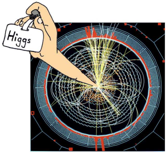
Determination of Higgs Couplings – present and future

Michael Rauch | Higgs Couplings 2012, Tokyo

INSTITUTE FOR THEORETICAL PHYSICS

Higgs properties

Verify nature of observed resonance
$\leftrightarrow$ "Higgs" properties



- spin-0 particle
  spin-1 disfavoured by $H \to \gamma\gamma$ [Landau-Yang theorem]
  spin-2: look at angular correlations
  [Hagiwara, Mawatari, Li; Frank, MR, Zeppenfeld; Ellis *et al.* ; Alves; Boughezal *et al.* ; . . .]
- CP-nature
  SM-Higgs CP-even; extended Higgs sectors also CP-odd or mixed states
  look at angular correlations
  [Zeppenfeld *et al.* ; Choi *et al.* ; Godbole *et al.* ; Englert *et al.* ; Ellis *et al.* ; Boughezal *et al.* ; . . .]
- 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)
    [Djouadi *et al.* ; Plehn *et al.* ; Baur *et al.* ; MR *et al.* ; Binoth *et al.* ; Dolan *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 free Higgs couplings
  Couplings from modified version of HDecay [Djouadi, Kalinowski, Mühlleitner, Spira]
- For Higgs couplings present in the Standard Model $x = W, Z, t, b, \tau$
  $$g_{xxH} \equiv g_x \longrightarrow g_x^{\mathrm{SM}}\ (1 + \Delta_x) \qquad (\rightarrow \Delta = -2 \text{ means sign flip})$$
- For loop-induced Higgs couplings $x = \gamma, g$
  $$g_x \longrightarrow g_x^{\mathrm{SM}}\ \left(1 + \Delta_x^{\mathrm{SM}} + \Delta_x\right)$$
  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 $\frac{g_x}{g_y} = \frac{g_x^{\mathrm{SM}}}{g_y^{\mathrm{SM}}}(1 + \Delta_{x/y})$
- Neglecting couplings only available from high-luminosity analyses
  (g_μ, $g_{HZ\gamma}^{\mathrm{eff}}$, g_{HHH}, g_{HHHH})
- Δ_H: single parameter modifying all (tree-level) couplings
- Total width
  $$\Gamma_{\mathrm{tot}} = \Sigma_{\mathrm{obs}} \Gamma_x < 2\ \mathrm{GeV} \quad \text{(plus generation universality)}$$
- Electro-weak corrections not yet relevant

SFitter

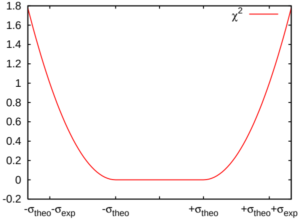
Algorithms:

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

[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 Couplings after ICHEP 2012

7 TeV $\mathcal{L}$ = 4.6-5.1 fb^{-1} $\otimes$ 8 TeV $\mathcal{L}$ = 5.1-5.9 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	$\gamma\gamma$	Cat2+3
ZZ $\to 4\ell$		$\gamma\gamma$	di-jet tight
WW	0-jet	$\gamma\gamma$	di-jet loose
WW	1-jet	ZZ $\to 4\ell$	
WW	2-jet	WW	0-jet
		WW	1-jet
		WW	2-jet
		$\tau\tau$	0/1-jet
		$\tau\tau$	Boosted
		$\tau\tau$	VBF
		$b\bar{b}$	Z_ℓH low-p_T
		$b\bar{b}$	Z_ℓH high-p_T
		$b\bar{b}$	Z_νH low-p_T
		$b\bar{b}$	Z_νH high-p_T
		$b\bar{b}$	WH low-p_T
		$b\bar{b}$	WH high-p_T

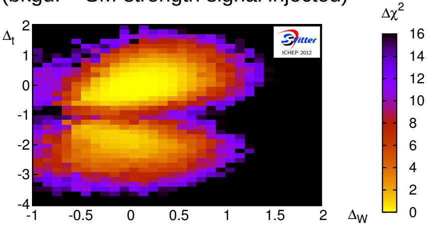
- background expectations, exp. errors, etc. from analyses
- cross-checked with exclusion and signal-strength plots

Global view

[Plehn, MR]

Δ_W vs. Δ_t

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



Expected 2012 results:

- Correct solution around SM value $\Delta = 0$
- 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

Global view

[Plehn, MR]

