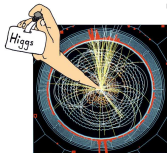


Results from

Michael Rauch | September 1st, 2011

INSTITUTE FOR THEORETICAL PHYSICS





Verify nature of observed resonance \leftrightarrow “Higgs” properties

- spin-0 particle
- CP-nature
- couplings

SM prediction fixed by already known quantities

- unitarity in $W_L W_L \rightarrow W_L W_L$ scattering
→ fixed coupling $g_{WWH} \propto m_W$
- fermion masses
→ $g_{f\bar{f}H} \propto m_f$
- 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 : $V = \sum_{n \geq 0} \frac{\lambda^n}{\Lambda^{2n}} \left(|\Phi|^2 + \frac{v^2}{2} \right)^{2+n}$

→ very challenging for LHC

[Plehn et al.; Baur et al.; MR et al.; Binoth et al.; ...]

How well can we determine the SM Higgs couplings?

Can we distinguish a non-Standard-Model-like Higgs sector?

- Theory: Standard Model plus general Higgs sector
- For Higgs couplings present in the Standard Model $j = W, Z, t, b, \tau$ replace general couplings by

$$g_{jjH} \longrightarrow g_{jjH}^{\text{SM}} (1 + \Delta_{jjH}) \quad (\rightarrow \Delta = -2 \text{ means sign flip})$$

- For loop-induced Higgs couplings $j = \gamma, g$ replace by

$$g_{jjH} \longrightarrow g_{jjH}^{\text{SM}} \left(1 + \Delta_{jjH}^{\text{SM}} + \Delta_{jjH} \right)$$

where g_{jjH}^{SM} : (loop-induced) coupling in the Standard Model

Δ_{jjH}^{SM} : contribution from modified tree-level couplings

to Standard-Model particles

Δ_{jjH} : additional (dimension-five) contribution

- Additional free parameters:
 - Higgs boson mass m_H
 - top- and bottom-quark mass m_t, m_b
- Neglecting couplings only available from high-luminosity analyses
($g_{H\mu\mu}, g_{HZ\gamma}^{\text{eff}}, g_{HHH}, g_{HHHH}$)



- Need to scan high-dimensional parameter space
- \Rightarrow SFitter
- General Higgs couplings from modified version of HDecay
- Three scanning techniques:
 - Weighted Markov Chain
 - Cooling Markov Chain (equivalent to simulated annealing)
 - Gradient Minimisation (Minuit)
- 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
- Already successfully used for SUSY parameter extraction study

[Lafaye, Plehn, MR, Zerwas]

[Spira]

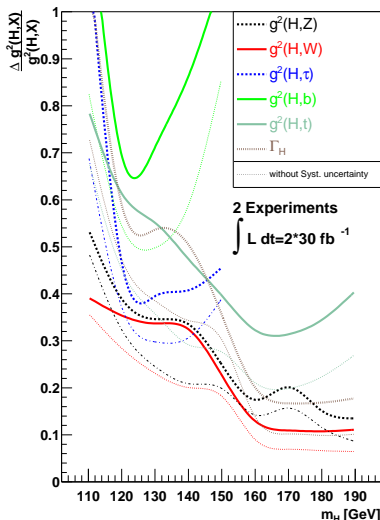
[EPJC 54(2008) [arXiv:0709.3985]]

[Zeppenfeld, Kinnunen, Nikitenko, Richter-Was; Dührssen et al.]

production	decay
$gg \rightarrow H$	ZZ
qqH	ZZ
$gg \rightarrow H$	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	$\tau\tau(1\ell)$
$t\bar{t}H$	$b\bar{b}$
<i>WHZH</i>	<i>bb (subject)</i>

