LHC: Standard and Hidden Scalar Bosons

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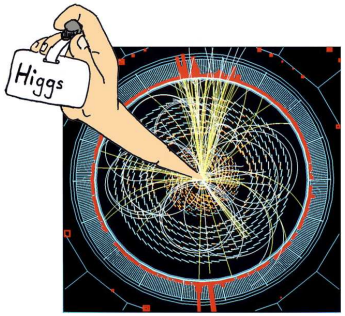
INSTITUTE FOR THEORETICAL PHYSICS

EBHGHK properties

Verify nature of observed resonance
$\leftrightarrow$ "EBHGHK" properties [Englert, Brout; Higgs; Guralnik, Hagen, Kibble]

- spin-0 particle
  spin-1 excluded by $H \to \gamma\gamma$ [Landau-Yang theorem]
  spin-2: look at angular correlations
  [Hagiwara, Mawatari, Li; Frank, MR, Zeppenfeld; Ellis, Hwang]
- CP-nature
  SM-Higgs CP-even; extended Higgs sectors also CP-odd or mixed states
  look at angular correlations [Plehn, Rainwater, Zeppenfeld; Klämke, Zeppenfeld]
  [Choi, Eberle, Miller, Mühlleitner, Zerwas]
  [Englert, Hackstein, Spannowsky]
- couplings
  SM prediction fixed by already known quantities
  - unitarity in $W_L W_L \to W_L W_L$ scattering
    $\longrightarrow$ fixed coupling $g_{WWH} \propto m_W$
  - fermion masses
    $\longrightarrow g_{f\bar{f}H} \propto m_f$
  - Higgs self-couplings
    determine shape of Higgs potential via trilinear and quartic couplings
    SM: $V = \mu^2|\Phi|^2 + \lambda|\Phi|^4 + \text{const.}$
    new scale Λ: $V = \sum_{n\geq 0} \frac{\lambda^n}{\Lambda^{2n}} \left(|\Phi|^2 + \frac{v^2}{2}\right)^{2+n}$
    $\longrightarrow$ very challenging for LHC (and ILC) [Plehn et al.; Baur et al.; MR et al.; Binoth et al.; ...]

Higgs properties



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$\leftrightarrow$ "Higgs" properties

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Generalized Higgs sector

How well can we determine the SM Higgs couplings?
Can we distinguish a non-Standard-Model-like Higgs sector?

- Theory: Standard Model plus free Higgs couplings
  Couplings from modified version of HDecay [Djouadi, Kalinowski, Spira]
- For Higgs couplings present in the Standard Model $i = W, Z, t, b, \tau$
  $$g_{iiH} \longrightarrow g_{iiH}^{\mathrm{SM}} \; (1 + \Delta_i) \qquad (\rightarrow \Delta = -2 \text{ means sign flip})$$
- For loop-induced Higgs couplings $i = \gamma, g$
  $$g_{iiH} \longrightarrow g_{iiH}^{\mathrm{SM}} \left(1 + \Delta_i^{\mathrm{SM}} + \Delta_i\right)$$
  where g_{iiH}^{SM}: (loop-induced) coupling in the Standard Model
  Δ_i^{SM}: contribution from modified tree-level couplings to Standard-Model particles
  Δ_i : additional (dimension-five) contribution
- Neglecting couplings only available from high-luminosity analyses ($g_{H\mu\mu}, g_{HZ\gamma}^{\mathrm{eff}}, g_{HHH}, g_{HHHH}$)
- Δ_H: single parameter modifying all (tree-level) couplings
- Total width
  $$\Gamma_{\mathrm{tot}} = \Sigma_{\mathrm{obs}} \Gamma_x \quad \text{(plus generation universality)}$$

SFitter

Algorithms:

- weighted Markov chain
- cooling Markov chain ($\sim$ simulated annealing)
- modified gradient fit (Minuit)
- grid scan

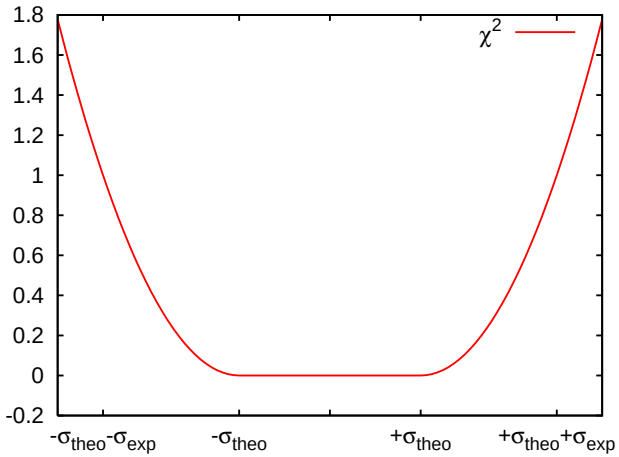
[Lafaye, Plehn, MR,Zerwas]

[Eur.Phys.J.C54:617-644,2008, [arXiv:0709.3985 [hep-ph]]]

[JHEP08(2009)009 [arXiv:0904.3866 [hep-ph]]]