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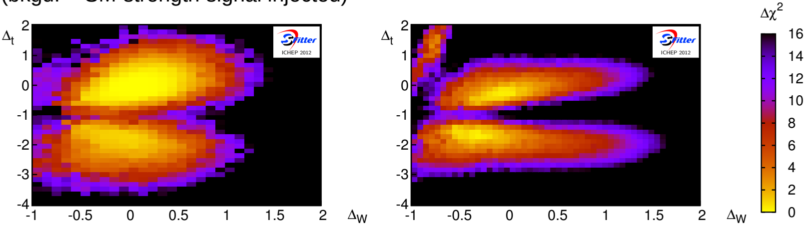
measured data



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  for flipped top Yukawa coupling
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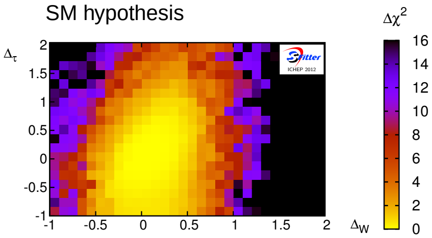
2012 results:

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

Global view

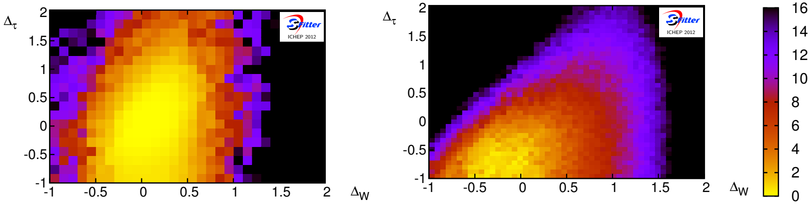
Δ_W vs. Δ_τ



Global view

Δ_W vs. Δ_τ

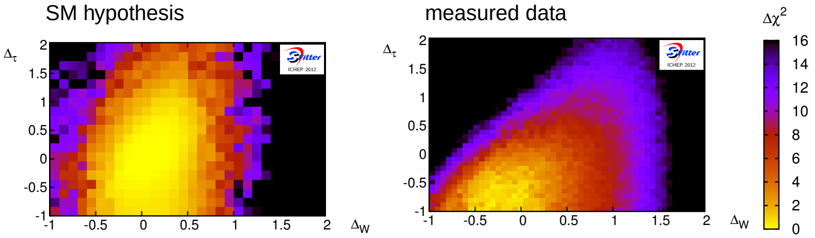
SM hypothesis measured data



More $H \to \tau\tau$ data needed for significant statement on $H\tau\tau$ coupling

Global view

Δ_W vs. Δ_τ



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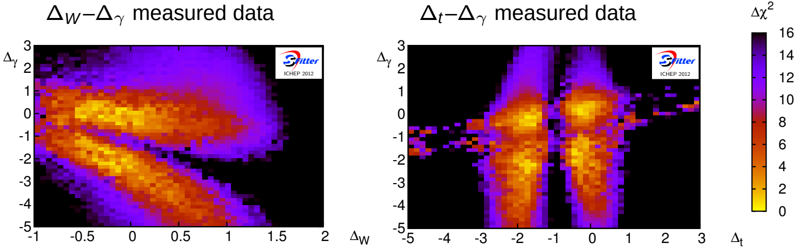
Best-fitting solutions:

Δ_W	Δ_Z	Δ_t	Δ_b	Δ_τ	χ^2/d.o.f.
-0.03	-0.02	-0.25	-0.25	-0.90	27.7/49
-0.05	-0.04	-0.34	-1.73	-0.70	27.6/49
-0.29	-0.09	-1.65	-0.32	-0.70	27.7/49

Global view

Independent contribution to photon coupling Δ_γ



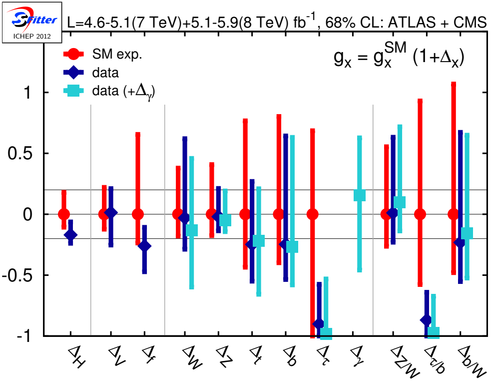
Standard Model-like solution plus secondary flipped-sign solutions

