Karlsruher Institut für Technologie

Higgs-Kopplungen

Michael Rauch | SS 2013

INSTITUTE FOR THEORETICAL PHYSICS

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, Mühlleitner, Spira]
- For Higgs couplings present in the Standard Model $x = W, Z, t, b, \tau$
  $$g_{xxH} \equiv g_x \longrightarrow g_x^{\text{SM}} \; (1 + \Delta_x) \qquad (\rightarrow \Delta = -2 \text{ means sign flip})$$
- For loop-induced Higgs couplings $x = \gamma, g$
  $$g_x \longrightarrow g_x^{\text{SM}} \left(1 + \Delta_x^{\text{SM}} + \Delta_x\right)$$
  where g_x^{SM}: (loop-induced) coupling in the Standard Model
  Δ_x^{SM}: contribution from modified tree-level couplings to Standard-Model particles
  Δ_x : additional (dimension-five) contribution
- Ratios $\frac{g_x}{g_y} = \frac{g_x^{\text{SM}}}{g_y^{\text{SM}}}(1 + \Delta_{x/y})$
- Neglecting couplings only available from high-luminosity analyses
  $(g_\mu, g_{HZ\gamma}^{\text{eff}}, g_{HHH}, g_{HHHH})$
- Δ_H: single parameter modifying all (tree-level) couplings
- Total width
  $$\Gamma_{\text{tot}} = \Sigma_{\text{obs}} \Gamma_x < 2 \text{ GeV} \quad \text{(plus generation universality)}$$
- Electro-weak corrections not yet relevant
  for later consistency: QCD corrections scale with couplings, EW ones not

SFitter

[Lafaye, Plehn, MR,Zerwas]

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

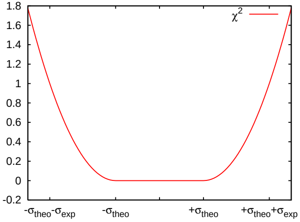
[JHEP08(2009)009 [arXiv:0904.3866 [hep-ph]]]

Algorithms:

- Weighted Markov chain
- Cooling Markov chain ($\sim$ simulated annealing)
- Modified gradient fit (Minuit)
- Grid scan
- Nested Sampling [Skilling; Feroz, Hobson]

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

Bayesian vs. Frequentist

- Bayesian *"How likely is a given parameter value given the data?"*
  - based on Bayes theorem: $p(m|d) = p(d|m)\frac{p(m)}{p(d)}$

    $p(m|d)$: probability of the model, given the data

    $p(d|m)$: probability of the data, given the model ("χ^2")

    $p(d)$: probability of the data, typically $p(d) = 1$

    $p(m)$: probability of the model = prior
  - prior $p(m)$: subjective quantity of initial knowledge/ignorance about parameters introduces measure in parameter space
  - typical choices:

    linear: $p(m) \propto const.$, flat in m

    logarithmic: $p(m) \propto \frac{1}{m}$, flat in $\log(m)$

    Gaussian: $p(m) \propto \exp^{-(m-\bar{m})^2/2\sigma^2}$
  - Nuisance Parameters:
    parameters which are "uninteresting" (*e.g.* SM parameters)
    $\rightarrow$ Marginalization (integrating over them)

- Frequentist *"How probable is the data, given certain parameters?"*

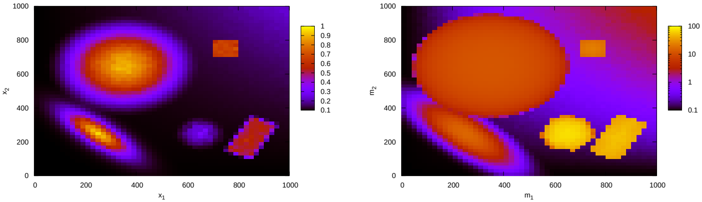
Bayesian vs. Frequentist

- Bayesian *"How likely is a given parameter value given the data?"*
- Frequentist *"How probable is the data, given certain parameters?"*
  - Frequency interpretation of probability
    Infinite repetition of the same experiment, statistically independent results
    Outcome distributed around true value
    (Gaussian, Poisson for counting experiments, ...)
  - $x\%$ Confidence level: in $x\%$ of the cases outcome at least as extreme
  - Defined only for single points in parameter space
  - Profile likelihood:
    Maximum likelihood over unseen parameters

Bayesian vs. Frequentist

Toy example (5-dim):