Errors:

- three types:
  - Gaussian – arbitrary correlations possible ($\rightarrow$ systematic errors)
  - Poisson
  - box-shaped (RFit) [CKMFitter]
- assignment as in exp. studies
- adaption to likelihood input easy



Output of SFitter:

- fully-dimensional log-likelihood map
- one- and two-dimensional distributions via
  - marginalization (Bayesian)
  - profile likelihood (Frequentist)
- list of best points

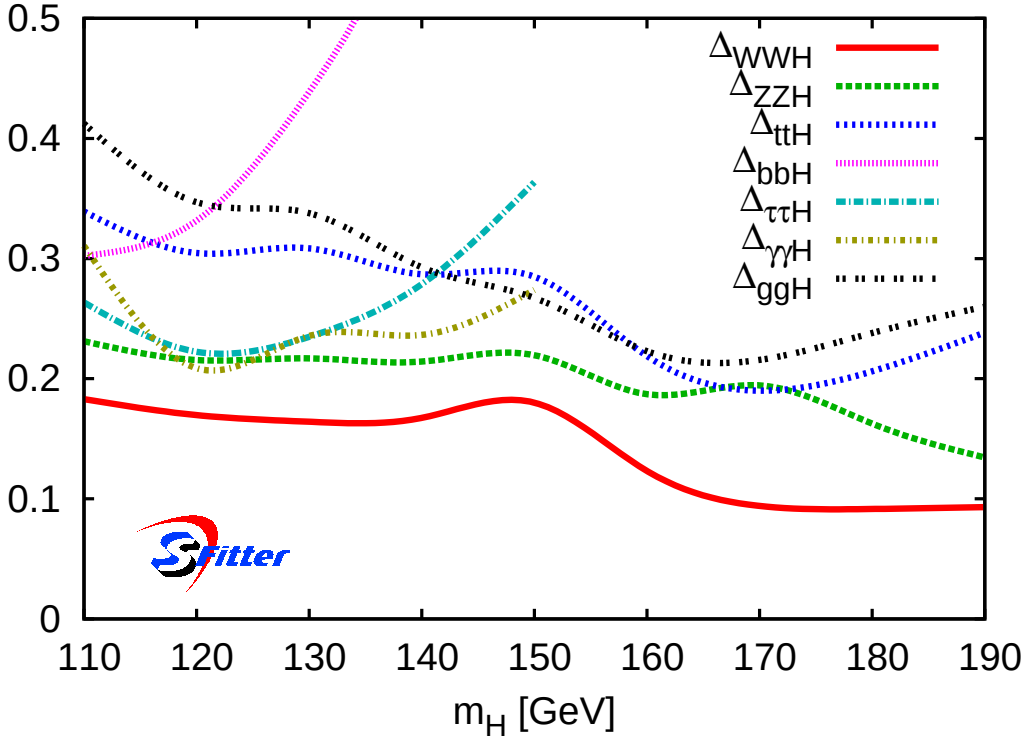
Higgs at the LHC

14 TeV expectations (30 fb^{-1}) [Zeppenfeld, Kinnunen, Nikitenko, Richter-Was; Dührssen et al.]

(Standard Model hypothesis)

production	decay
$gg \to H$	ZZ
qqH	ZZ
$gg \to H$	WW
qqH	WW
$t\bar{t}H$	$WW(3\ell)$
$t\bar{t}H$	$WW(2\ell)$
inclusive	$\gamma\gamma$
qqH	$\gamma\gamma$
$t\bar{t}H$	$\gamma\gamma$
WH	$\gamma\gamma$
ZH	$\gamma\gamma$
qqH	$\tau\tau(2\ell)$
qqH	$\tau\tau(1\ell)$
$t\bar{t}H$	$b\bar{b}$
WH/ZH	$b\bar{b}$ (subjet)

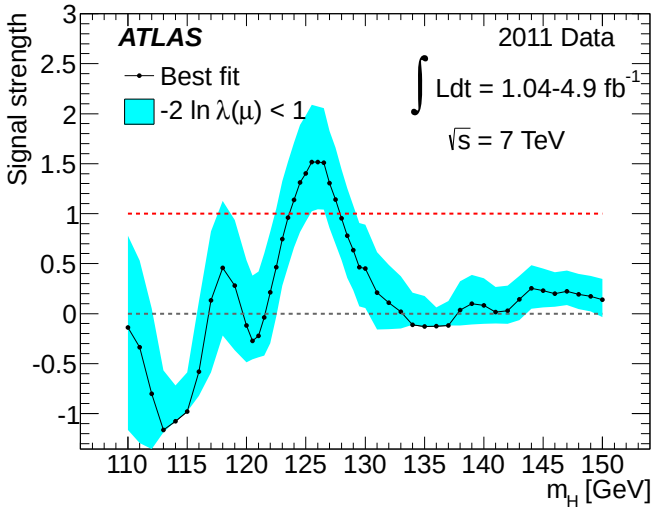
[Lafaye, Plehn, MR, Zerwas, Dührssen 2009]