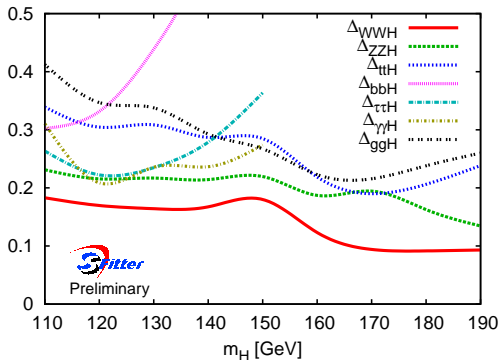
Total width

- degeneracy $\sigma \cdot BR \propto g_p^2 \frac{g_a^2}{\Gamma_H}$ ($\Gamma_H \propto g^2$)
- Here: $\Gamma_H = \sum_{SM} \Gamma_i$



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

production	decay
$gg \rightarrow H$	ZZ
qqH	ZZ
$gg \rightarrow H$	WW
qqH	WW
$t\bar{t}H$	$WW(3\ell)$
$t\bar{t}H$	$WW(2\ell)$
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$t\bar{t}H$	$\gamma\gamma$
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	$b\bar{b}$ (subject)



Total width

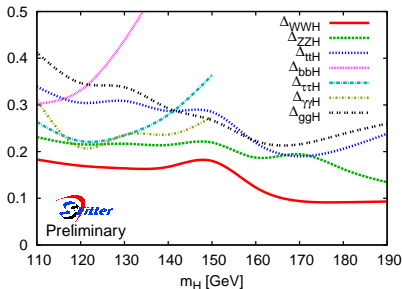
- degeneracy $\sigma \cdot BR \propto g_p^2 \frac{g_a^2}{\Gamma_H}$ ($\Gamma_H \propto g^2$)
- Here: $\Gamma_H = \sum_{SM} \Gamma_i$

Errors obtained by 10,000 toy experiments:

SM hypothesis, $m_H = 120 \text{ GeV}$, $\mathcal{L} = 30 \text{ fb}^{-1}$ @ 14 TeV

Fit with Gaussian of the central part within one standard deviation

	no eff. couplings			with eff. couplings			ratio Δ_{jjH}/WWH		
	σ_{symm}	σ_{neg}	σ_{pos}	σ_{symm}	σ_{neg}	σ_{pos}	σ_{symm}	σ_{neg}	σ_{pos}
Δ_{WWH}	± 0.23	-0.21	$+0.26$	± 0.24	-0.21	$+0.27$	—	—	—
Δ_{ZZH}	± 0.36	-0.40	$+0.35$	± 0.31	-0.35	$+0.29$	± 0.41	-0.40	$+0.41$
Δ_{ttH}	± 0.41	-0.37	$+0.45$	± 0.53	-0.65	$+0.43$	± 0.51	-0.54	$+0.48$
Δ_{bbH}	± 0.45	-0.33	$+0.56$	± 0.44	-0.30	$+0.59$	± 0.31	-0.24	$+0.38$
$\Delta_{\tau\tau H}$	± 0.33	-0.21	$+0.46$	± 0.31	-0.19	$+0.46$	± 0.28	-0.16	$+0.40$
$\Delta_{\gamma\gamma H}$	—	—	—	± 0.31	-0.30	$+0.33$	± 0.30	-0.27	$+0.33$
Δ_{ggH}	—	—	—	± 0.61	-0.59	$+0.62$	± 0.61	-0.71	$+0.46$



$\mathcal{L} = 30 \text{ fb}^{-1}$
with eff. couplings
SM hypothesis

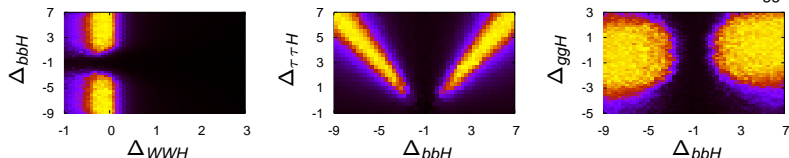
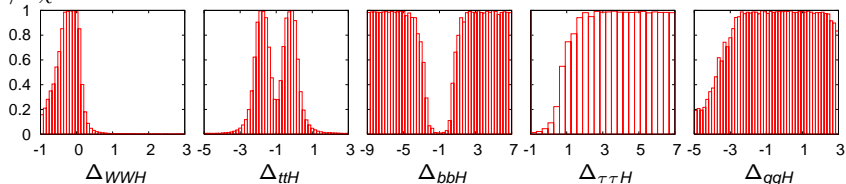
Non-decoupling Supersymmetric Higgs

