

# Extended Scalar Sector and Fat Jets

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# General 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 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  $g_{jjH}^{\text{SM}}$ : (loop-induced) coupling in the Standard Model

$\Delta_{jjH}^{\text{SM}}$ : contribution from modified tree-level couplings  
to Standard-Model particles

$\Delta_{jjH}$ : additional (dimension-five) contribution

- Additional free parameters:

- Higgs boson mass  $m_H$
- Top-quark mass  $m_t$
- Bottom-quark mass  $m_b$



- Need to scan high-dimensional parameter space
- ⇒ SFitter
- General Higgs couplings from modified version of HDecay [Lafaye, Plehn, MR, Zerwas]
- 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 [EPJC 54(2008) [arXiv:0709.3985]]

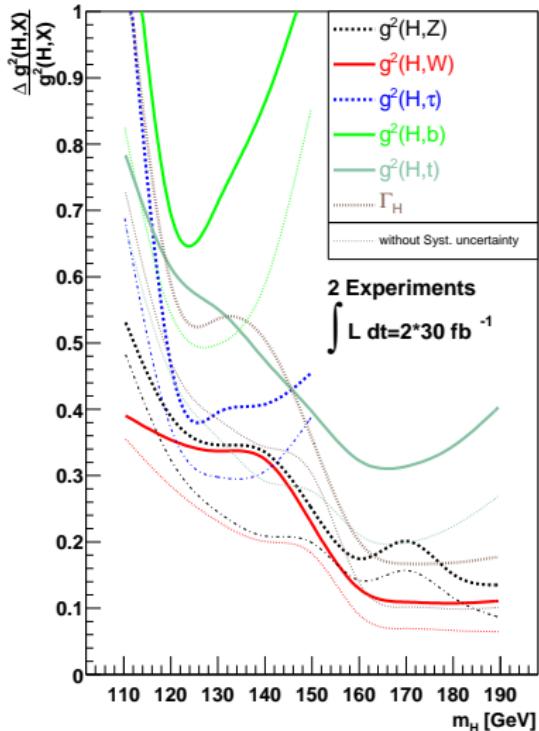
# Higgs at the LHC

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

production	decay
$gg \rightarrow H$	$ZZ$
$qqH$	$ZZ$
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inclusive	$\gamma\gamma$
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$t\bar{t}H$	$b\bar{b}$
$WH/ZH$	$bb$

Total width

- degeneracy  $\sigma \cdot BR \propto g_p^2 \frac{g_d^2}{\Gamma_H}$  ( $\Gamma_H \propto g^2$ )
- $WW \rightarrow WW$  unitarity:  $g_{WWH} \lesssim g_{WWH}^{\text{SM}} \rightarrow \Gamma_H|_{\max}$
- Here:  $\Gamma_H = \sum_{\text{obs.}} \Gamma_i (\equiv \Gamma_H|_{\min})$



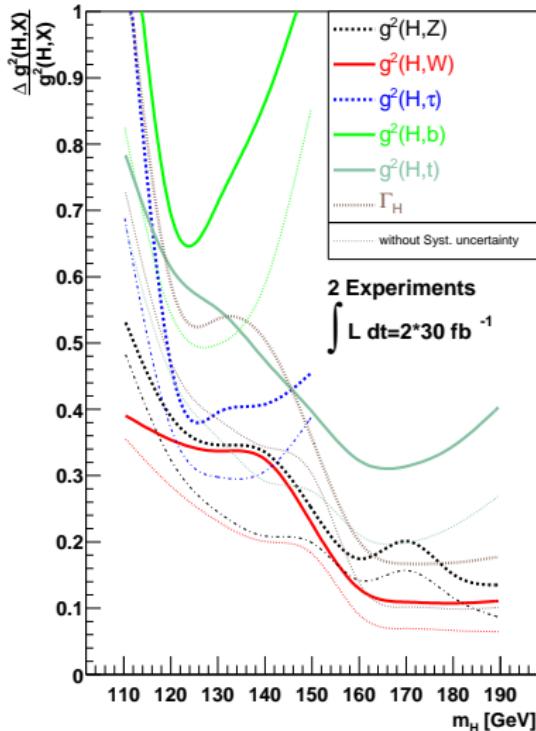
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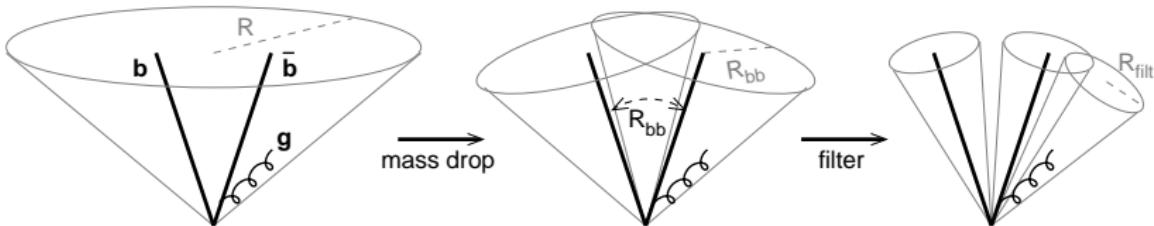
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# Fat Jets