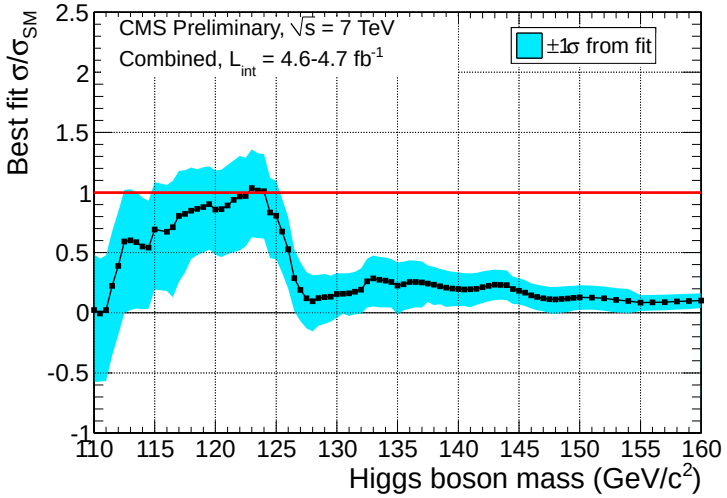


The 7 TeV Case

Higgs boson channels, $\mathcal{L}$ = 2.1-4.9 fb^{-1}

ATLAS	WW	0-jet
	WW	1-jet
	$\gamma\gamma$	
	$ZZ \to 4\ell$	
CMS	$\gamma\gamma$	
	$\gamma\gamma$	di-jet
	$ZZ \to 4\ell$	
	WW	0-jet
	WW	1-jet
	WW	2-jet
	$\tau\tau$	0/1-jet
	$\tau\tau$	Boosted
	$\tau\tau$	VBF
	$b\bar{b}$	WH
	$b\bar{b}$	$Z(\to \ell\bar{\ell})H$
	$b\bar{b}$	$Z(\to \nu\bar{\nu})H$





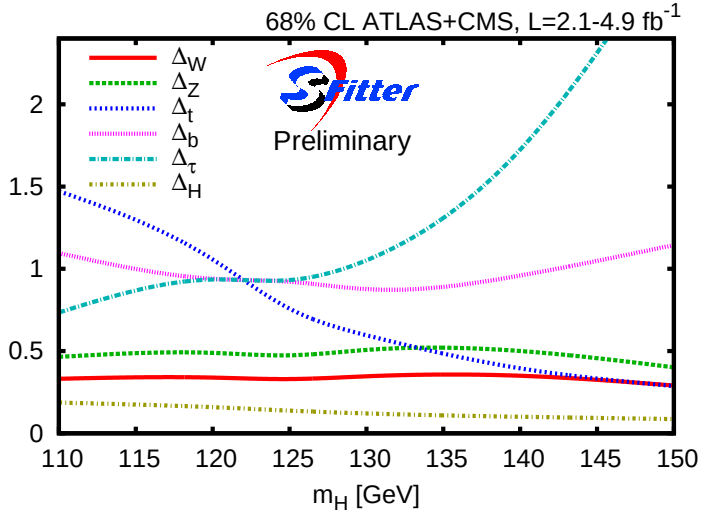
- background expectations, exp. errors, etc. from analyses
- cross-checked with exclusion and signal-strength plots

What about individual couplings?

Standard Model hypothesis

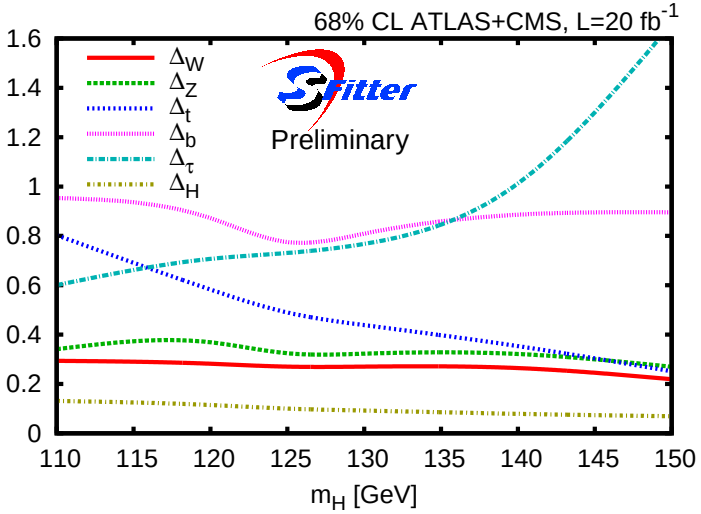
[Klute, Lafaye, Plehn, MR, Zerwas]

Currently



- precision on $\Delta_H \sim 14\%$
- *HWW* and *HZZ* couplings fairly precise over whole mass range
- $Ht\bar{t}$ from gluon-fusion, $H \to WW$ $\Rightarrow$ more precise for higher Higgs masses

