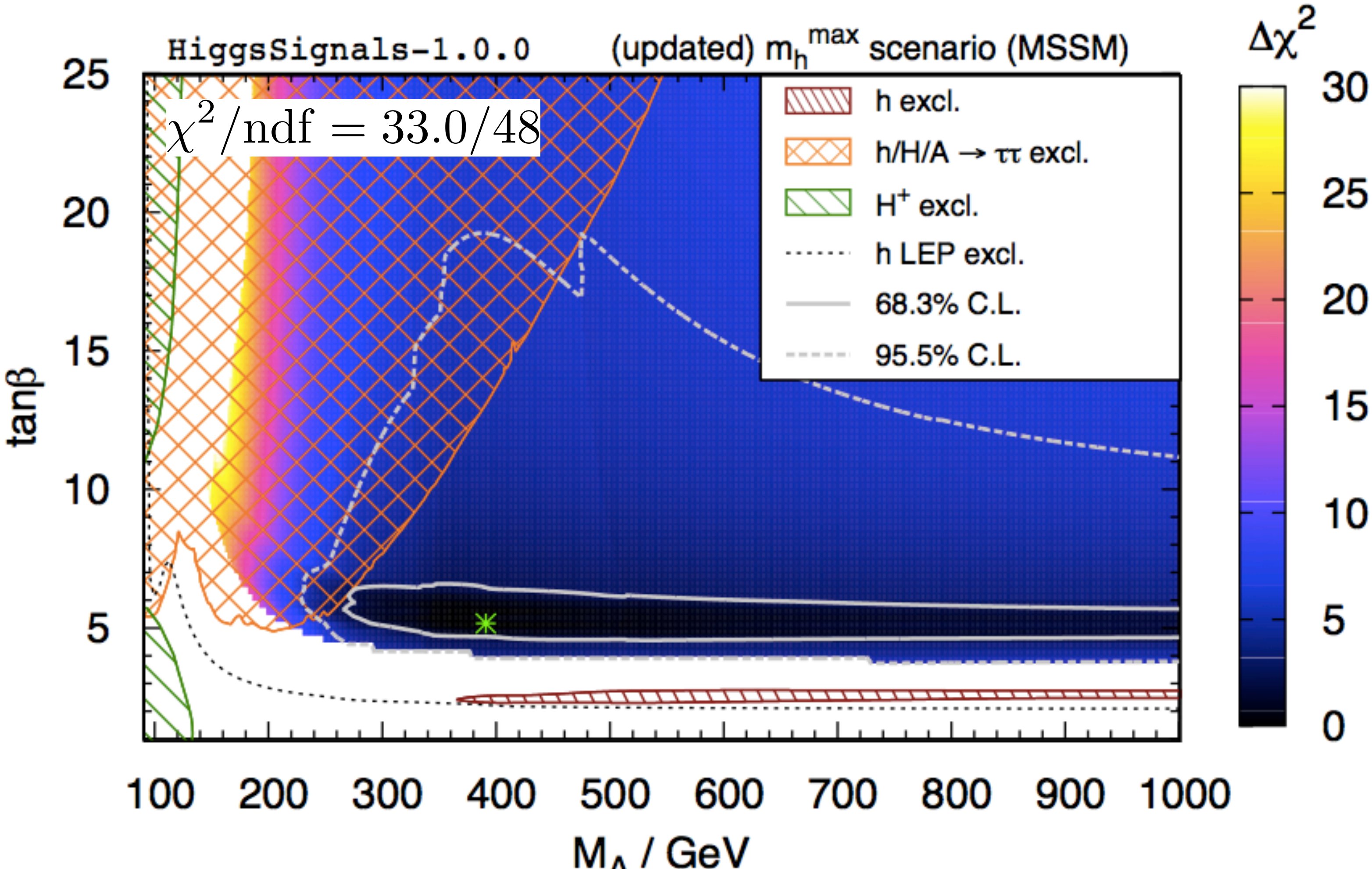






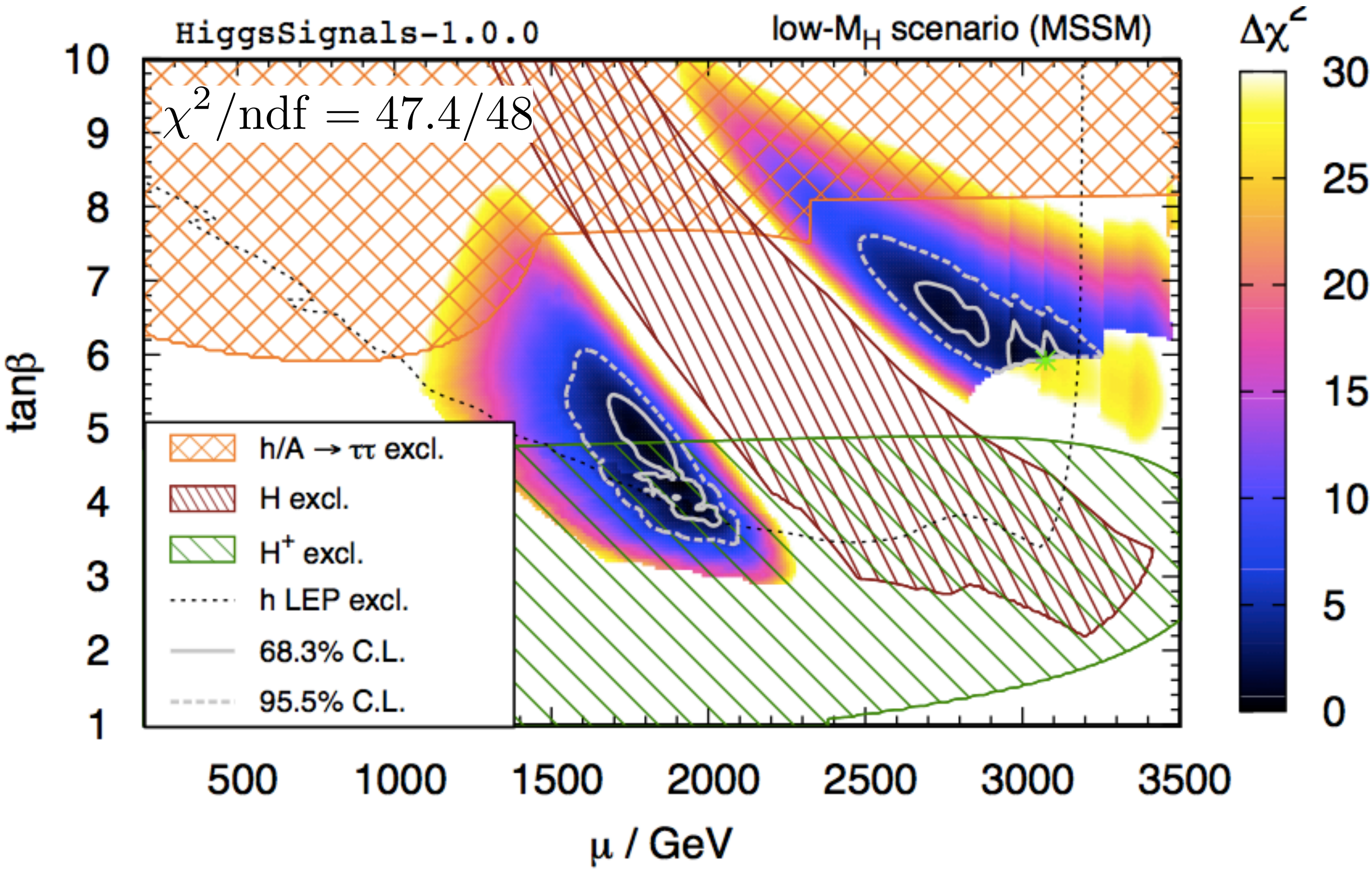
MSSM benchmark scenarios

- New benchmark scenarios for LHC MSSM Higgs searches [1302.7033]
- Compatibility with observed 125 GeV Higgs signal (HS/HB) (SM-like lightest Higgs boson h in decoupling limit)



Example: Low-M_H MSSM scenario

- Heavy CP-even MSSM Higgs at 125 GeV
  Lightest Higgs below (SM) LEP limit, suppressed hZZ couplings