SPS1a-inspired scenario with

$t_\beta = 7$, $A_t = -1100$ GeV, $m_A = 151$ GeV, $m_{h^0} = 120$ GeV

LHC data set with $\mathcal{L} = 30 \text{ fb}^{-1}$, Profile likelihood, True dataset

$1/\Delta\chi^2$ true: -0.13 -0.19 3.27 3.29 -0.28 = Δ



- Clear deviation from Standard Model:
 $q(d_{\text{SUSY}}|m_{\text{SM}}) < q(d_{\text{SM}}|m_{\text{SM}}) : 77\%$ at 90% CL
- Favouring of new physics more difficult: only 4% better described by SUSY model
- Strong correlation between Δ_{bbH} and $\Delta_{\tau\tau H}$ via total width
- No upper limit on g_{bbH} as $BR \simeq 1$ compatible with data

Additional hidden sector as singlet under SM gauge groups

[[Pat, 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:

$$\phi_{s/h} \rightarrow (v_{s/h} + H_{s/h})/\sqrt{2}$$

H_s and H_h mix into mass eigenstates:

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

$$\sigma = \cos^2 \chi \cdot \sigma^{\text{SM}}$$

$$\Gamma_{\text{vis}} = \cos^2 \chi \cdot \Gamma_{\text{vis}}^{\text{SM}}$$

$$\Gamma_{\text{inv}} = \cos^2 \chi \cdot \Gamma_{\text{inv}}^{\text{SM}} + \Gamma_{\text{hid}}$$

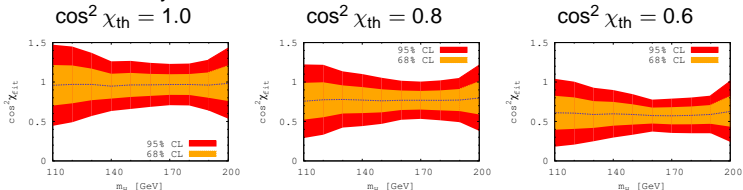
($\Gamma_{\text{inv}}^{\text{SM}}$: Decay $H \rightarrow ZZ \rightarrow 4\nu$ (negligible))

The Higgs Portal

Fit of $\cos^2 \chi_{\text{fit}}$ without constraints

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

- No invisible decay modes



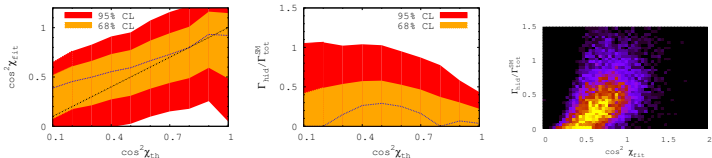
\Rightarrow If $\cos^2 \chi_{\text{th}} < 0.6$ can exclude SM at the 95% CL with 30 fb^{-1}

- Measuring invisible decays in VBF-Higgs production

Signature: Two VBF-jets plus missing E_T

[Eboli, Zeppenfeld; MC-study: ATLAS]

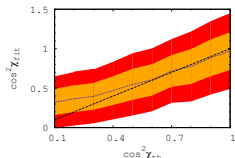
$$\Gamma_{\text{hid}} = \sin^2 \chi \cdot \Gamma_{\text{tot}}^{\text{SM}} \quad (\text{rhs: } \cos^2 \chi_{\text{th}} = 0.6)$$



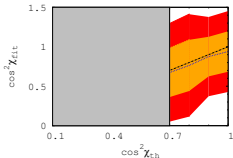
Significant backgrounds in Higgs measurement channels

- Measure signal plus background in signal region
- Extrapolate background from signal-free control regions (sidebands, etc.) and subtract
- Background from theory typically not better
- \Rightarrow B from control regions can be larger than S+B in signal region