- Bayesian (left) *"How likely is a given parameter value given the data?"*



- Frequentist (right) *"How probable is the data, given certain parameters?"*
  Objects:
  - Small Hypersphere $r = 100$, $V_{\text{max}} = 75$ @ (650, 250, 350, 350, 350)
  - Cuboid $d = (173, 120, 200, 200, 200)$, $V_{\text{max}} = 60$ @ (850, 225, 650, 650, 650)
  - Cube $d = (100, 100, 300, 300, 300)$, $V_{\text{max}} = 25$ @ (750, 750, 450, 450, 450)
  - Gaussian $\sigma = (50, 150, 150, 150, 150)$, $V_{\text{max}} = 16$ @ (250, 250, 550, 550, 550)
  - Big Hypersphere $r = 300$, $V_{\text{max}} = 12$ @ (350, 650, 650, 650, 650)
  - Background $V = 0.1 + 4 \cdot 10^{-30} \cdot x_1^2 x_2^2 x_3^2 x_4^2 x_5^2$

Higgs Couplings after Moriond 2013

7 TeV $\mathcal{L}$ = 4.6-5.1 fb^{-1} $\otimes$ 8 TeV $\mathcal{L}$ = 12-21 fb^{-1}

7 TeV

ATLAS		CMS	
$\gamma\gamma$		$\gamma\gamma$	
ZZ (4ℓ)		$\gamma\gamma$	di-jet
WW	0-jet	ZZ (4ℓ)	
WW	1-jet	WW	0-jet
WW	2-jet	WW	1-jet
$\tau\tau$	0-jet	WW	2-jet
$\tau\tau$	1-jet	$\tau\tau$	0/1-jet
$\tau\tau$	VBF	$\tau\tau$	Boosted
$\tau\tau$	VH	$\tau\tau$	VBF
$b\bar{b}$	WH	$b\bar{b}$	WH
$b\bar{b}$	Z_ℓH	$b\bar{b}$	Z_ℓH
$b\bar{b}$	Z_νH	$b\bar{b}$	Z_νH
		$b\bar{b}$	$t\bar{t}$H

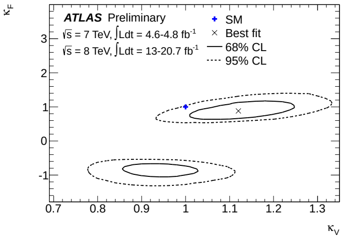
8 TeV

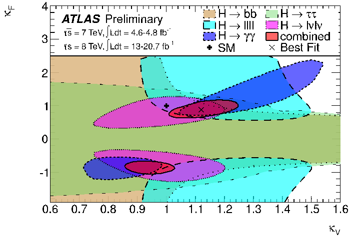
ATLAS		CMS	
$\gamma\gamma$	low-p_T	$\gamma\gamma$	Cat0
$\gamma\gamma$	high-p_T	$\gamma\gamma$	Cat1
$\gamma\gamma$	di-jet lml	$\gamma\gamma$	Cat2+3
$\gamma\gamma$	di-jet hml	$\gamma\gamma$	di-jet tight
$\gamma\gamma$	di-jet tight	$\gamma\gamma$	di-jet loose
$\gamma\gamma$	E_T(miss)	ZZ $\to 4\ell$	
$\gamma\gamma$	1ℓ	WW	0-jet
ZZ $\to 4\ell$		WW	1-jet
WW	0-jet	WW	2-jet
WW	1-jet	$\tau\tau$	0/1-jet
WW	2-jet	$\tau\tau$	Boosted
$\tau\tau$	0-jet	$\tau\tau$	VBF
$\tau\tau$	1-jet	$b\bar{b}$	Z_ℓH low-p_T
$\tau\tau$	Boosted	$b\bar{b}$	Z_ℓH high-p_T
$\tau\tau$	VBF	$b\bar{b}$	Z_νH low-p_T
$\tau\tau$	VH	$b\bar{b}$	Z_νH high-p_T
$b\bar{b}$	WH	$b\bar{b}$	WH low-p_T
$b\bar{b}$	Z_ℓH	$b\bar{b}$	WH high-p_T
$b\bar{b}$	Z_νH		

