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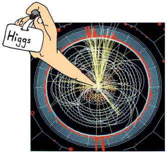
Measuring the Higgs boson couplings

Michael Rauch | June 1st, 2011

INSTITUT FOR THEORETICAL PHYSICS

Higgs properties



Verify that observed resonance is “Higgs”

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

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 general Higgs sector
- For Higgs couplings present in the Standard Model $j = W, Z, t, b, \tau$ replace general couplings by
$$g_{jjH} \longrightarrow g_{jjH}^{\mathrm{SM}} \left(1 + \Delta_{jjH}\right) \qquad (\rightarrow \Delta = -2 \text{ means sign flip})$$
- For loop-induced Higgs couplings $j = \gamma, g$ replace by
$$g_{jjH} \longrightarrow g_{jjH}^{\mathrm{SM}} \left(1 + \Delta_{jjH}^{\mathrm{SM}} + \Delta_{jjH}\right)$$
where g_{jjH}^{SM}: (loop-induced) coupling in the Standard Model
$\Delta_{jjH}^{\mathrm{SM}}$: 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 ($g_{H\mu\mu}$, $g_{HZ\gamma}^{\mathrm{eff}}$, g_{HHH}, g_{HHHH})

SFitter

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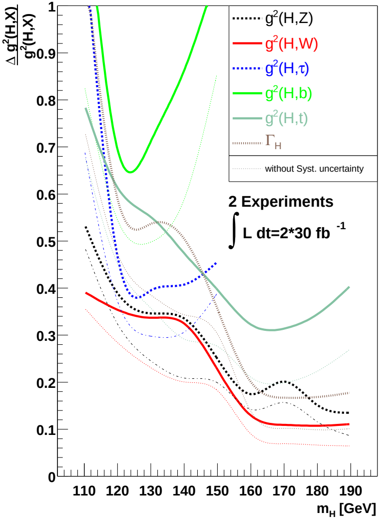
- Need to scan high-dimensional parameter space
- $\Rightarrow$ SFitter [Lafaye, Plehn, MR, Zerwas]
- General Higgs couplings from modified version of HDecay [Spira]
- Three scanning techniques:
  - Weighted Markov Chain
  - Cooling Markov Chain (equivalent to simulated annealing)
  - Gradient Minimisation (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
$gg \to H$	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)



Total width

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

Higgs at the LHC

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

production	decay
$gg \to H$	ZZ
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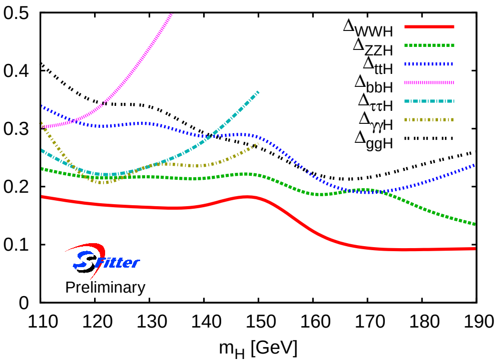

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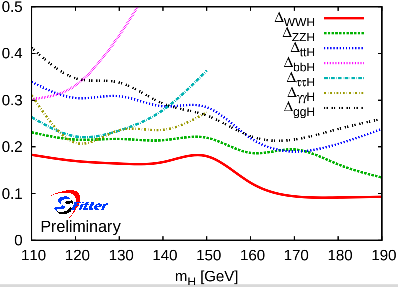
Error analysis

Errors obtained by 10,000 toy experiments:
SM hypothesis, $m_H = 120\ \mathrm{GeV}$, $\mathcal{L} = 30\ \mathrm{fb}^{-1}$
Fit with Gaussian of the central part within one standard deviation

	no eff. couplings			with eff. couplings			ratio $\Delta_{jjH/WWH}$		
	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	$+0.46$