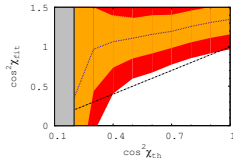
positive number
of signal events



$S > 2 * \Delta S$
for nominal SM rate



$S > 2 * \Delta S$
for actual rate



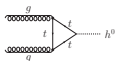
- \Rightarrow Careful treatment necessary
Observation of Higgs bosons favors larger couplings
Cross-check using all predicted channels

- Determining the Higgs-boson couplings important for our understanding of electroweak symmetry breaking
- Independent of explicit realisation of new physics (if any): Standard Model with effective Higgs couplings
- Expected accuracy of 20 – 50% in Standard Model with 30 fb^{-1} @ 14 TeV
- Recent jet substructure analysis significantly improves result on bottom-quark coupling
- Influences accuracy of all other couplings via total width
- Extended Models (SUSY, Portal Higgs, ...) can lead to simple one-parameter deviations which can be tested
- Beware of observation bias and degenerate solutions

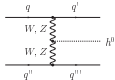
Higgs production modes

Main Higgs-boson production modes:

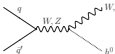
- gluon-gluon fusion



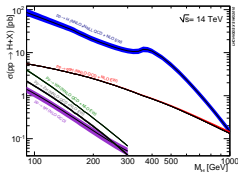
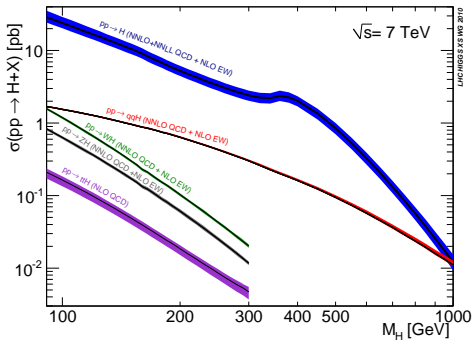
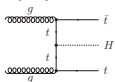
- vector-boson fusion



- associated production with gauge bosons

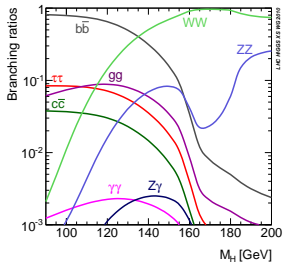


- associated production with top-quark-antiquark pair



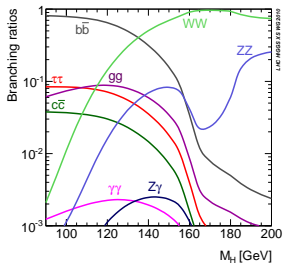
Higgs decay modes

- $H \rightarrow b\bar{b}$
 - main decay mode ($\sim 90\%$) for light Higgs bosons, as suggested by electroweak precision data
 - hard to extract from QCD backgrounds
 - recent suggestion of WH/ZH production plus jet substructure analysis looks promising (3.7σ @ 30 fb^{-1} & 14 TeV)
[Butterworth, Davison, Rubin, Salam; ATL-PHYS-PUB-088]
- $H \rightarrow \tau\bar{\tau}$
 - need to reconstruct invariant mass of the two taus
→ limits production channel to vector-boson fusion
 - one of the discovery channels for light Higgs bosons
[Plehn, Rainwater, Zeppenfeld]
- $H \rightarrow WW$
- $H \rightarrow ZZ$
- $H \rightarrow \gamma\gamma$



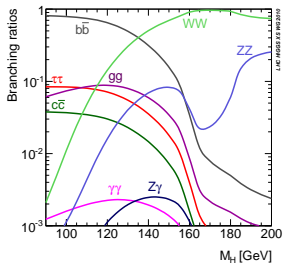
Higgs decay modes

- $H \rightarrow b\bar{b}$
- $H \rightarrow \tau\bar{\tau}$
- $H \rightarrow WW$
 - main decay mode for heavier Higgs bosons ($m_H \gtrsim 140$ GeV)
 - gluon and vector-boson fusion relevant even if W s are off-shell
- $H \rightarrow ZZ$
 - “Golden Channel” due to four-lepton final state
 - statistically limited to larger Higgs masses
- $H \rightarrow \gamma\gamma$