Expectations for $\mathcal{L}$ = 20 fb^{-1}

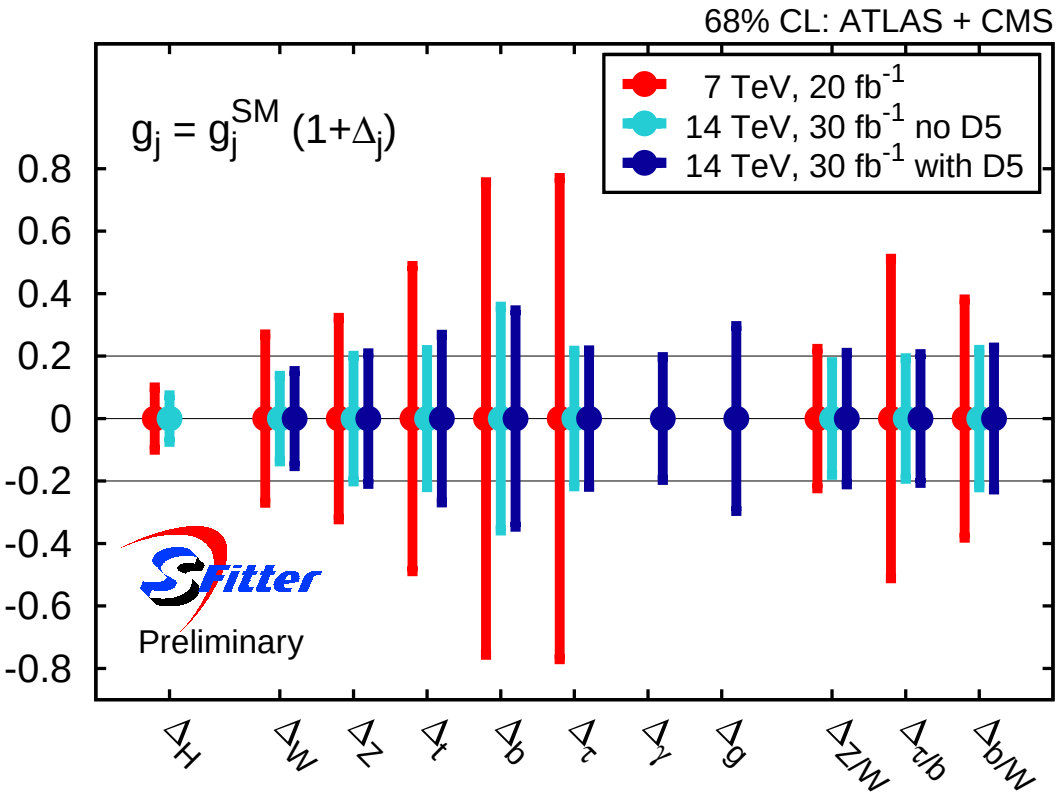


- precision on $\Delta_H \sim 10\%$
- mostly scaling
- systematic errors non-negligible

[see also Carmi et al., Asatov et al., Espinosa et al.]

Expectations for $m_H = 125$ GeV

If there is indeed a SM Higgs boson at ~ 125 GeV ...



- coupling ratios help for fermionic couplings at 7 TeV
  not much improvement at 14 TeV
- precision on $\Delta_H \sim 9\%$ for 14 TeV
- Standard Model hypothesis $\rightarrow$ central value 0
  (information not in all analyses available)
  $\rightarrow$ actual values post-Moriond

The Higgs Portal

Additional hidden sector as singlet under SM gauge groups

[Binoth, van der Bij; Hill, van der Bij; Schabinger, Wells; Patt, Wilczek; . . .]

Only possible connection to SM:

$$\mathcal{L} \propto \Phi_s^\dagger \Phi_s \Phi_h^\dagger \Phi_h$$

$\Phi_{s/h}$: Higgs field of SM/hidden sector

Electro-weak symmetry breaking:
$\phi_{s/h} \to (v_{s/h} + H_{s/h})/\sqrt{2}$

H_s and H_h mix into mass eigenstates:

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\chi & \sin\chi \\ -\sin\chi & \cos\chi \end{pmatrix} \begin{pmatrix} H_s \\ H_h \end{pmatrix}$$

Modifications for H_1: ($\cos\chi \mathrel{\widehat{=}} \Delta_H$)

$$\sigma = \cos^2\chi \cdot \sigma^{\mathrm{SM}}$$
$$\Gamma_{\mathrm{vis}} = \cos^2\chi \cdot \Gamma_{\mathrm{vis}}^{\mathrm{SM}}$$
$$\Gamma_{\mathrm{inv}} = \cos^2\chi \cdot \Gamma_{\mathrm{inv}}^{\mathrm{SM}} + \Gamma_{\mathrm{hid}}$$

($\Gamma_{\mathrm{inv}}^{\mathrm{SM}}$: Decay $H \to ZZ \to 4\nu$ (negligible))

similarly for H_2 with $\cos\chi \leftrightarrow \sin\chi$ plus possibly Γ_2^{HH} : $H_2 \to H_1 H_1$

The Higgs Portal

[C. Englert, Plehn, Rauch, D. Zerwas, P.M. Zerwas]