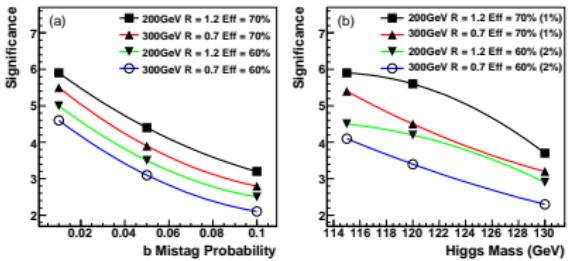
[Butterworth, Davison, Rubin, Salam]

- Decay into  $b\bar{b}$  main channel for light Higgs ( $\sim 80\%$ )
- Suffers from large QCD backgrounds → 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
  - 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



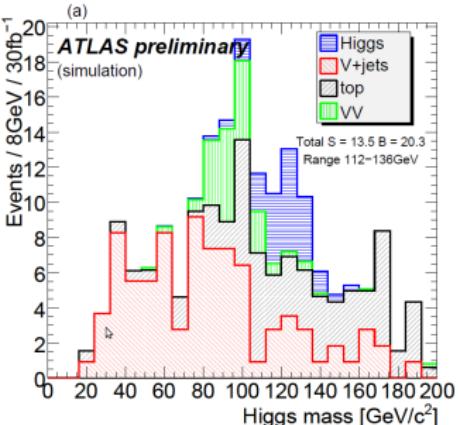
■  $t\bar{t}H$

■  $H$  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

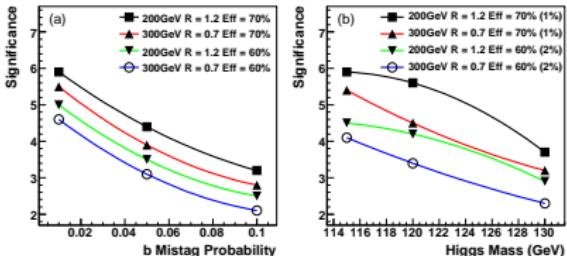


[Plehn, Salam, Spannowsky]

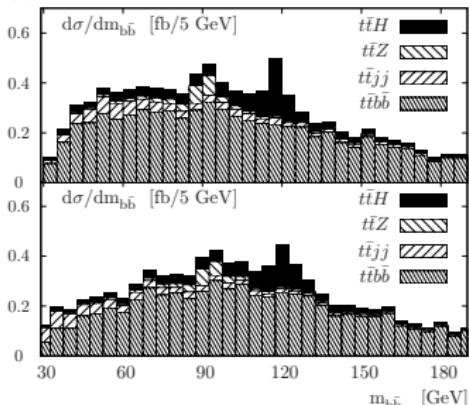
[Kribs, Martin, Roy, Spannowsky]

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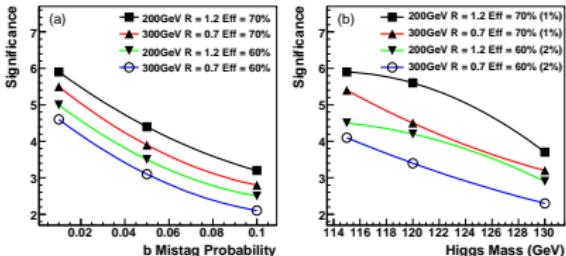
[Plehn, Salam, Spannowsky]