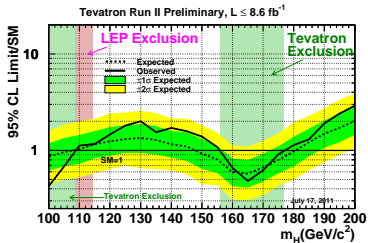
Higgs decay modes

- $H \rightarrow b\bar{b}$
- $H \rightarrow \tau\bar{\tau}$
- $H \rightarrow WW$
- $H \rightarrow ZZ$
- $H \rightarrow \gamma\gamma$
 - loop-induced coupling by (mainly) W and t
 - only fully reconstructable channel for a light Higgs boson
 - small branching ratio ($\lesssim 0.2\%$)
 - promising discovery channel for light Higgs bosons, background can be subtracted via sidebands
 - Higgs mass measurement up to 100 MeV

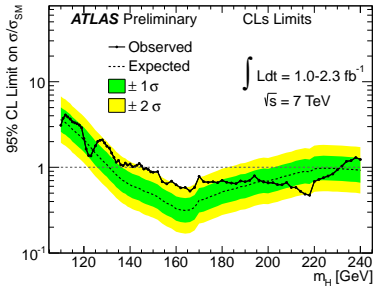
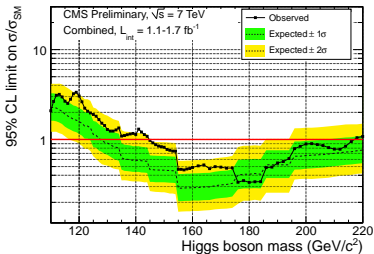


Discovering the Higgs boson

Tevatron results



LHC results



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

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

production	decay	$S + B$	B	S	$\Delta S^{(\text{exp})}$	$\Delta S^{(\text{theo})}$
$gg \rightarrow H$	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
$gg \rightarrow H$	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

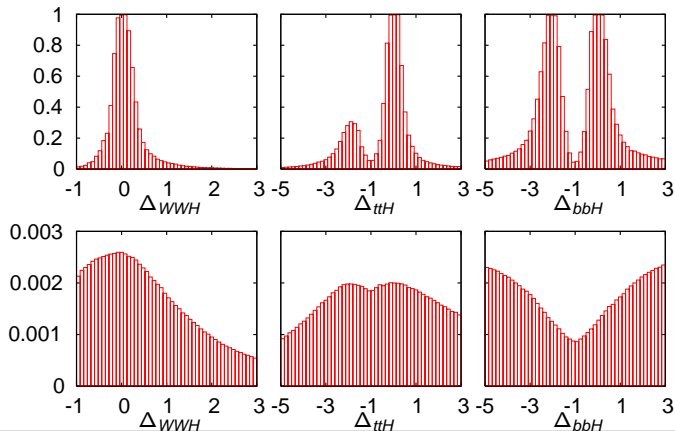
Last line obtained using subjet techniques ([Butterworth, Davison, Rubin, Salam]),
 theoretical results confirmed by ATLAS ([ATL-PHYS-PUB-2009-088])
 (stricter cuts, statistical significance basically unchanged)

Distribution of parameters

One-dimensional distributions

- Slow-falling distributions with single peaks prefer profile likelihood
- Higher luminosity qualitatively similar, quantitatively better
- Including effective couplings allows sign degeneracy for ttH coupling
- Smearing the dataset does not change picture substantially either