Conclusions

- HiggsBounds is an established and convenient tool to apply exclusion limits from direct Higgs searches to arbitrary models
- A new sister code, HiggsSignals, has been published to take into account LHC/Tevatron *measurements* and evaluate the χ^2 function for compatibility data <-> theory
- Our general strategy for this code is to take all public information into account, and try to keep the code up to date with latest results
- HiggsSignals has been validated against official coupling fits
  First applications to coupling scale factors and the MSSM

http://higgsbounds.hepforge.org

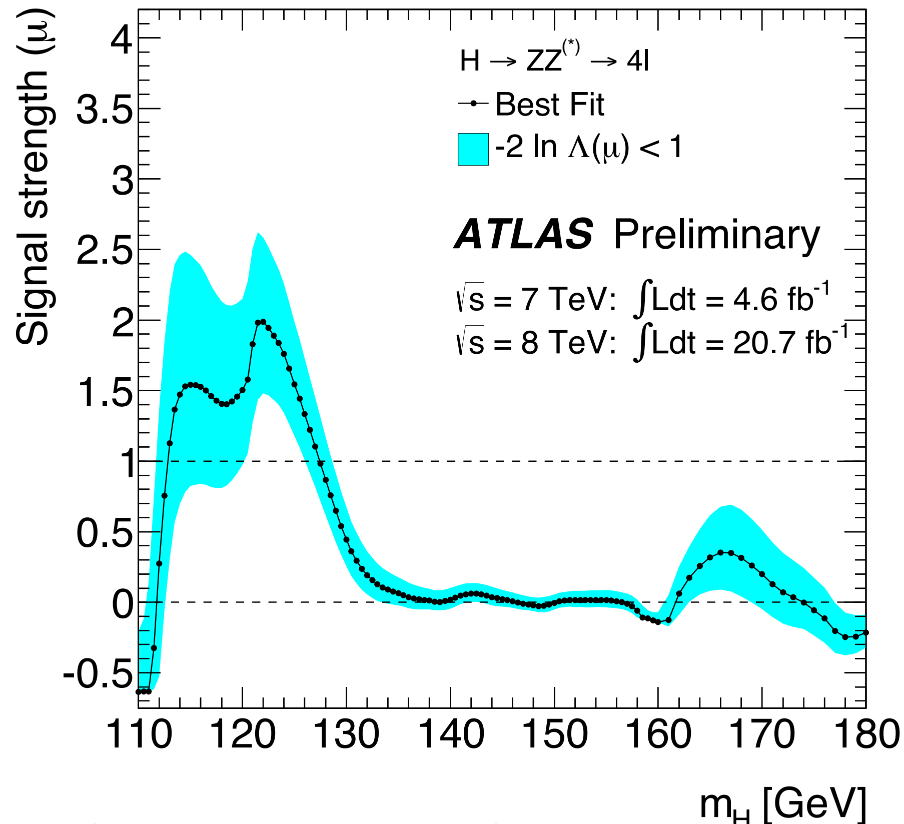
Backup

Mass-Centered χ^2 method

- Compares model prediction to measured data directly at the *predicted* Higgs mass values

- Combines rate predictions for Higgs bosons that are "nearby" in mass (within exp. resolution)

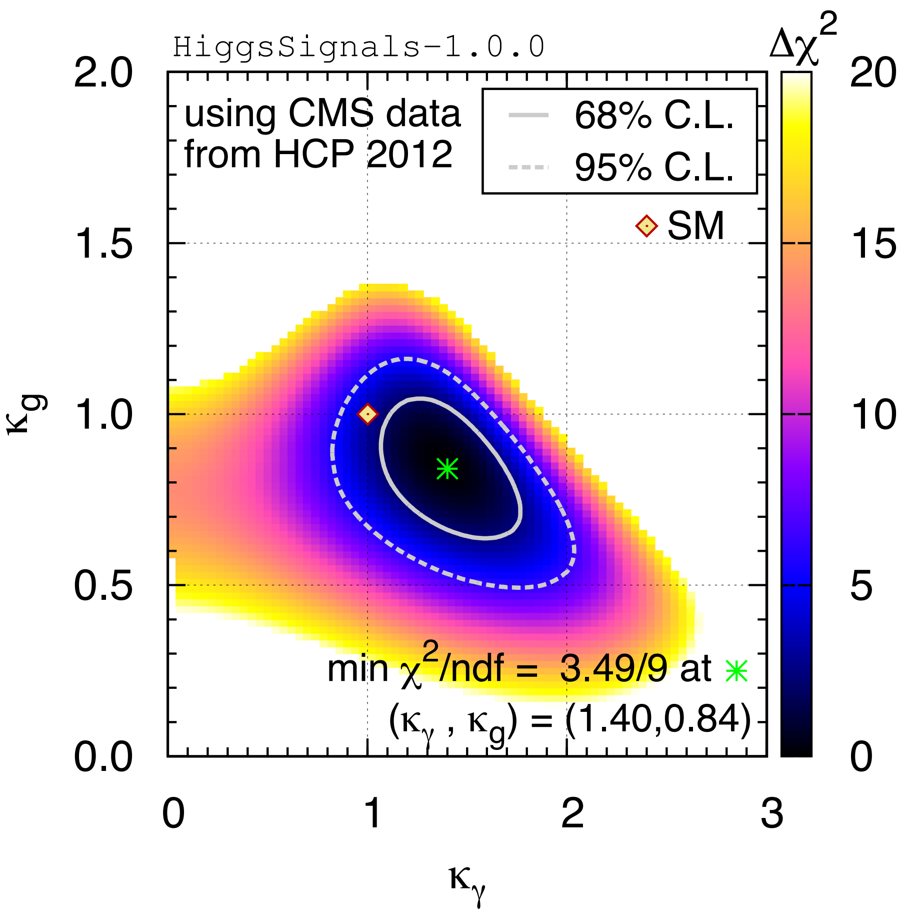
- Applicability of this method is currently limited by available exp. results, e.g. M_H < 200 GeV