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

Invisible vs. Unobserved

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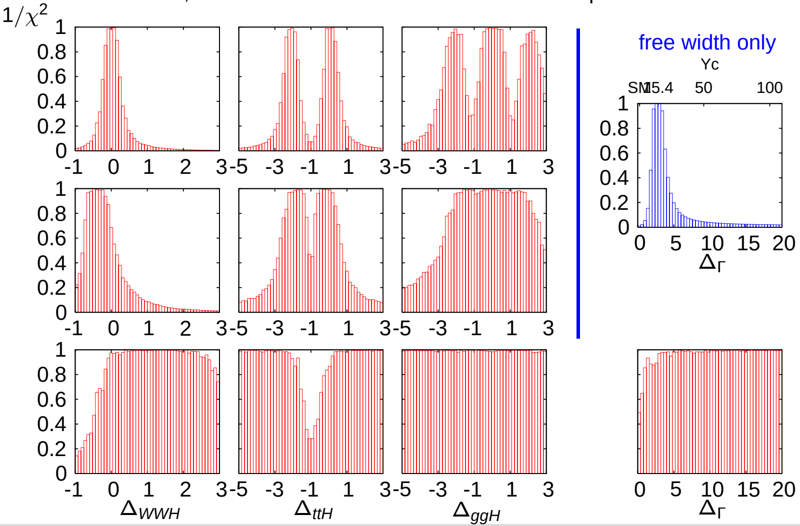
- Invisible Higgs decays actually observable
  - Vector-Boson Fusion: tagging jets plus missing E_T [Eboli, Zeppenfeld]
  - WH/ZH: recoil against nothing [Choudhury, Roy; Godbole, Guchait, Mazumdar, Moretti, Roy]

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

Invisible vs. Unobserved

- Unobservable decays into particles with large backgrounds (like $H \to$ 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



The Higgs Portal

Additional hidden sector as singlet under SM gauge groups [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:
$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\chi & \sin\chi \\ -\sin\chi & \cos\chi \end{pmatrix} \begin{pmatrix} H_s \\ H_h \end{pmatrix}$

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

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

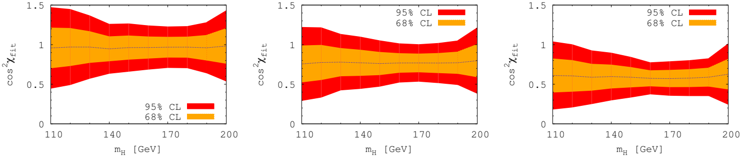
The Higgs Portal

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

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

- No invisible decay modes

$\cos^2 \chi_{\rm th} = 1.0$ $\qquad$ $\cos^2 \chi_{\rm th} = 0.8$ $\qquad$ $\cos^2 \chi_{\rm th} = 0.6$

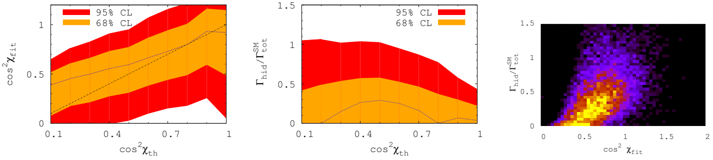


$\Rightarrow$ If $\cos^2 \chi_{\rm th} < 0.6$ can exclude SM at the 95% CL with 30 fb^{-1}

- Measuring invisible decays in VBF-Higgs production
  Signature: Two VBF-jets plus missing E_T

[Eboli, Zeppenfeld; MC-study: ATLAS]

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

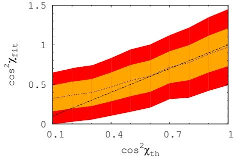


Observation Bias

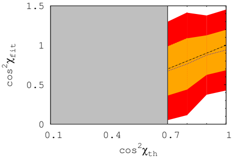
Significant backgrounds in Higgs measurement channels

- 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

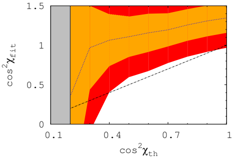
positive number of signal events



$S > 2 * \Delta S$ 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

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:

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

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

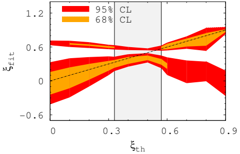
Significant and observable deviations also in Higgs self-couplings [Gröber, Mühlleitner]

MCHM5

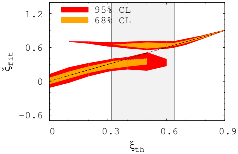
[Bock, Lafaye, Plehn, MR, D. Zerwas, P.M. Zerwas]

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

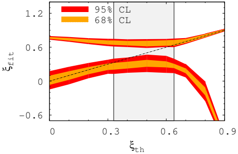
$m_H = 120$ GeV



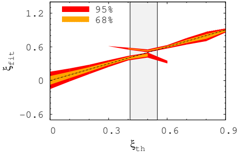
$m_H = 160$ GeV



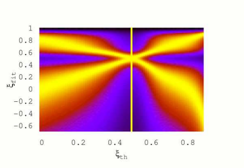
$m_H = 200$ GeV



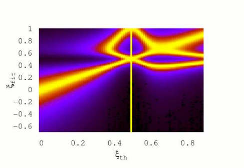
$\mathcal{L} = 300$ fb^{-1}



Gluon fusion $H \to \gamma\gamma$



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



Not a true degeneracy

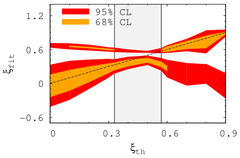
$\to$ Each (smeared) toy experiment has unique solution

MCHM5

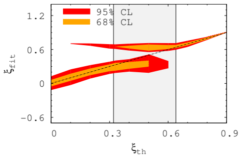
[Bock, Lafaye, Plehn, MR, D. Zerwas, P.M. Zerwas]

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

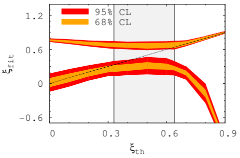
$m_H = 120$ GeV



$m_H = 160$ GeV

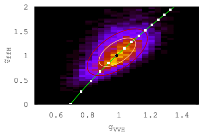


$m_H = 200$ GeV

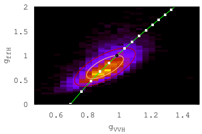


Independent fit of common vector and fermion couplings

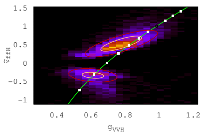
$\xi_{\text{th}} = 0$



$\xi_{\text{th}} = 0.2$



$\xi_{\text{th}} = 0.6$



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

Conclusions

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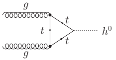
- Determining the Higgs-boson couplings next step after discovery
  Important for our understanding of electroweak symmetry breaking
- Independent of explicit realisation of new physics (if any):
  Standard Model with effective Higgs couplings
- Expected accuracy of $20 - 50\%$ in Standard Model at 30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

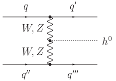
Higgs production modes

Main Higgs-boson production modes:

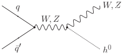
- gluon-gluon fusion



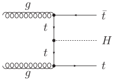
- vector-boson fusion

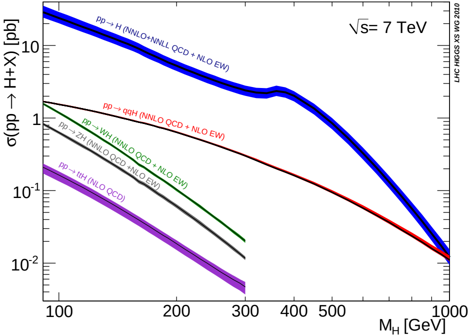


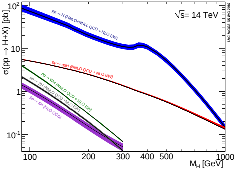
- associated production with gauge bosons