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

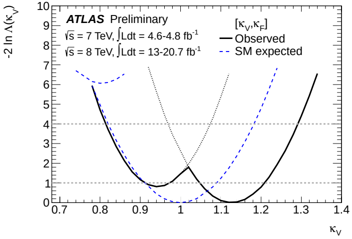
Higgs Couplings – ATLAS

Correlation of the coupling scale factors κ_F and κ_V

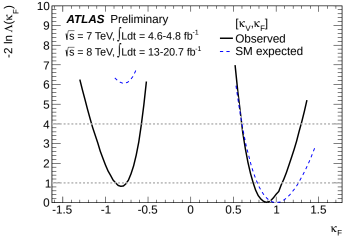




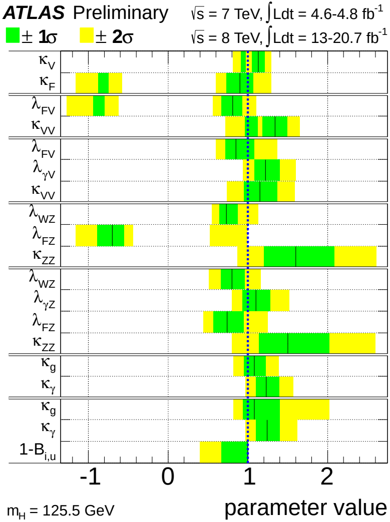
Coupling scale factor κ_V



Coupling scale factor κ_F



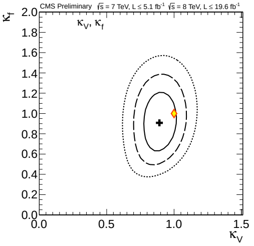
Higgs Couplings – ATLAS

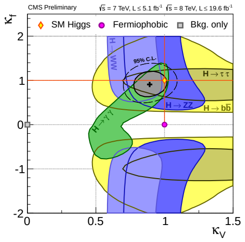


$$\kappa_{XX} = \frac{\kappa_X \cdot \kappa_X}{\kappa_H}$$

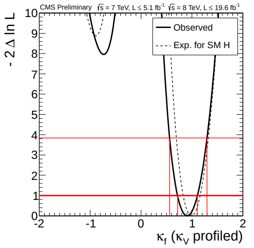
Higgs Couplings – CMS

Correlation of the coupling scale factors κ_F and κ_V

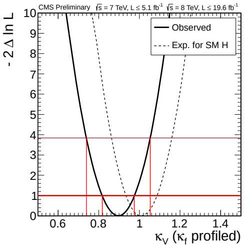




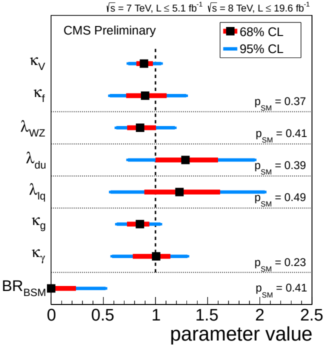
Coupling scale factor κ_V

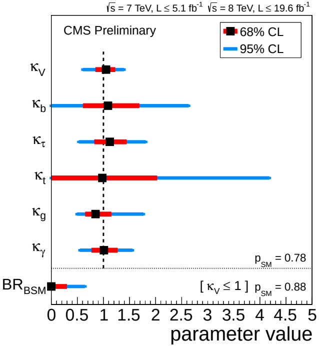


Coupling scale factor κ_F



Higgs Couplings – CMS



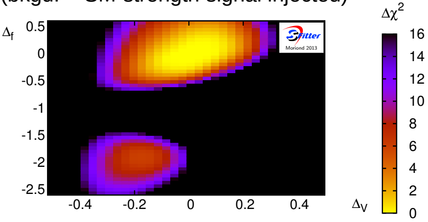


Global view

[Plehn, MR]

Δ_V vs. Δ_f

SM hypothesis
(bkgd. + SM-strength signal injected)



Expected 2012 results:

- Correct solution around SM value $\Delta = 0$
- Secondary solution for opposite fermion coupling $\rightarrow$ photon coupling enhanced
- $\sim 2.5\sigma$ discrimination power between both signs

Global view

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[Plehn, MR]

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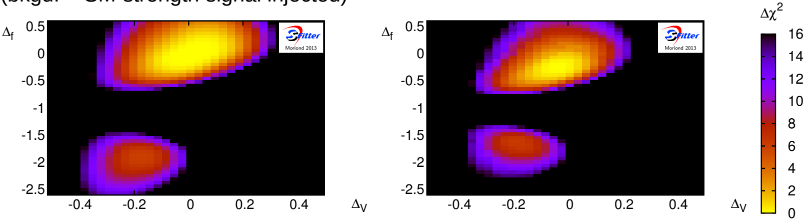
measured data



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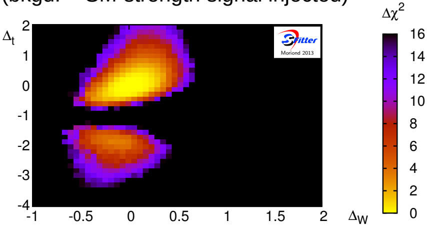
2012 results:

- similar to expectation
- opposite-sign solution clearly disfavoured

Global view

Δ_W vs. Δ_t

SM hypothesis
(bkgd. + SM-strength signal injected)



Expected 2012 results:

- Correct solution around SM value
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- Secondary solution
  for flipped top Yukawa coupling
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- Large-Δ_t solution of 2011 killed
  by $t\bar{t}H$, $H \rightarrow b\bar{b}$ measurement