No surprising new features

Best-fitting solutions:

Δ_W	Δ_Z	Δ_t	Δ_b	Δ_τ	Δ_γ	χ^2/d.o.f.
-0.13	-0.05	-0.22	-0.27	-0.98	0.16	27.3/48
-0.17	-0.07	-1.67	-0.34	-0.87	-0.22	27.3/48

Local View on 8 TeV data



- Δ_H already very precise
- Δ_V-Δ_f also well determined g_f lower than expected

- 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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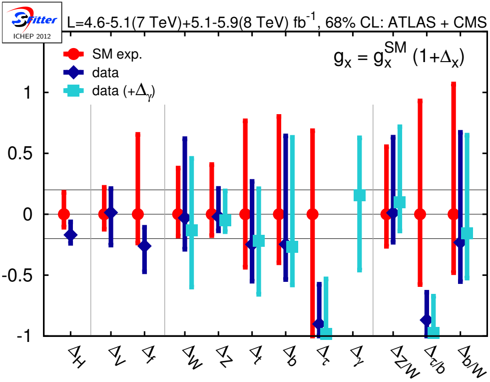

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- g_W, g_Z okay
- g_b and g_t indirectly preferred smaller
- g_τ inconclusive in data
- ratios: no improvement over direct measurements

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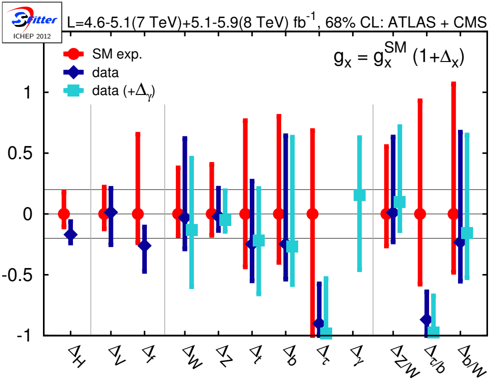

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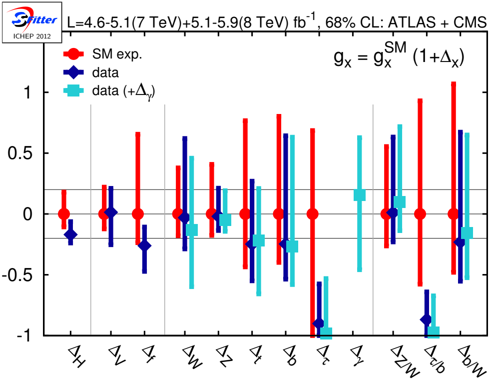

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Moving towards Standard Model?

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

Couplings beyond LHC at ICHEP

- Tevatron impact (no subjet measurement at LHC yet):
  - Assume meas. determine mainly $\Delta_b^{\text{input}} = 0.4 \pm 0.25$
  - $\Rightarrow$ central value of Δ_b moves up
  - error on Δ_b, Δ_τ reduced $\Delta_b = 0.3^{-0.34}_{+0.25}$

- HCP update of ATLAS & CMS (personal ad-hoc interpretation)

		ICHEP		HCP	
$H \to WW$	ATLAS	0.5 ± 0.6	(5+0)	—	
		1.9 ± 0.7	(0+6)	1.4 ± 0.6	(0+13)
		1.3 ± 0.5	(5+6)	—	
	CMS	0.82 ± 0.38	(5+5)	0.74 ± 0.25	(5+12)
$H \to ZZ$	ATLAS	1.2 ± 0.6	(5+6)	—	
	CMS	$\sim 0.7 \pm 0.4$	(5+5)	0.8 ± 0.3	(5+12)
$H \to \gamma\gamma$	ATLAS	1.8 ± 0.5	(5+6)	—	
	CMS	1.56 ± 0.43	(5+5)	—	
$H \to \tau\tau$	ATLAS	$\sim 0.5 \pm 1.5$	(5+0)	0.7 ± 0.7	(5+13)
	CMS	$\sim 0.0 \pm 0.9$	(5+0)	0.72 ± 0.52	(5+12)
$H \to b\bar{b}$	ATLAS	$\sim 0.5 \pm 2.0$	(5+0)	-0.4 ± 1.1	(5+13)
	CMS	$\sim 0.5 \pm 0.8$	(5+5)	1.3 ± 0.7	(5+12)