True dataset, 30 fb⁻¹; Profile likelihood vs. Bayesian

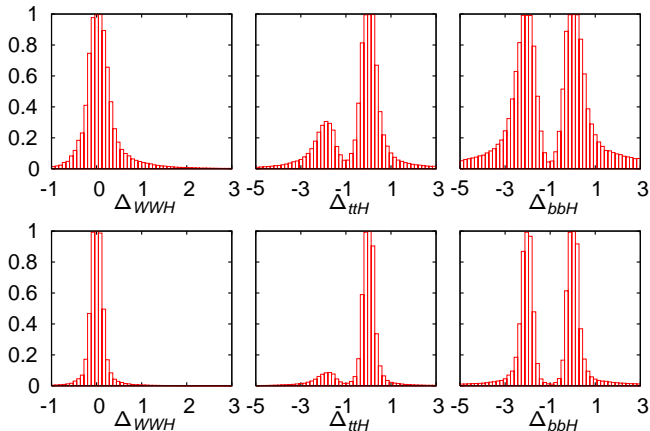


Distribution of parameters

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True dataset, Profile likelihood; 30 fb^{-1} vs. 300 fb^{-1}

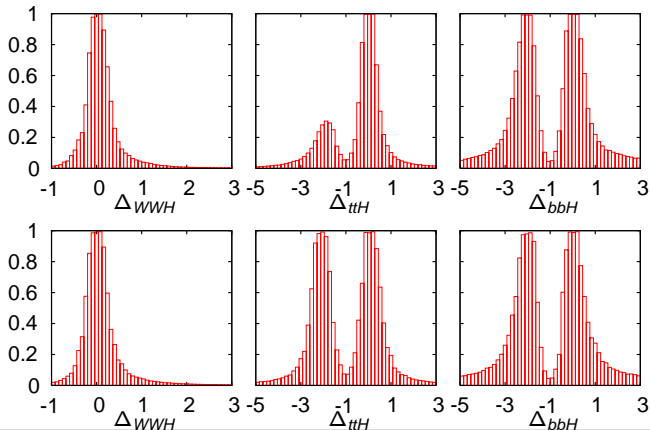


Distribution of parameters

One-dimensional distributions

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True dataset, Profile likelihood, 30 fb^{-1} ; Without vs. including eff. couplings

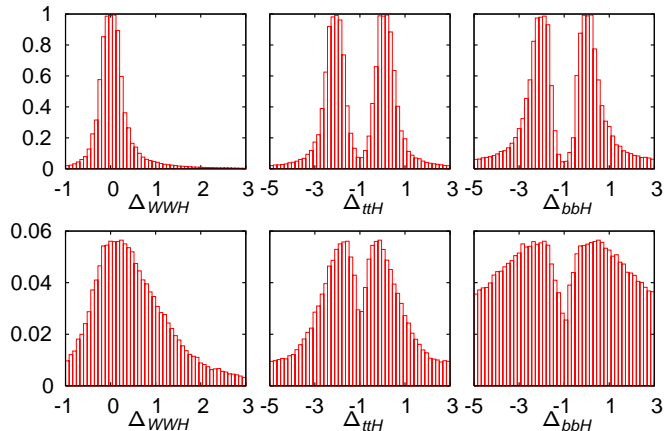


Distribution of parameters

One-dimensional distributions

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- Smearing the dataset does not change picture substantially either