Global view

Δ_W vs. Δ_t

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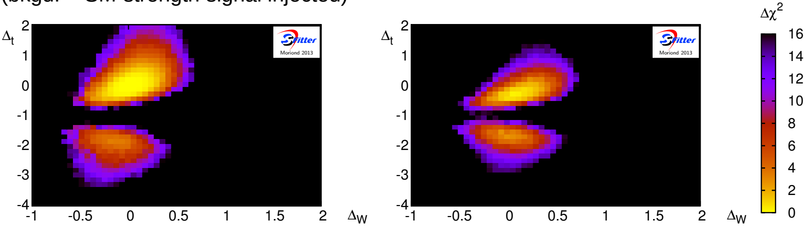

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- Secondary solution
  for flipped top Yukawa coupling
  $\rightarrow$ photon coupling enhanced
- Large-Δ_t solution of 2011 killed by $t\bar{t}H$, $H \rightarrow b\bar{b}$ measurement

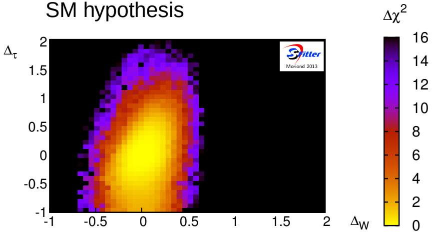
2012 results:

- similar to expectation
- flipped-top coupling basically equal log-likelihood
- small remnant of large-Δ_t solution

Global view

Δ_W vs. Δ_τ

SM hypothesis



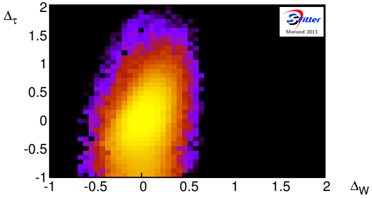
Expected 2012 results:

- Clear indication of non-vanishing $H\tau\tau$ coupling

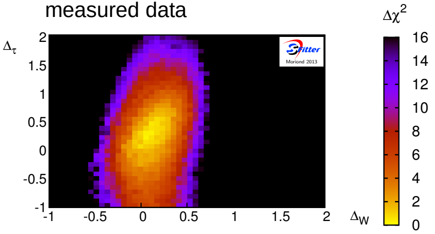
Global view

Δ_W vs. Δ_τ

SM hypothesis



measured data



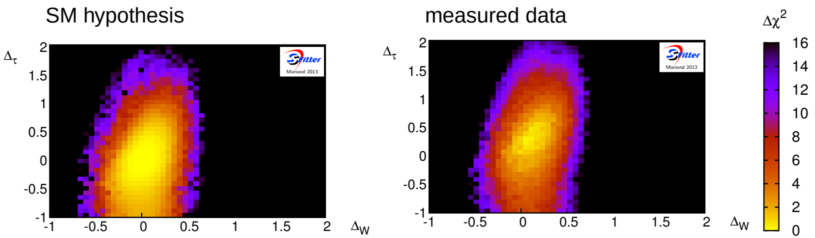
Expected 2012 results:

- Clear indication of non-vanishing $H\tau\tau$ coupling

- Finally seen
- First direct evidence for coupling to fermions!

Global view

Δ_W vs. Δ_τ



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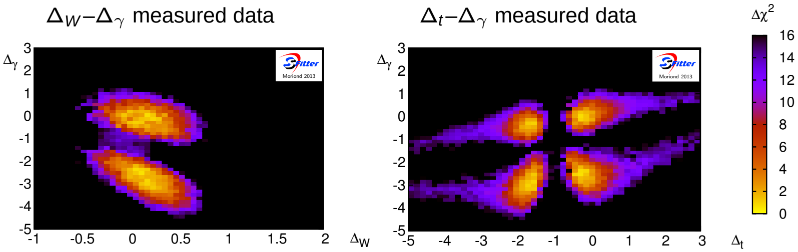
Best-fitting solutions:

Δ_W	Δ_Z	Δ_t	Δ_b	Δ_τ	χ^2/d.o.f.
-0.11	-0.04	-0.20	-0.27	-0.04	15.8/58
-0.26	-0.02	-1.70	-0.30	0.03	16.8/58