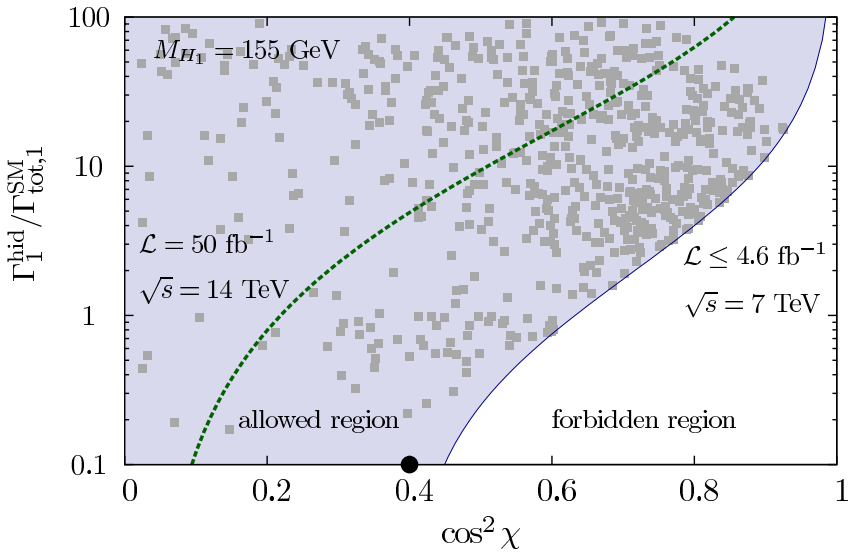
- bounds are determined by measurement of twin ratios

$$\left(\frac{\Gamma_p \Gamma_d}{\Gamma_{\text{tot}}}\right) / \left(\frac{\Gamma_p \Gamma_d}{\Gamma_{\text{tot}}}\right)^{\text{SM}} = (\sigma_p \times \text{BR}_d)/(\sigma_p \times \text{BR}_d)^{\text{SM}}$$

$$\frac{\sigma(pp \to H_1 \to F)}{\sigma(pp \to H_1 \to F)^{\text{SM}}} = \frac{\cos^2\chi}{1 + \tan^2\chi(\Gamma_1^{\text{hid}}/\Gamma_{\text{tot},1}^{\text{SM}})} \leq \mathcal{R}$$

$$\frac{\sigma(pp \to H_1 \to inv)}{\sigma(pp \to H_1)^{\text{SM}}} = \frac{\sin^2\chi(\Gamma_1^{\text{hid}}/\Gamma_{\text{tot},1}^{\text{SM}})}{1 + \tan^2\chi(\Gamma_1^{\text{hid}}/\Gamma_{\text{tot},1}^{\text{SM}})} \leq \mathcal{J}$$

- additional constraint: electroweak precision data (dots: compatible points)



Example: $M_{H_1} = 155$ GeV
$\Rightarrow \mathcal{R} \lesssim 0.4$ @ 95% CL

- bound weakened by invisible decays
- whole area left of it still possible
- significant improvement with higher statistics

The Higgs Portal

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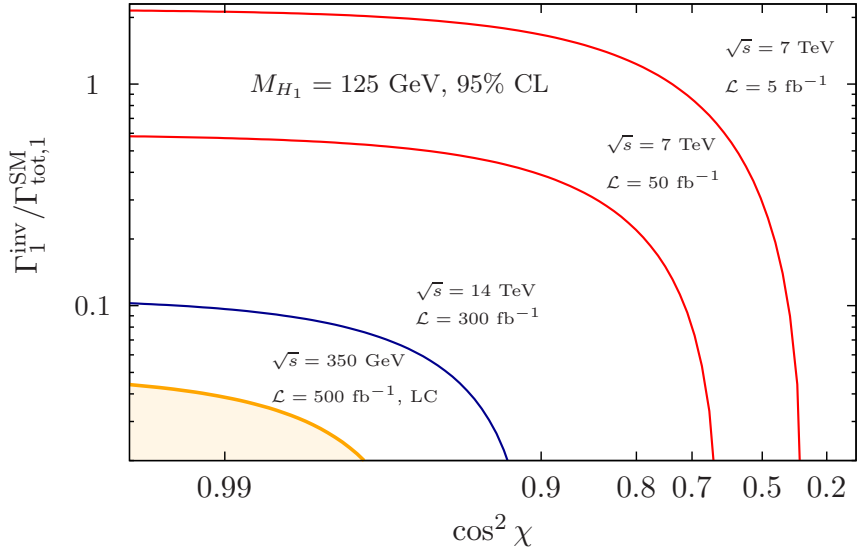


- Standard Model: limit $\mathcal{R} \to 1$
- quantify coincidence by possible deviations left
- (invisible decays hard at LHC: $\to$ Linear Collider)

Strongly-Interacting Light Higgs

[Giudice, Grojean, Pomarol, Rattazzi; Espinosa, Grojean, Mühlleitner]

Higgs pseudo-Goldstone boson of new strongly interacting sector
Modifications parametrized by $\xi = (v/f)^2$ *(f: Goldstone scale)*

- MCHM4:

  Scaling of all couplings with $\sqrt{1-\xi}$
  $\Rightarrow$ Identify $\cos^2\chi = 1-\xi$
  $\Gamma_{\text{hid}} = 0$

- MCHM5:

  Scaling:

  $g_{VVH} = g_{VVH}^{\text{SM}} \cdot \sqrt{1-\xi}$

  $g_{f\bar{f}H} = g_{f\bar{f}H}^{\text{SM}} \cdot \frac{1-2\xi}{\sqrt{1-\xi}}$

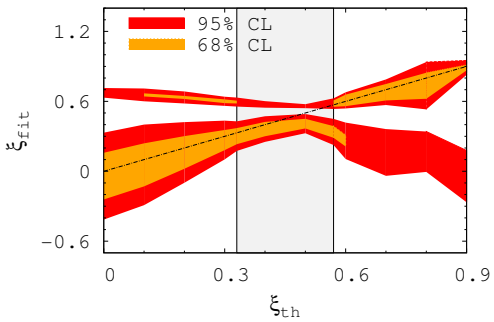
Significant and observable deviations also in Higgs self-couplings [Gröber, Mühlleitner]

MCHM5

[Bock, Lafaye, Plehn, MR, D. Zerwas, P.M. Zerwas]

Secondary solutions appear (sign of $f\bar{f}H$ coupling)

$m_H = 120$ GeV



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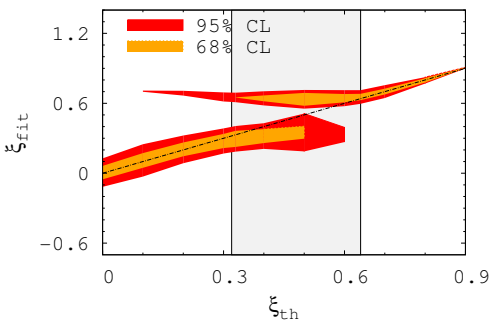

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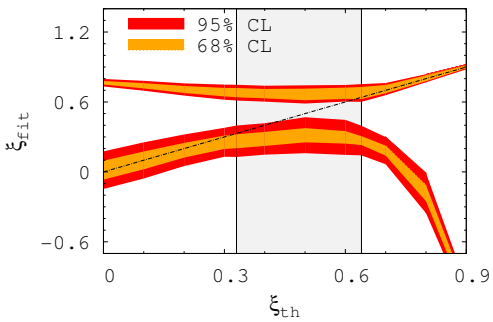
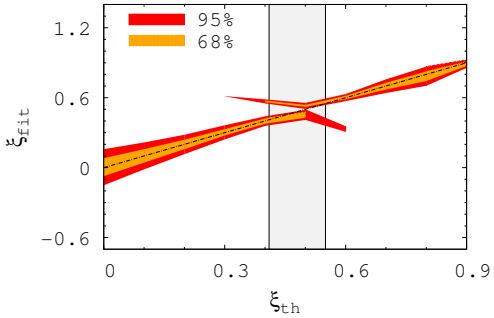
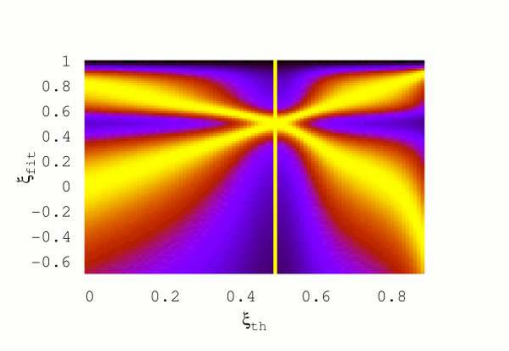


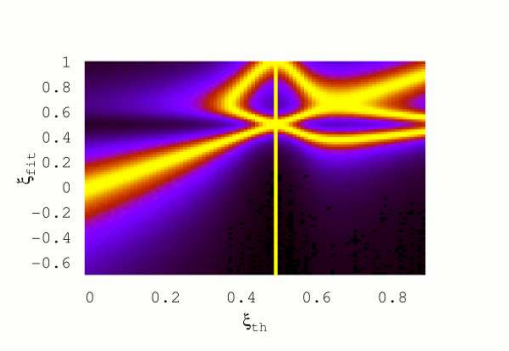
$\mathcal{L} = 300$ fb^{-1}



Gluon fusion $H \to \gamma\gamma$



$WH/ZH, H \to b\bar{b}$



Not a true degeneracy
$\to$ Each (smeared) toy experiment has unique solution

Conclusions

- Determining the Higgs-boson couplings important for our understanding of electroweak symmetry breaking
  $\rightarrow$ Standard Model with effective Higgs couplings

- All errors including correlations fully implemented
  (SFitter: collaboration of theorists and experimentalists)

- Current accuracy between 33% (HWW) and 92% ($Hb\bar{b}$, $H\tau\bar{\tau}$),
  Portal precision $\sim$ 14%, for Standard Model couplings

- Extended Models (Portal Higgs, SILH, ...) can lead to simple one-parameter deviations which can be tested