Profile likelihood, 30 fb^{-1} ; True vs. smeared dataset

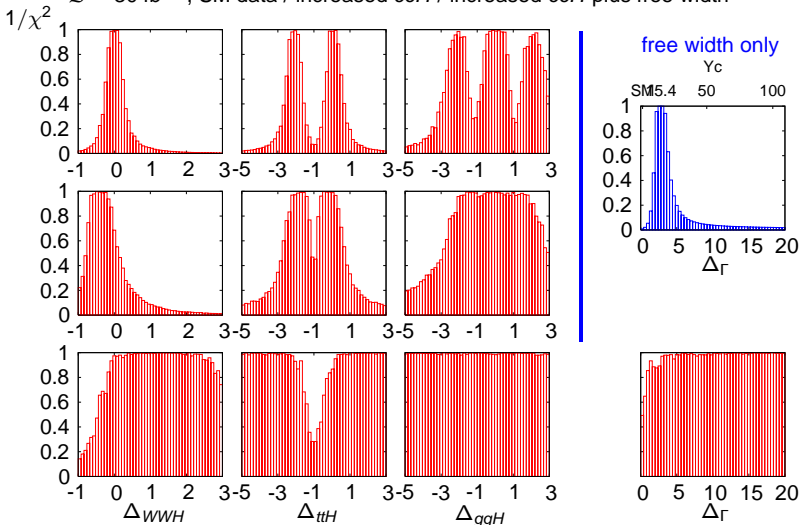


- Invisible Higgs decays actually observable
 - Vector-Boson Fusion: tagging jets plus missing E_T [Eboli, Zeppenfeld]
 - WH/ZH : recoil against nothing [Choudhury, Roy; Godbole, Guchait, Mazumdar, Moretti, Roy]

- Unobservable decays into particles with large backgrounds (like $H \rightarrow$ jets)
e.g. increased ccH coupling (corresponding to 15.4 GeV Yukawa coupling)

Invisible vs. Unobserved

- Unobservable decays into particles with large backgrounds (like $H \rightarrow$ jets)
 e.g. increased ccH coupling (corresponding to 15.4 GeV Yukawa coupling)
 $\mathcal{L} = 30 \text{ fb}^{-1}$, SM data / increased ccH / increased ccH plus free width



[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:

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

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

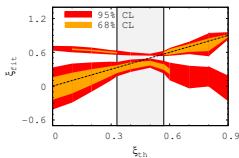
Significant and observable deviations also in Higgs self-couplings

[Gröber, Mühlleitner]

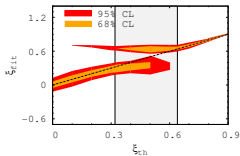
[Bock, Lafaye, Plehn, MR, D. Zerwas, P.M. Zerwas]

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

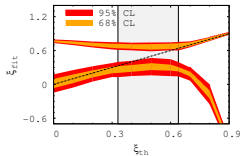
$m_H = 120$ GeV



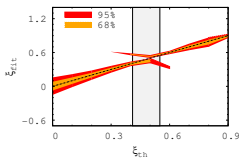
$m_H = 160$ GeV



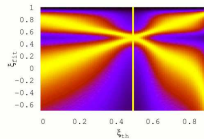
$m_H = 200$ GeV



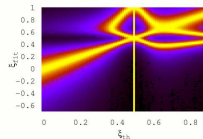
$\mathcal{L} = 300 \text{ fb}^{-1}$



Gluon fusion $H \rightarrow \gamma\gamma$



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



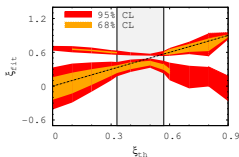
Not a true degeneracy

→ Each (smeared) toy experiment has unique solution

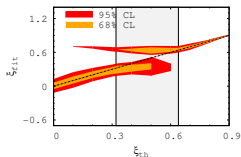
[Bock, Lafaye, Plehn, MR, D. Zerwas, P.M. Zerwas]

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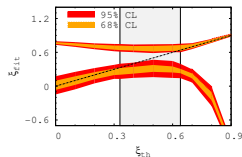
$m_H = 120$ GeV



$m_H = 160$ GeV

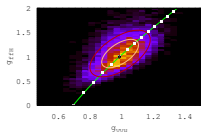


$m_H = 200$ GeV

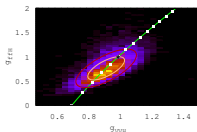


Independent fit of common vector and fermion couplings

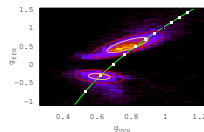
$\xi_{th} = 0$



$\xi_{th} = 0.2$



$\xi_{th} = 0.6$



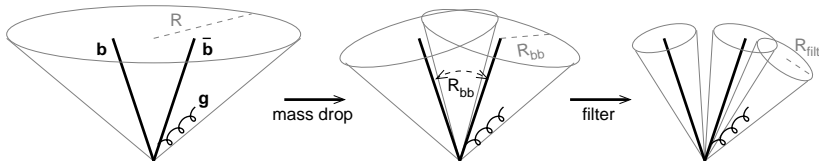
Not a true degeneracy

→ Each (smeared) toy experiment has unique solution



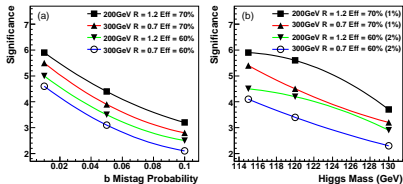
[Butterworth, Davison, Rubin, Salam]