$\chi^2(\text{SM}) = 16.4$

Global view

Independent contribution to photon coupling Δ_γ

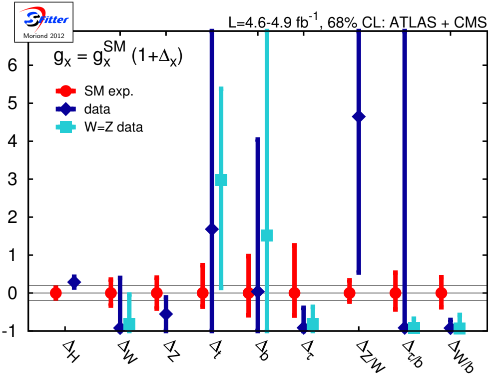


Standard Model-like solution plus secondary flipped-sign solutions

(Anti-)correlations between parameters as expected

No surprising new features

Local View on data



- One year ago ... (Moriond 2012)

- best-fit point from Markov-chain Monte Carlo
- Error bars: 5000 toy MC, 68% CL coverage
- horizontal lines: $\pm 20\%$

[see also Carmi *et al.* ; Asatov *et al.* ; Espinosa *et al.* ; Giardino *et al.* ; Ellis *et al.* ; Farina *et al.* ; . . .]

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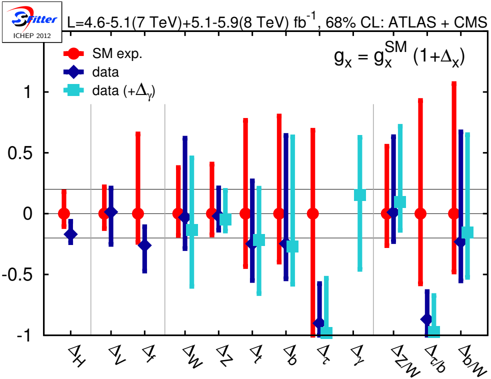

- Discovery ...
  (ICHEP 2012)

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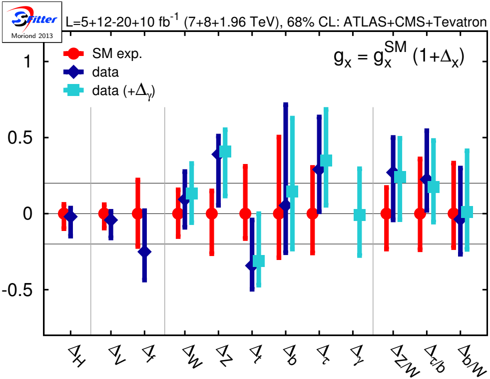

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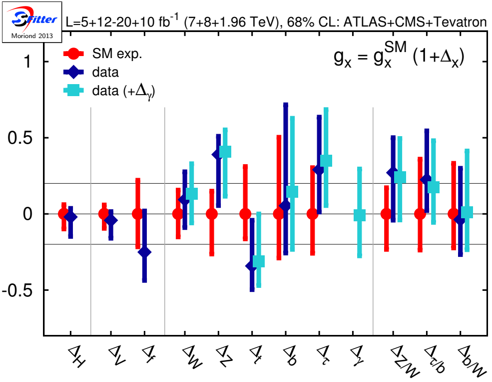

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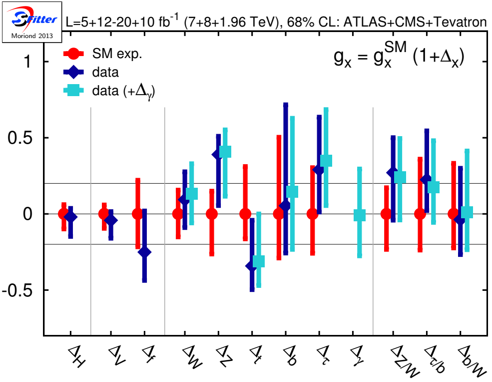

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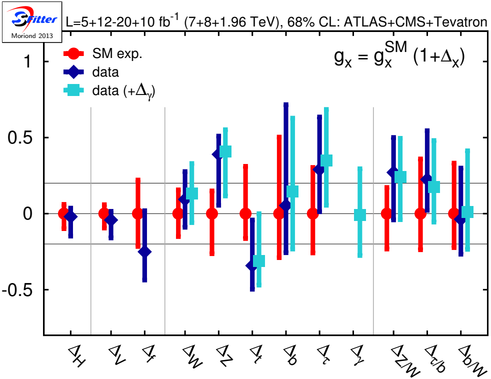

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Standard Model-like Higgs

[see also Carmi *et al.* ; Asatov *et al.* ; Espinosa *et al.* ; Giardino *et al.* ; Ellis *et al.* ; Farina *et al.* ; . . .]