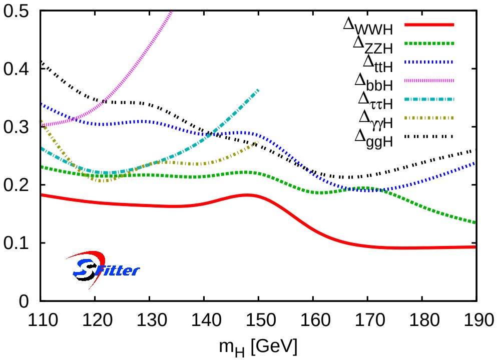
Higgs at the LHC

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

(Standard Model hypothesis)

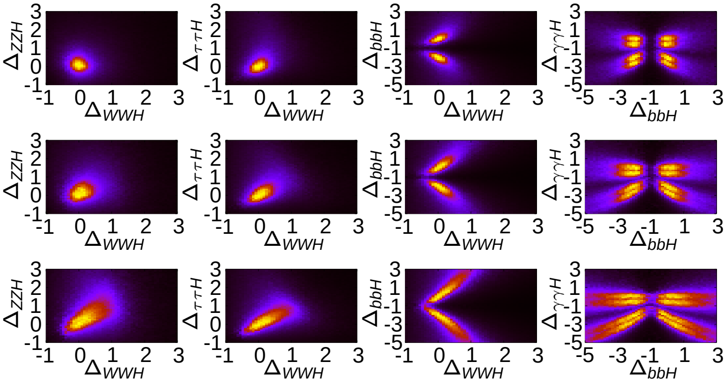
[Lafaye, Plehn, MR, Zerwas, Dührssen 2009]

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

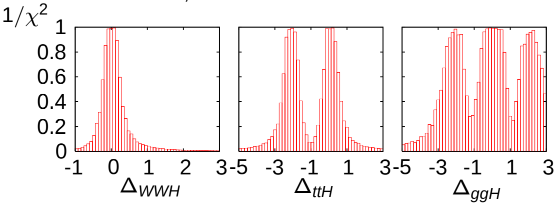
$$\sigma \cdot BR = \frac{\Delta_H^2}{1 + \frac{\Delta_\Gamma}{\Delta_H^2}} \left(\sigma \cdot BR\right)_{\text{SM}}$$

- 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

- 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



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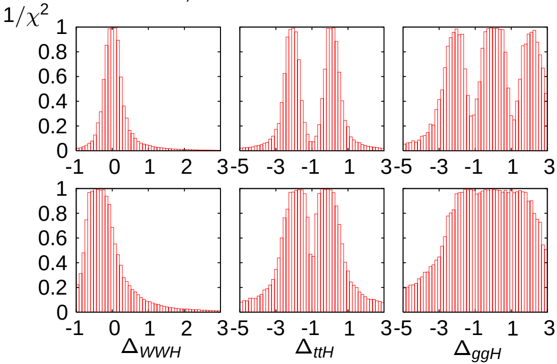

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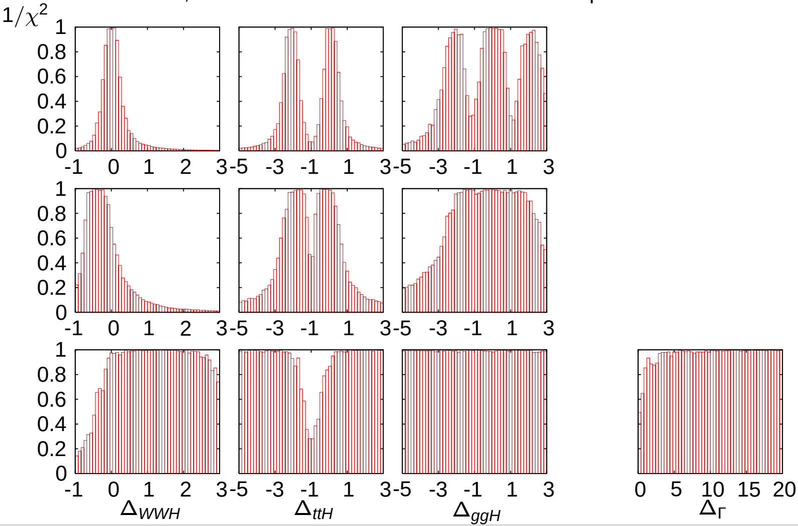