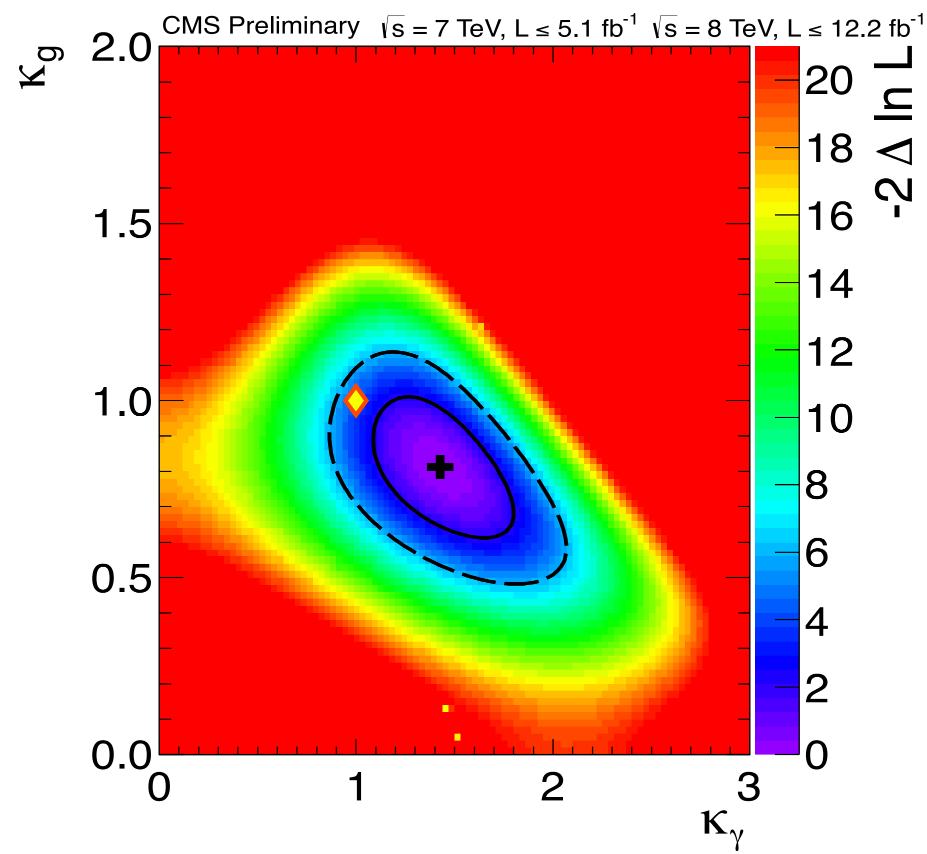


- Can be used simultaneously with peak-centered method for Higgs bosons that have not been assigned to any signal

Validation

- Tree-level couplings kept as in the SM, only loop-induced couplings fitted (probe of new physics contributions)





Higgs coupling scale factors

- Interim framework proposed by LHCXSWG for fitting (small) deviations from the SM Higgs couplings

[1209.0040]

- Assumes structure of couplings unchanged from SM, only coupling *strengths* modified

- Large deviations from the SM should be interpreted with care

1) $\kappa_u = \kappa_d = \kappa_\ell = \kappa_F$

$\kappa_W = \kappa_Z = \kappa_V$

Optional:

$\mathrm{BR}(H \to \mathrm{NP})$

2) $\kappa_u, \kappa_d, \kappa_\ell$

$\kappa_W = \kappa_Z = \kappa_V$

κ_g, κ_γ

$\mathrm{BR}(H \to \mathrm{NP})$

Derived scale factors

$$\kappa_{\mathrm{g}}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}}) = \frac{\kappa_{\mathrm{t}}^2 \cdot \sigma_{\mathrm{ggH}}^{\mathrm{tt}}(m_{\mathrm{H}}) + \kappa_{\mathrm{b}}^2 \cdot \sigma_{\mathrm{ggH}}^{\mathrm{bb}}(m_{\mathrm{H}}) + \kappa_{\mathrm{t}}\kappa_{\mathrm{b}} \cdot \sigma_{\mathrm{ggH}}^{\mathrm{tb}}(m_{\mathrm{H}})}{\sigma_{\mathrm{ggH}}^{\mathrm{tt}}(m_{\mathrm{H}}) + \sigma_{\mathrm{ggH}}^{\mathrm{bb}}(m_{\mathrm{H}}) + \sigma_{\mathrm{ggH}}^{\mathrm{tb}}(m_{\mathrm{H}})}$$

$$\kappa_{\gamma}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{\gamma\gamma}^{ij}(m_{\mathrm{H}})}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}(m_{\mathrm{H}})}$$

Higgs coupling scale factors

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ggH}}} = \begin{cases} \kappa_{\mathrm{g}}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}}) \\ \kappa_{\mathrm{g}}^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma^{\mathrm{SM}}_{\mathrm{VBF}}} = \kappa_{\mathrm{VBF}}^2(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_{\mathrm{H}})$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma^{\mathrm{SM}}_{\mathrm{WH}}} = \kappa_{\mathrm{W}}^2$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ZH}}} = \kappa_{\mathrm{Z}}^2$$

$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma^{\mathrm{SM}}_{\mathrm{t\bar{t}H}}} = \kappa_{\mathrm{t}}^2$$

Detectable decay modes

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma^{\mathrm{SM}}_{\mathrm{WW}^{(*)}}} = \kappa_{\mathrm{W}}^2$$

$$\frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma^{\mathrm{SM}}_{\mathrm{ZZ}^{(*)}}} = \kappa_{\mathrm{Z}}^2$$

$$\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{b\bar{b}}}} = \kappa_{\mathrm{b}}^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{\mathrm{SM}}_{\tau^-\tau^+}} = \kappa_{\tau}^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{\mathrm{SM}}_{\gamma\gamma}} = \begin{cases} \kappa_{\gamma}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa_{\gamma}^2 \end{cases}$$

$$\frac{\Gamma_{\mathrm{Z}\gamma}}{\Gamma^{\mathrm{SM}}_{\mathrm{Z}\gamma}} = \begin{cases} \kappa_{(\mathrm{Z}\gamma)}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa_{(\mathrm{Z}\gamma)}^2 \end{cases}$$

Parameter values for MSSM benchmark scenarios

Parameter	$m_h^{\max}$	$m_h^{\text{mod}+}$	$m_h^{\text{mod}-}$	*light stop*	*light stau*	*τ-phobic*	*low-M_H*
m_t	173.2	173.2	173.2	173.2	173.2	173.2	173.2
M_A	varied	varied	varied	varied	varied	varied	110
$\tan\beta$	varied	varied	varied	varied	varied	varied	varied
M_{SUSY}	1000	1000	1000	500	1000	1500	1500
$M_{\tilde{l}_3}$	1000	1000	1000	1000	245 (250)	500	1000
$X_t^{\text{OS}}/M_{\text{SUSY}}$	2.0	1.5	-1.9	2.0	1.6	2.45	2.45
$X_t^{\overline{\text{MS}}}/M_{\text{SUSY}}$	$\sqrt{6}$	1.6	-2.2	2.2	1.7	2.9	2.9
A_t				Given by $A_t = X_t + \mu\cot\beta$			
A_b	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$
A_τ	$= A_t$	$= A_t$	$= A_t$	$= A_t$	0	$= A_t$	$= A_t$
μ	200	200	200	350	500 (450)	2000	varied
M_1				Fixed by GUT relation to M_2			
M_2	200	200	200	350	200 (400)	200	200
$m_{\tilde{g}}$	1500	1500	1500	1500	1500	1500	1500
$M_{\tilde{q}_{1,2}}$	1500	1500	1500	1500	1500	1500	1500
$M_{\tilde{l}_{1,2}}$	500	500	500	500	500	500	500
$A_{f\neq t,b,\tau}$	0	0	0	0	0	0	0