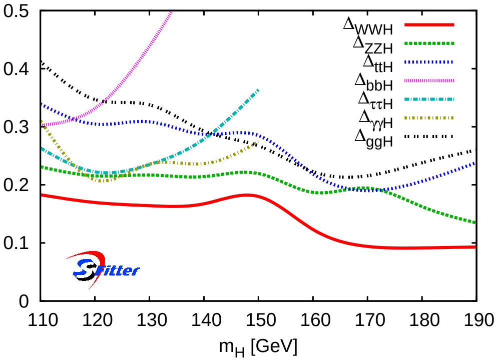
Higgs at the LHC

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

(Standard Model hypothesis)

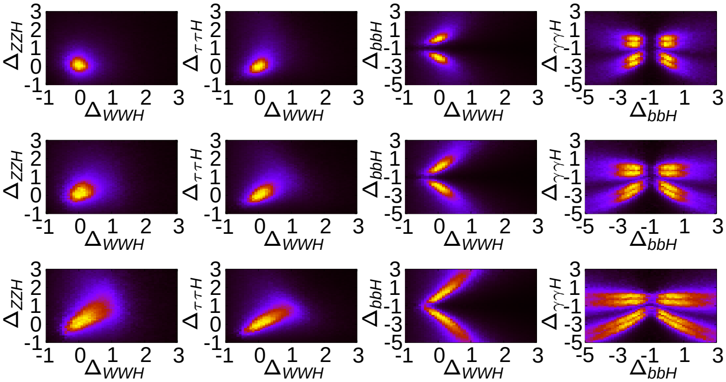
[Lafaye, Plehn, MR, Zerwas, Dührssen 2009]

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)



Impact of subjet analysis

[SFitter]



Top to bottom: • VH, $H \to b\bar{b}$ subjet analysis with full strength

[Butterworth, Davison, Rubin, Salam; ATLAS-MC]

- sensitivity reduced by 50%
- subjet analysis removed

$\leftrightarrow$ No test of subjet analysis with data yet

Invisible vs. Unobserved

Additional decays into "invisible" final states possible

$$\Gamma_{\text{tot}} = \Gamma_{\text{tot}}^{SM} + \Gamma_{\text{inv}} \equiv \Gamma_{\text{tot}}^{SM} \left(1 + \Delta_\Gamma\right)$$

Can be compensated by global scaling of couplings

$$\sigma \cdot BR = \frac{\Delta_H^2}{1 + \frac{\Delta_\Gamma}{\Delta_H^2}} \left(\sigma \cdot BR\right)_{\text{SM}}$$

- 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; Englert, Spannowsky, Wymant]

- 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

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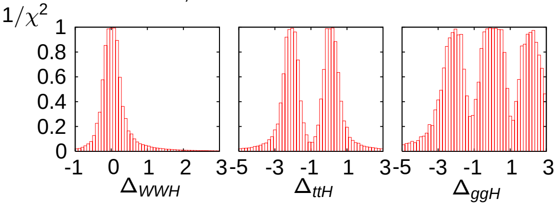
  e.g. increased *ccH* coupling (corresponding to 15.4 GeV Yukawa coupling)
  $\mathcal{L} = 30\ \text{fb}^{-1}$, SM data / increased *ccH* / increased *ccH* plus free width



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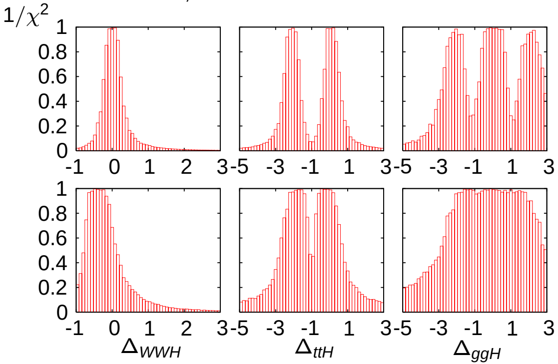

Invisible vs. Unobserved

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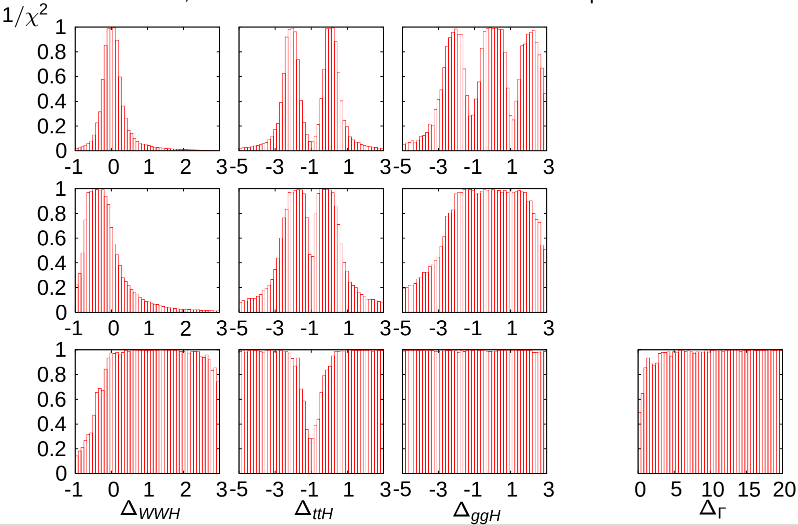