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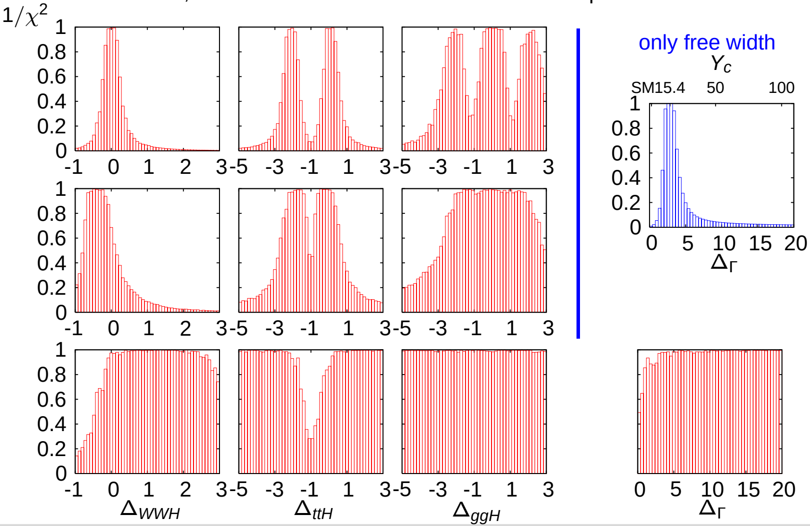
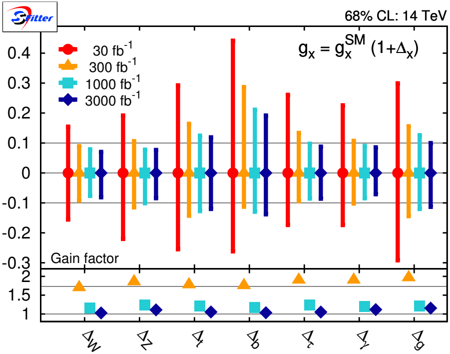


LHC in the future

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

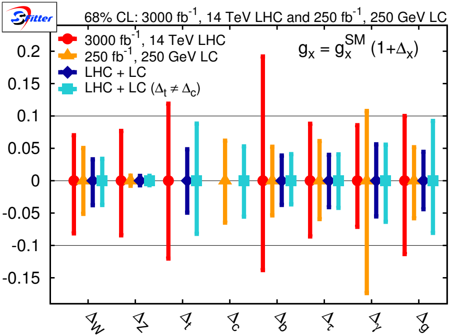


- extrapolation done blindly (only stat. improvements) starting from MC expectation at 14 TeV, 30 fb^{-1}
- full set including effective couplings

- 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}
ILC precision from DBD draft, errors only Gauss (→ talk by Keisuke Fujii)



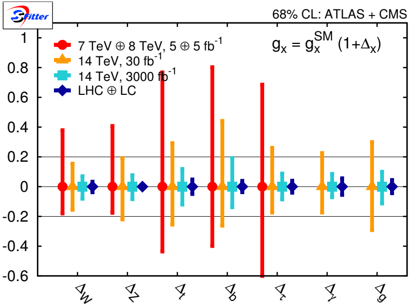
- reminder: $\Delta_t = \Delta_c$ (generation universality)
- LHC: no Δ_c (no obs. channel)
- ILC: no Δ_t (below $t\bar{t}H$ threshold)

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

+ ILC($\sqrt{S} = 500$ GeV, $L = 500$ fb^{-1}) run: ILC precision surpasses LHC everywhere

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
- 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

- 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]

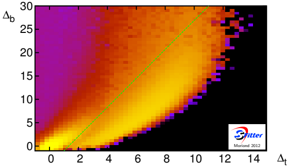
The 7 TeV Case

Higgs boson channels, $\mathcal{L}$ = 4.6-4.9 fb^{-1}

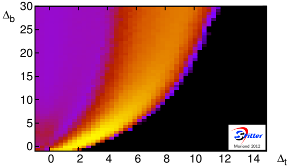
ATLAS		CMS	
$\gamma\gamma$		$\gamma\gamma$	
ZZ $\to 4\ell$		$\gamma\gamma$	di-jet
WW	0-jet	ZZ $\to 4\ell$	
WW	1-jet	WW	0-jet
WW	2-jet	WW	1-jet
$\tau\tau$	0-jet	WW	2-jet
$\tau\tau$	1-jet	$\tau\tau$	0/1-jet
$\tau\tau$	VBF	$\tau\tau$	Boosted
$\tau\tau$	VH	$\tau\tau$	VBF
$b\bar{b}$	WH	$b\bar{b}$	WH
$b\bar{b}$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