SFitter

- Need to scan high-dimensional parameter space
- $\Rightarrow$ SFitter [Lafaye, Plehn, MR, Zerwas]
- General Higgs couplings from modified version of HDecay [Djouadi, Kalinowski, Spira]
- Three scanning techniques:
  - Weighted Markov Chain
  - Cooling Markov Chain (equivalent to simulated annealing)
  - Gradient Minimisation (Minuit)
  - Nested Sampling [Skilling; Feroz, Hobson]
- Output of SFitter:
  - Fully-dimensional log-likelihood map
  - Reduction to plotable one- or two-dimensional distributions via both
    - Bayesian (marginalisation) or
    - Frequentist (profile likelihood) techniques
  - List of best points
- Also successfully used for SUSY parameter extraction studies

[partly in coll. with Adam, Kneur; Turlay]

Higgs at the LHC

Input data [Dührssen (ATL-PHYS-2002-030), ATLAS CSC Note; CMS results comparable]

$m_H = 120\ \mathrm{GeV}; \quad \mathcal{L} = 30\ \mathrm{fb}^{-1}$

production	decay	$S+B$	B	S	$\Delta S^{(\mathrm{exp})}$	$\Delta S^{(\mathrm{theo})}$
$gg \to H$	ZZ	13.4	6.6 ($\times$ 5)	6.8	3.9	0.8
qqH	ZZ	1.0	0.2 ($\times$ 5)	0.8	1.0	0.1
$gg \to H$	WW	1019.5	882.8 ($\times$ 1)	136.7	63.4	18.2
qqH	WW	59.4	37.5 ($\times$ 1)	21.9	10.2	1.7
$t\bar{t}H$	$WW(3\ell)$	23.9	21.2 ($\times$ 1)	2.7	6.8	0.4
$t\bar{t}H$	$WW(2\ell)$	24.0	19.6 ($\times$ 1)	4.4	6.7	0.6
inclusive	$\gamma\gamma$	12205.0	11820.0 ($\times$ 10)	385.0	164.9	44.5
qqH	$\gamma\gamma$	38.7	26.7 ($\times$ 10)	12.0	6.5	0.9
$t\bar{t}H$	$\gamma\gamma$	2.1	0.4 ($\times$ 10)	1.7	1.5	0.2
WH	$\gamma\gamma$	2.4	0.4 ($\times$ 10)	2.0	1.6	0.1
ZH	$\gamma\gamma$	1.1	0.7 ($\times$ 10)	0.4	1.1	0.1
qqH	$\tau\tau(2\ell)$	26.3	10.2 ($\times$ 2)	16.1	5.8	1.2
qqH	$\tau\tau(1\ell)$	29.6	11.6 ($\times$ 2)	18.0	6.6	1.3
$t\bar{t}H$	$b\bar{b}$	244.5	219.0 ($\times$ 1)	25.5	31.2	3.6
WH/ZH	$b\bar{b}$	228.6	180.0 ($\times$ 1)	48.6	20.7	4.0

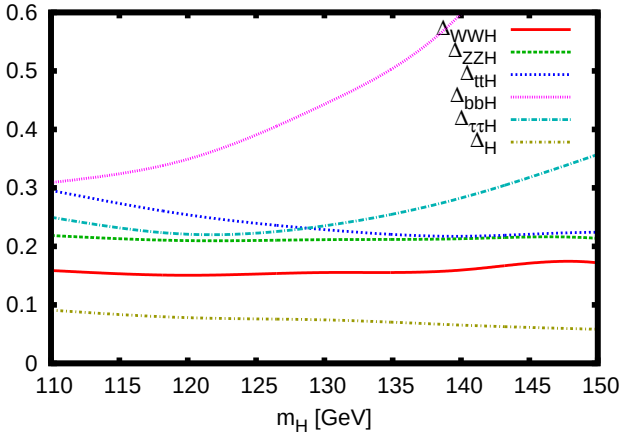
Last line obtained using subjet techniques ([Butterworth, Davison, Rubin, Salam]),
theoretical results confirmed by ATLAS ([ATL-PHYS-PUB-2009-088])
(stricter cuts, statistical significance basically unchanged)

From 14 to 7 TeV

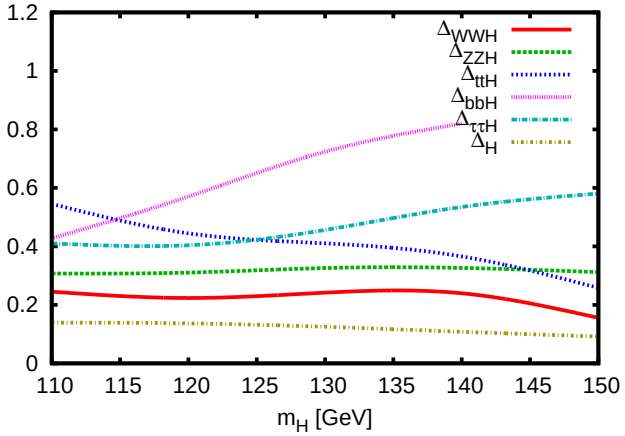
Extrapolate analyses from 14 TeV to 7 TeV