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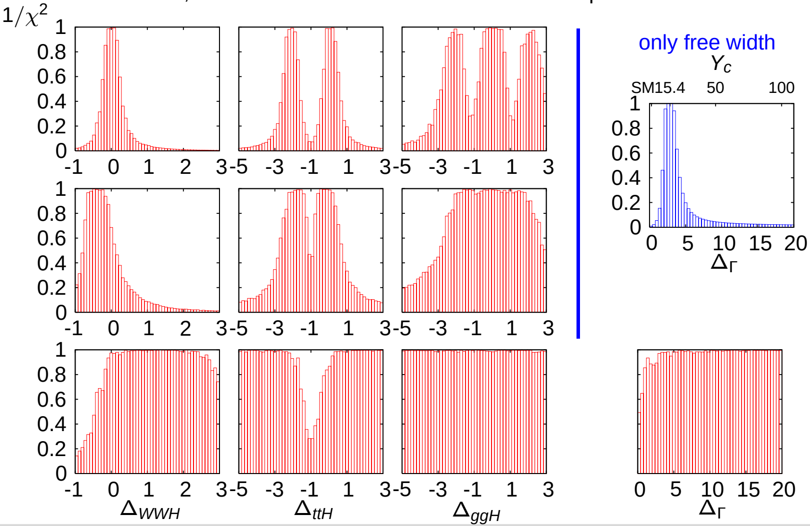
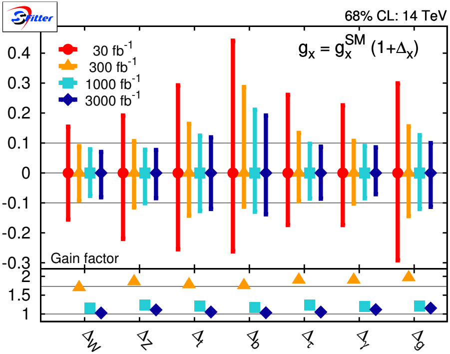


LHC in the future

LHC high-luminosity run: 14 TeV, 3000 fb^{-1}
Standard Model hypothesis



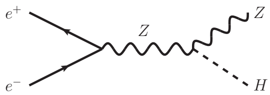
- extrapolation done blindly (only stat. improvements) starting from MC expectation at 14 TeV, 30 fb^{-1}
- full set including effective couplings

- gain factor less than 3 (30→300 fb^{-1}), $\sqrt{3}$ (300→1000 fb^{-1}, 1000→3000 fb^{-1})
- ⇒ statistical scaling does not apply any longer
- best obtainable precison $\simeq$ 10%
- all couplings limited by systematic and theory error

Linear Collider

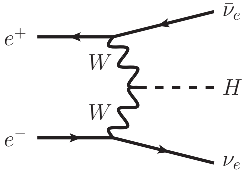
Linear Collider:
proposed first run: $\sqrt{S} = 250$ GeV, $L = 250$ fb^{-1},
upgrade to $\sqrt{S} = 500$ GeV, $L = 500$ fb^{-1}
ILC measurements (from DBD draft) [Peskin (ed.) *et al.*]

Main production mode *ZH*



Allows measuring inclusive *ZH* cross section via recoil technique
(use all events where *Z* decay products kinematically compatible with *ZH* production; *H* decay products stay unobserved)

WW-fusion channel



Important ingredient to reconstruct total width

Combine four measurements

1. Higgs-strahlung inclusive (σ_{ZH})
2. Higgs-strahlung, $H \to b\bar{b}$ (σ_{Zbb})
3. Higgs-strahlung, $H \to WW$ (σ_{ZWW})
4. *WW*-fusion with $H \to b\bar{b}$ ($\sigma_{\nu\nu bb}$)

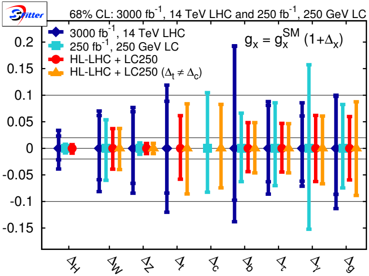
and four unknowns Δ_W, Δ_Z, Δ_b, and Γ_{tot}:

$$\Gamma_{\text{tot}} \leftarrow \frac{\sigma_{\nu\nu bb}/\sigma_{Zbb}}{\sigma_{ZWW}/\sigma_{ZH}} \times \sigma_{ZH}$$