- Decay into $b\bar{b}$ main channel for light Higgs ($\sim 80\%$)
- Suffers from large QCD backgrounds \rightarrow Use high- p_T region
 - Higgs and W/Z more likely to be central, $Z \rightarrow \nu\bar{\nu}$ visible
 - $t\bar{t}$ kinematics cannot simulate background
 - Much smaller cross section ($1/20$ for $p_T(H) > 200$ GeV)
 - $R \gtrsim \frac{3m_H}{p_T}$: resolve one jet in 75% of cases
- Algorithm to find fat jet":
 - ① Start with high- p_T jet (Cambridge/Aachen algorithm)
 - ② Undo last stage of clustering (\equiv reduce R): $J \rightarrow J_1, J_2$
 - ③ If $\max(m_1, m_2) \lesssim 0.67m$, call this a mass drop [else goto 1]
 - ④ Require $y_{12} = \frac{\min(p_{T1}^2, p_{T2}^2)}{m_{12}^2} \Delta R_{12} \simeq \frac{\min(z_1, z_2)}{\max(z_1, z_2)} > 0.09$ [else goto 1]
 - ⑤ Require each subjet to have b-tag [else reject event]
 - ⑥ Filter the jet: Reconsider region of interest at smaller $R_{\text{filt}} = \min(0.3, R_{bb}/2)$
 - ⑦ Take 3 hardest subjets



Fat Jets in Higgs channels

■ WH/ZH

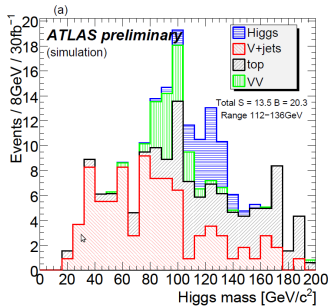


- $t\bar{t}H$
- H plus new physics (SUSY, ...)

[Butterworth, Davison, Rubin, Salam; ATLAS]

ATLAS $\mathcal{L} = 30 \text{ fb}^{-1}$, $m_H = 120 \text{ GeV}$
Significance:

- No systematics: 3.7
- 15% systematics: 3.0

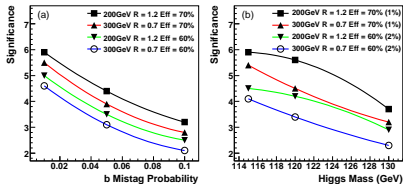


[Plehn, Salam, Spannowsky]

[Kribs, Martin, Roy, Spannowsky]

Fat Jets in Higgs channels

■ WH/ZH

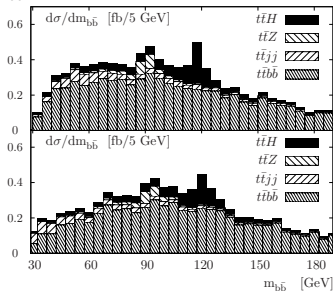


[Butterworth, Davison, Rubin, Salam; ATLAS]

ATLAS $\mathcal{L} = 30 \text{ fb}^{-1}$, $m_H = 120 \text{ GeV}$
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- No systematics: 3.7
- 15% systematics: 3.0

■ $t\bar{t}H$



[Plehn, Salam, Spannsky]

$\mathcal{L} = 100 \text{ fb}^{-1}$	S	B	S/B	S/\sqrt{B}
$m_H = 115 \text{ GeV}$	57	118	1/2.1	5.2
120 GeV	48	115	1/2.4	4.5
130 GeV	29	103	1/3.6	2.9

■ H plus new physics (SUSY, ...)

[Kribs, Martin, Roy, Spannsky]