$\mathcal{L} = 100 \text{ fb}^{-1}$	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

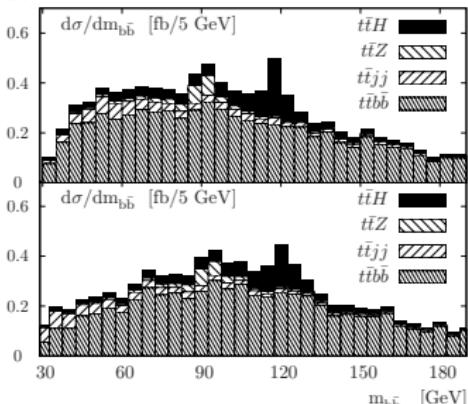
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[Kribs, Martin, Roy, Spannowsky]

# Combining Errors

- Statistical errors on individual channels of Poisson type
- Systematic errors (luminosity, tagging efficiency, ...) extracted from large event samples  $\Rightarrow$  Gaussian
- Need to combine
  - Poisson  $P_P(d, m) = \frac{\exp(-m)m^d}{\Gamma(d+1)}$  and
  - Gaussian  $P_G(d, m, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(d-m)^2}{2\sigma^2}\right)$  errors
- Mathematically correct way: convolution
- No analytic solution, numerical integration too time-consuming
- $\Rightarrow$  Approximate formula:

$$\frac{1}{\tilde{\chi}^2} \equiv \frac{1}{-2 \log L} = \sum_i \frac{1}{-2 \log L_i}$$

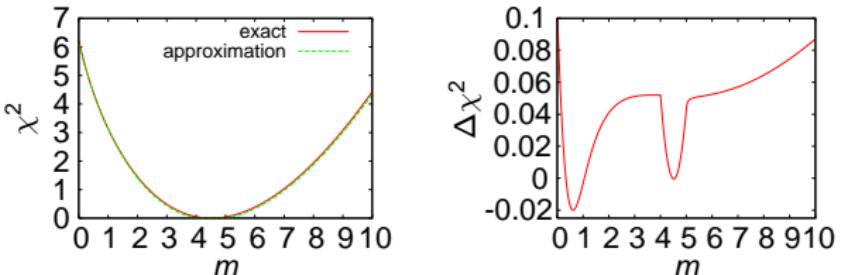
- Yields exact formula for Gaussian-only (adding errors in quadrature)
- Gives correct result when one error approaches 0 or  $\infty$

# Combining Errors

- ⇒ Approximate formula:

$$\frac{1}{\tilde{\chi}^2} \equiv \frac{1}{-2 \log L} = \sum_i \frac{1}{-2 \log L_i}$$

- Example: Poisson( $d = 5$ ), Gauss( $\sigma = 0.5$ )



- ⇒ Very good agreement with exact convolution
- Difference almost always positive ⇒ slight overestimation of Higgs-coupling errors (good!)

# SFitter error analysis

[Dührssen, Lafaye, Plehn, MR, Zerwas]

Errors obtained by 10,000 toy experiments:

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

Fit with Gaussian of the central part within one standard deviation

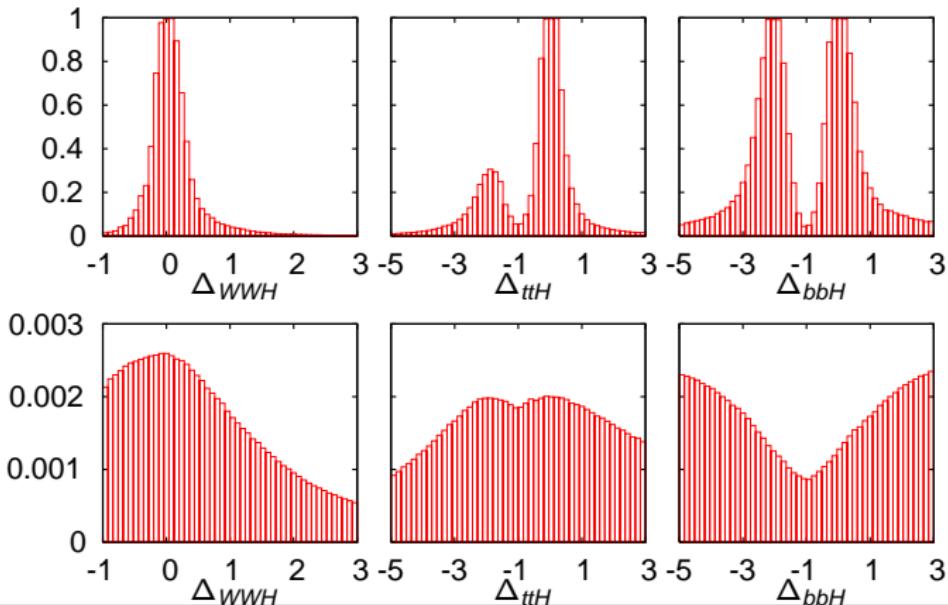
	no eff. couplings			with eff. couplings			ratio $\Delta_{jjH}/WWH$		
	$\sigma_{\text{symm}}$	$\sigma_{\text{neg}}$	$\sigma_{\text{pos}}$	$\sigma_{\text{symm}}$	$\sigma_{\text{neg}}$	$\sigma_{\text{pos}}$	$\sigma_{\text{symm}}$	$\sigma_{\text{neg}}$	$\sigma_{\text{pos}}$
$\Delta_{WWH}$	$\pm 0.23$	-0.21	+0.26	$\pm 0.24$	-0.21	+0.27	—	—	—
$\Delta_{ZZH}$	$\pm 0.36$	-0.40	+0.35	$\pm 0.31$	-0.35	+0.29	$\pm 0.41$	-0.40	+0.41
$\Delta_{ttH}$	$\pm 0.41$	-0.37	+0.45	$\pm 0.53$	-0.65	+0.43	$\pm 0.51$	-0.54	+0.48
$\Delta_{bbH}$	$\pm 0.45$	-0.33	+0.56	$\pm 0.44$	-0.30	+0.59	$\pm 0.31$	-0.24	+0.38
$\Delta_{\tau\tau H}$	$\pm 0.33$	-0.21	+0.46	$\pm 0.31$	-0.19	+0.46	$\pm 0.28$	-0.16	+0.40
$\Delta_{\gamma\gamma H}$	—	—	—	$\pm 0.31$	-0.30	+0.33	$\pm 0.30$	-0.27	+0.33
$\Delta_{ggH}$	—	—	—	$\pm 0.61$	-0.59	+0.62	$\pm 0.61$	-0.71	+0.46
$m_H$	$\pm 0.26$	-0.26	+0.26	$\pm 0.25$	-0.26	+0.25			
$m_b$	$\pm 0.071$	-0.071	+0.071	$\pm 0.071$	-0.071	+0.072			
$m_t$	$\pm 1.00$	-1.03	+0.98	$\pm 0.99$	-1.00	+0.98			

# 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  $t\bar{t}H$  coupling
- Smearing the dataset does not change picture substantially either

True dataset,  $30 \text{ fb}^{-1}$ ; Profile likelihood vs. Bayesian

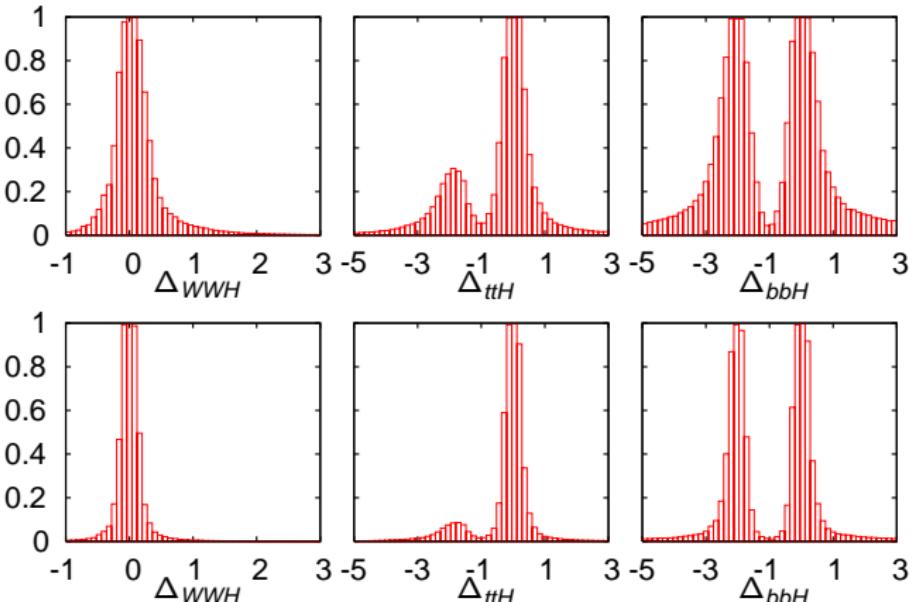


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True dataset, Profile likelihood;  $30 \text{ fb}^{-1}$  vs.  $300 \text{ fb}^{-1}$