- associated production with top-quark–antiquark pair

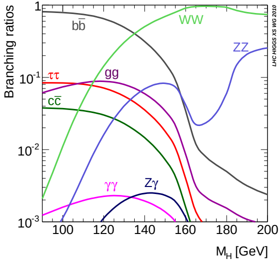






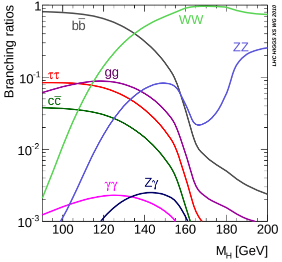
Higgs decay modes

- $H \to b\bar{b}$
  - 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]
- $H \to \tau\bar{\tau}$
  - need to reconstruct invariant mass of the two taus $\to$ limits production channel to vector-boson fusion
  - one of the discovery channels for light Higgs bosons
    [Plehn, Rainwater, Zeppenfeld]
- $H \to WW$
- $H \to ZZ$
- $H \to \gamma\gamma$



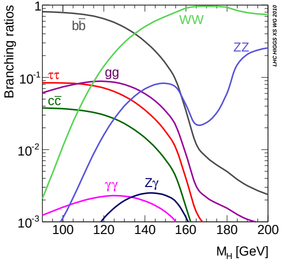
Higgs decay modes

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

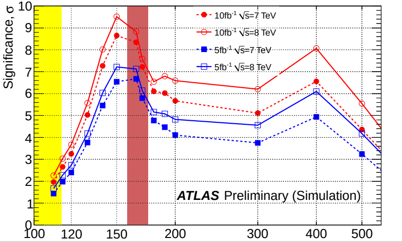


Higgs decay modes

- $H \to b\bar{b}$
- $H \to \tau\bar{\tau}$
- $H \to WW$
- $H \to ZZ$
- $H \to \gamma\gamma$
  - 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

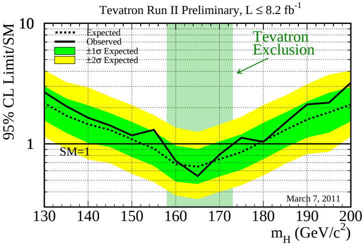


Discovery prospects for 7 and 8 TeV

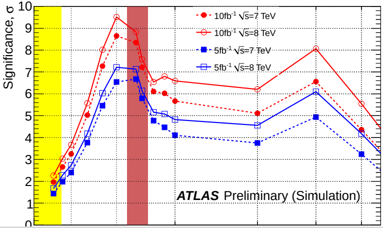


Discovering the Higgs boson

Tevatron results



Prospects for 7 and 8 TeV



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

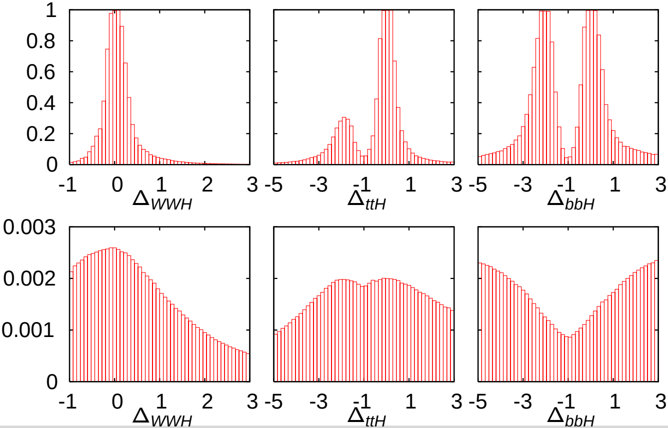
Last line obtained using subjet techniques ([Butterworth, Davison, Rubin, Salam]),
theoretical results confirmed by ATLAS ([ATL-PHYS-PUB-2009-088])
(stricter cuts, statistical significance basically unchanged)