LHC-ILC interplay

[Klute, Lafaye, Plehn, MR, Zerwas]

$\sqrt{S} = 250$ GeV, $L = 250$ fb^{-1}



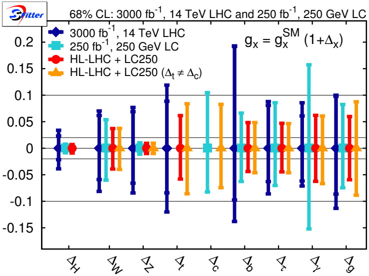
- reminder: $\Delta_t = \Delta_c$ (generation universality)
- LHC: no Δ_c (no obs. channel)
- ILC: no Δ_t (below $t\bar{t}H$ threshold)

- dramatic improvement on Δ_Z, Δ_b
- complementary: combination better than each alone
- testing $\Delta_t \stackrel{?}{=} \Delta_c$ possible

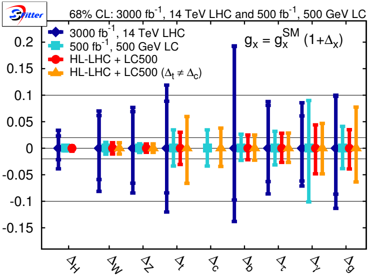
LHC-ILC interplay

[Klute, Lafaye, Plehn, MR, Zerwas]

$\sqrt{S} = 250$ GeV, $L = 250$ fb^{-1}



$+ \sqrt{S} = 500$ GeV, $L = 500$ fb^{-1}

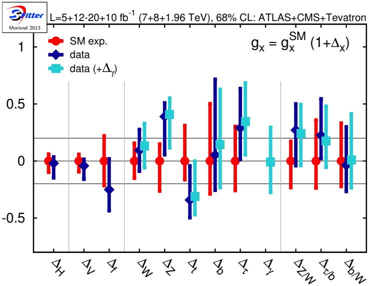


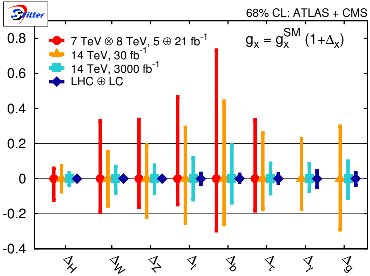
- dramatic improvement on Δ_Z, Δ_b
- complementary: combination better than each alone
- testing $\Delta_t \stackrel{?}{=} \Delta_c$ possible

+ 500 GeV run: ILC precision surpasses LHC everywhere

Conclusions & Outlook

- Determining the Higgs-boson couplings important for our understanding of electroweak symmetry breaking
  $\to$ Standard Model with effective Higgs couplings
- All errors including correlations fully implemented
- Already wealth of measurements from LHC
- Precision on single-parameter modifier $\Delta_H \simeq 10\%$ already now
- SM Higgs Boson good explanation of observed resonance





SFitter

Karlsruher Institut für Technologie

- 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]

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

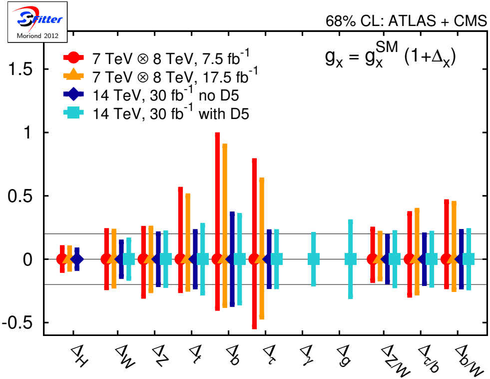
Last line obtained using subjet techniques ([Butterworth, Davison, Rubin, Salam]),
theoretical results confirmed by ATLAS ([ATL-PHYS-PUB-2009-088])
(stricter cuts, statistical significance basically unchanged)

In the future

2012, 2014, . . . (assuming m_H = 125 GeV)

Scenarios: 2012_{low}: $(7.5\ \text{fb}^{-1}, 8\ \text{TeV}) \otimes (5\ \text{fb}^{-1}, 7\ \text{TeV})$
2012_{high}: $(17.5\ \text{fb}^{-1}, 8\ \text{TeV}) \otimes (5\ \text{fb}^{-1}, 7\ \text{TeV})$
2014: $(30\ \text{fb}^{-1}, 14\ \text{TeV})$

Standard Model hypothesis
Extrapolation 7→8 TeV done blindly
(only statistical improvements, based on 2011 measurements)



- VBF measurements giving important information
- $t\bar{t}H$ and $H \to b\bar{b}$ measurements
- g_g and g_γ accessible independently

⇒ exciting prospects