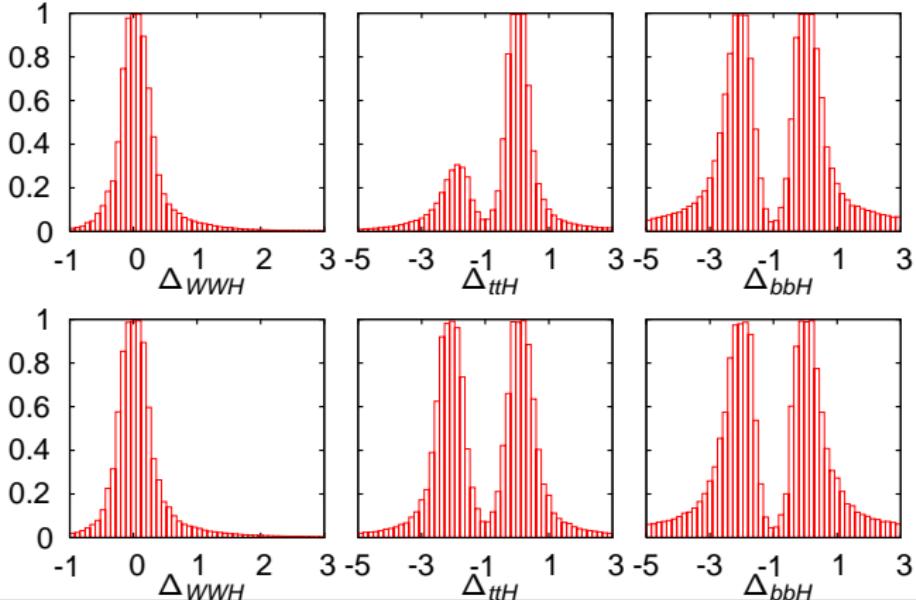


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True dataset, Profile likelihood,  $30 \text{ fb}^{-1}$ ; Without vs. including eff. couplings

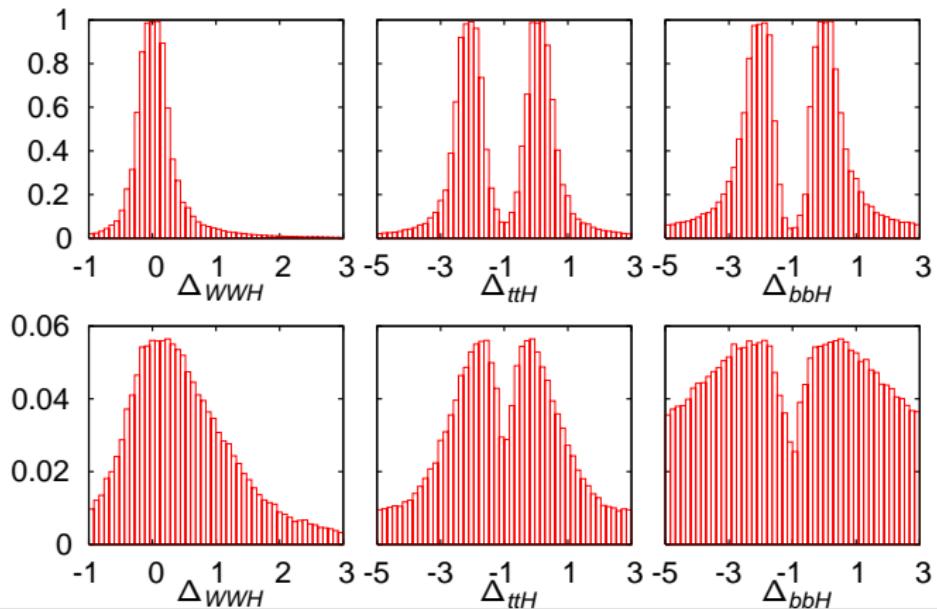


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Profile likelihood,  $30 \text{ fb}^{-1}$ ; True vs. smeared dataset