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



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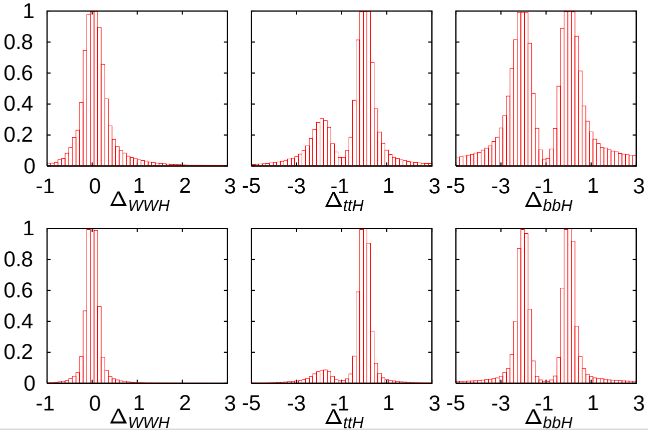
True dataset, Profile likelihood;   30 fb^{-1} vs. 300 fb^{-1}



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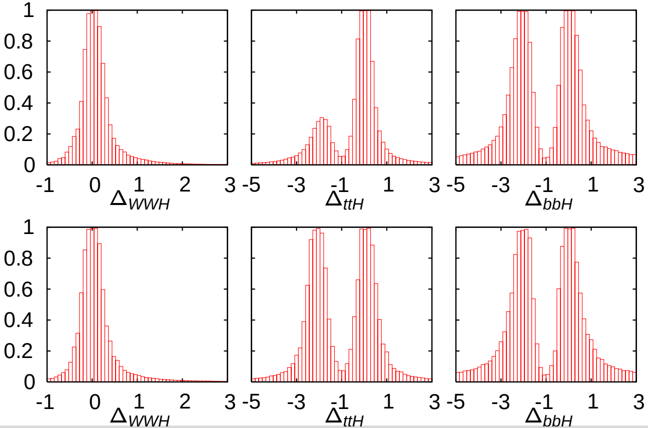
True dataset, Profile likelihood, 30 fb^{-1}; Without vs. including eff. couplings