- Higgs sector: no effective couplings
- Signal cross sections from LHC Higgs XS WG
- Background cross sections scaled with SHERPA

14 TeV, 30 fb^{-1}



7 TeV, 20 fb^{-1}



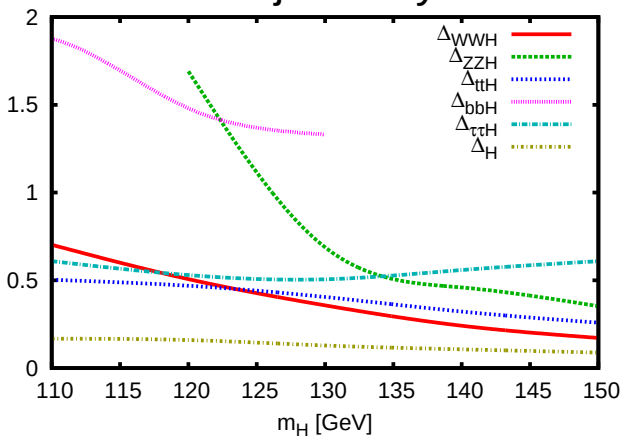
Δ_H: single parameter modifying all (tree-level) couplings

precision on $\Delta_H \sim 10\%$

without subjet analyses:

- precision similar for most couplings
- $b\bar{b}H$-coupling undetermined (decay side)
- ZZH-coupling undetermined (production side)

without subjet analyses



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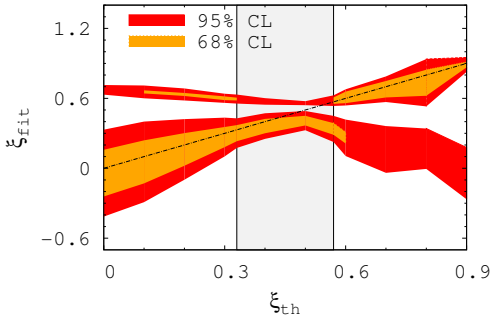

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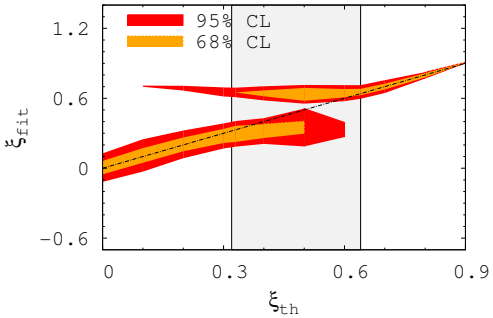

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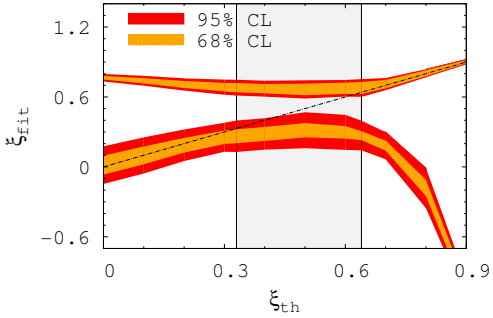

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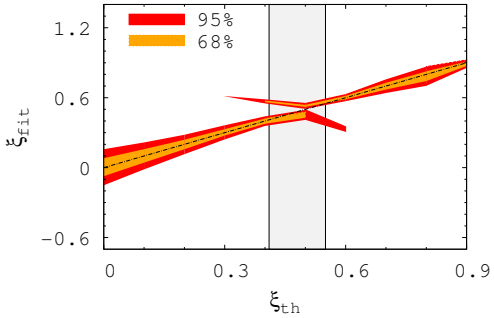
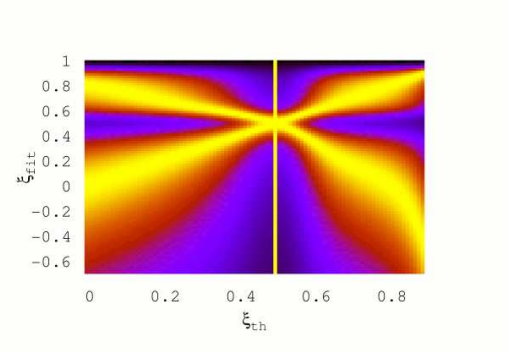
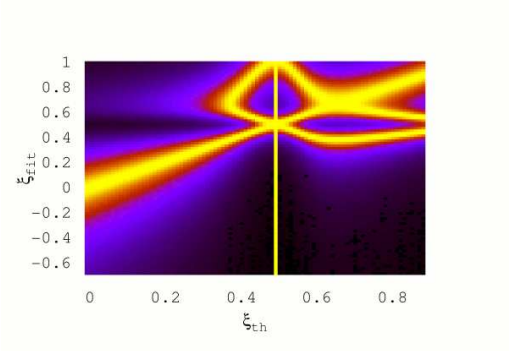


Gluon fusion $H \to \gamma\gamma$



$WH/ZH, H \to b\bar{b}$



Not a true degeneracy
$\to$ Each (smeared) toy experiment has unique solution