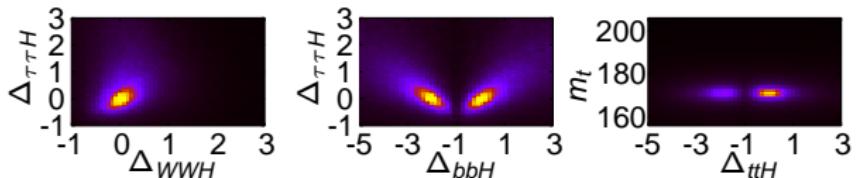


# Distribution of parameters

Two-dimensional distributions (Correlations)

- Correlations dominated by effects via total width  
Basically no correlations with masses
- Additional effective couplings remove correlations and add ambiguities

True dataset,  $30 \text{ fb}^{-1}$ , no effective couplings

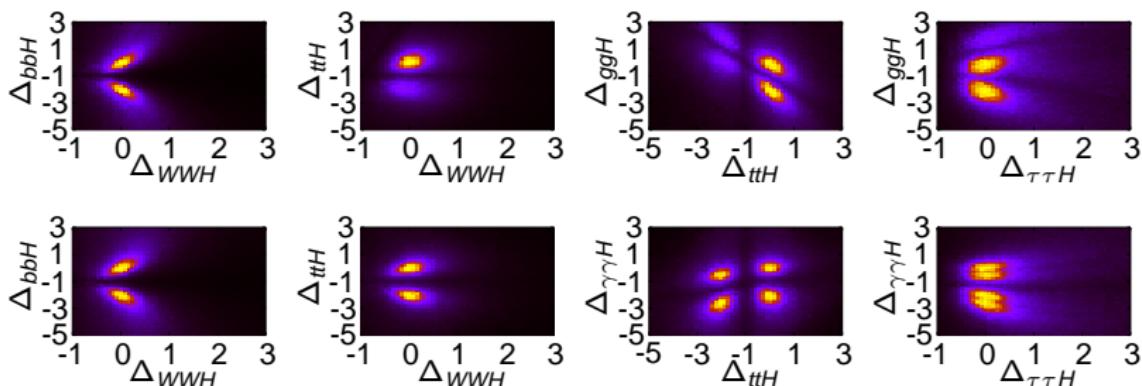


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True dataset,  $30 \text{ fb}^{-1}$ ;  $ggH$  vs.  $\gamma\gamma H$  effective coupling