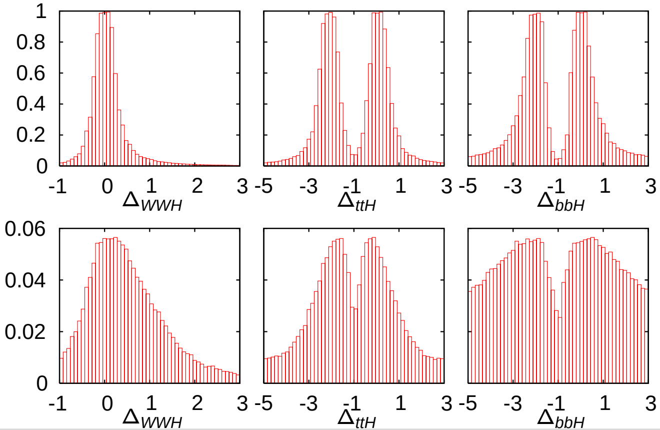


Distribution of parameters

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

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

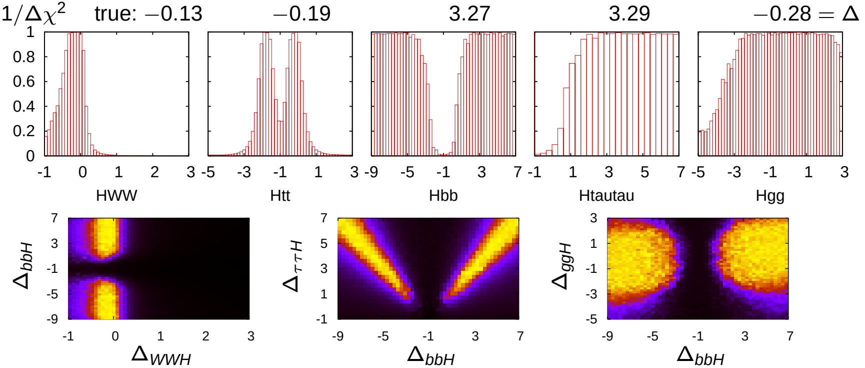


Non-decoupling Supersymmetric Higgs

SPS1a-inspired scenario with

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

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

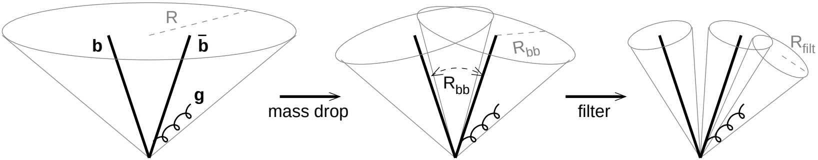


- Clear deviation from Standard Model:
  $q(d_{\mathrm{SUSY}}|m_{\mathrm{SM}}) < q(d_{\mathrm{SM}}|m_{\mathrm{SM}})$: 77% at 90% CL
- Favouring of new physics more difficult: only 4% better described by SUSY model
- Strong correlation between Δ_{bbH} and $\Delta_{\tau\tau H}$ via total width
- No upper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

Fat Jets

[Butterworth, Davison, Rubin, Salam]

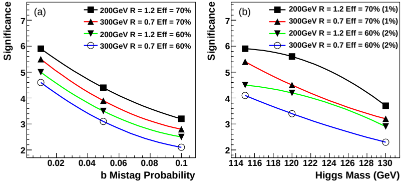
- Decay into $b\bar{b}$ main channel for light Higgs ($\sim 80\%$)
- Suffers from large QCD backgrounds $\rightarrow$ Use high-p_T region
  - Higgs and W/Z more likely to be central, $Z \rightarrow \nu\bar{\nu}$ visible
  - $t\bar{t}$ kinematics cannot simulate background
  - Much smaller cross section ($1/20$ for $p_T(H) > 200\ \mathrm{GeV}$)
  - $R \gtrsim \frac{3m_H}{p_T}$: resolve one jet in 75% of cases
- Algorithm to find fat jet":
  0. Start with high-p_T jet (Cambridge/Aachen algorithm)
  1. Undo last stage of clustering ($\equiv$ reduce R): $J \rightarrow J1, J2$
  2. If $\max(m_1, m_2) \lesssim 0.67m$, call this a mass drop [else goto 1]
  3. 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]
  4. Require each subjet to have b-tag [else reject event]
  5. Filter the jet: Reconsider region of interest at smaller $R_{\mathrm{filt}} = \min(0.3, R_{bb}/2)$
  6. Take 3 hardest subjets



Fat Jets in Higgs channels

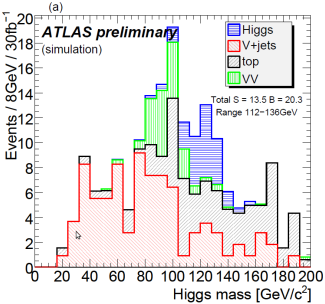
- *WH/ZH*

[Butterworth, Davison, Rubin, Salam; ATLAS]



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

- No systematics: 3.7
- 15% systematics: 3.0

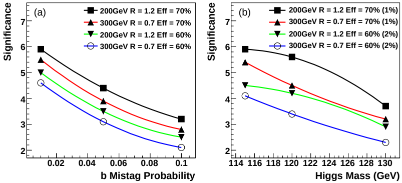


- $t\bar{t}H$ [Plehn, Salam, Spannowsky]
- H plus new physics (SUSY, . . .) [Kribs, Martin, Roy, Spannowsky]

Fat Jets in Higgs channels

- *WH*/*ZH*

[Butterworth, Davison, Rubin, Salam; ATLAS]



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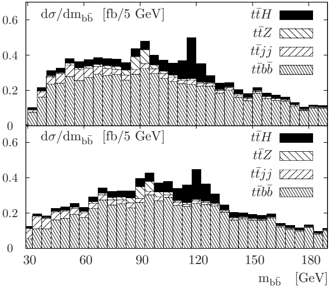
Significance:

- No systematics: 3.7
- 15% systematics: 3.0

- $t\bar{t}H$

[Plehn, Salam, Spannowsky]



$\mathcal{L} = 100\ \text{fb}^{-1}$	S	B	S/B	$S/\sqrt{B}$
$m_H =$ 115 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, Spannowsky]