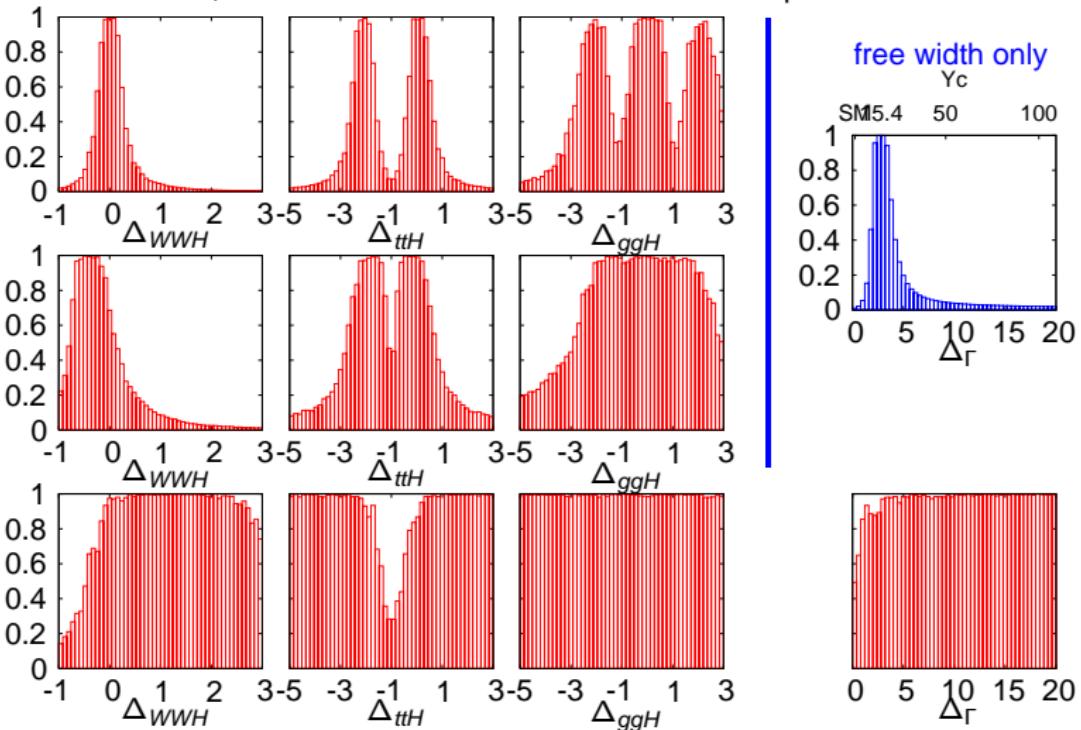


# Invisible vs. Unobserved

- Invisible Higgs decays actually observable
  - Vector-Boson Fusion: tagging jets plus  $\cancel{E}_T$  [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)

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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



# Conclusions

- Determining the Higgs-boson couplings next step after discovery  
Important for our understanding of electroweak symmetry breaking
- Independent of explicit realisation of new physics (if any):  
Standard Model with effective Higgs couplings
- Problem of high-dimensional parameter space with correlated measurements  
⇒ Dedicated tool: SFitter
- Obtain Standard Model couplings within errors for SM scenario
- Alternative solutions due to sign degeneracy of couplings
- Recent jet substructure analysis significantly improves  
result on bottom-quark coupling
- Influences accuracy of all other couplings via total width

# Higgs at the LHC

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
$q\bar{q}H$	$WW$	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
$WH/ZH$	$bb$	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)

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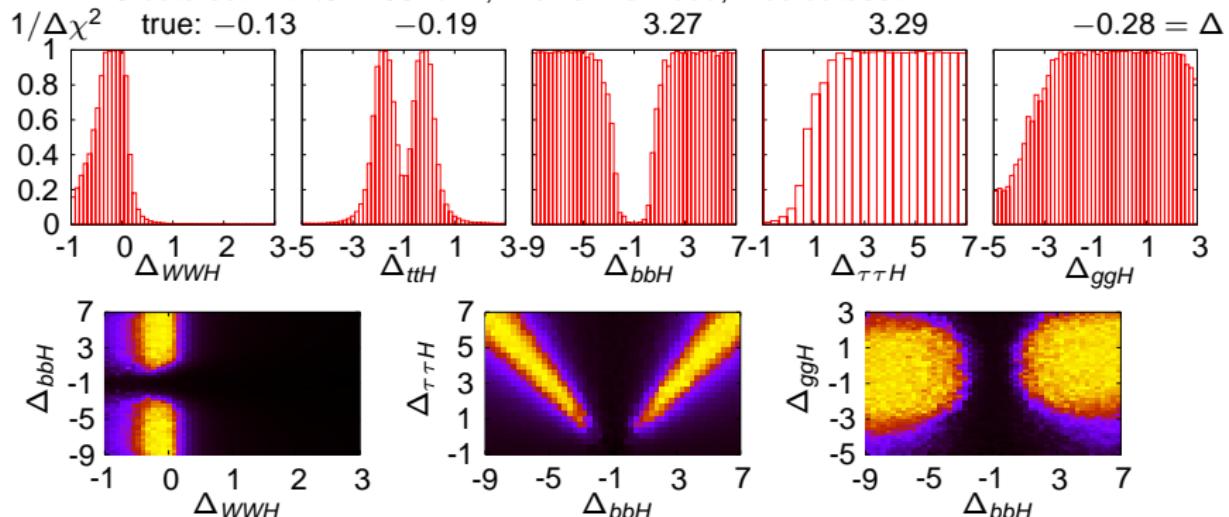
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# Non-decoupling Supersymmetric Higgs

SPS1a-inspired scenario with

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

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



- 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  $\Delta_{bbH}$  and  $\Delta_{\tau\tau H}$  via total width
- No upper limit on  $g_{bbH}$  as  $BR \simeq 1$  compatible with data