SM hypothesis Δ_t vs. Δ_b



7 TeV data Δ_t vs. Δ_b



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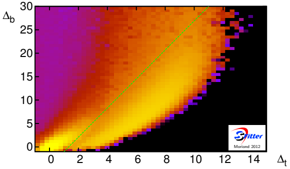
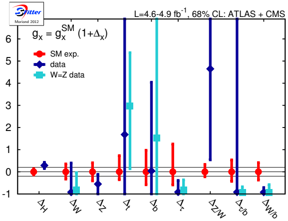
WW	0-jet	ZZ $\to 4\ell$	
WW	1-jet	WW	0-jet
WW	2-jet	WW	1-jet
$\tau\tau$	0-jet	WW	2-jet
$\tau\tau$	1-jet	$\tau\tau$	0/1-jet
$\tau\tau$	VBF	$\tau\tau$	Boosted
$\tau\tau$	VH	$\tau\tau$	VBF
$b\bar{b}$	WH	$b\bar{b}$	WH
$b\bar{b}$	Z($\to \ell\bar{\ell}$)H	$b\bar{b}$	Z($\to \ell\bar{\ell}$)H
$b\bar{b}$	Z($\to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

SM hypothesis Δ_t vs. Δ_b



Higgs couplings 7 TeV data



Higgs at the LHC

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

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

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

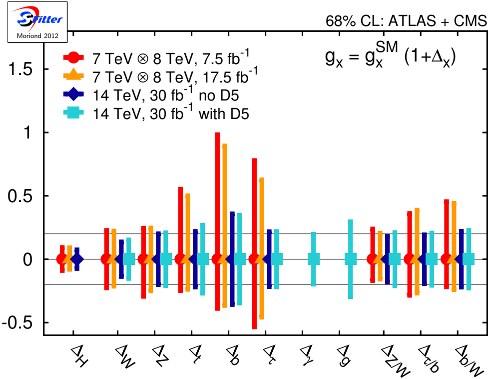
Last line obtained using subjet techniques ([Butterworth, Davison, Rubin, Salam]),
theoretical results confirmed by ATLAS ([ATL-PHYS-PUB-2009-088])
(stricter cuts, statistical significance basically unchanged)

In the future

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

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

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

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

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

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

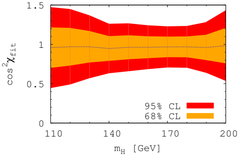
The Higgs Portal

Fit of $\cos^2\chi_{\text{fit}}$ without constraints (14 TeV, 30 fb^{-1})

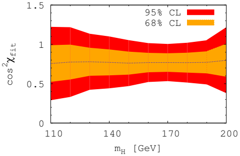
[Bock, Lafaye, Plehn, MR, D. Zerwas, P.M. Zerwas]

- No invisible decay modes

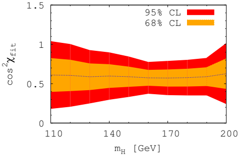
$\cos^2\chi_{\text{th}} = 1.0$



$\cos^2\chi_{\text{th}} = 0.8$



$\cos^2\chi_{\text{th}} = 0.6$

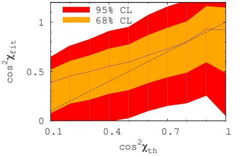


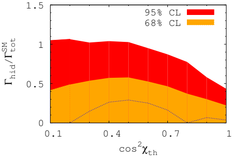
$\Rightarrow$ If $\cos^2\chi_{\text{th}} < 0.6$ can exclude SM at the 95% CL with 30 fb^{-1}

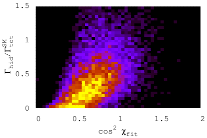
- Measuring invisible decays in VBF-Higgs production
  Signature: Two VBF-jets plus missing E_T

[Eboli, Zeppenfeld; MC-study: ATLAS]

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







The Higgs Portal

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

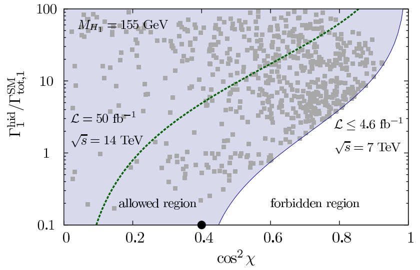
- bounds are determined by measurement of twin ratios

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

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

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

- 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

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

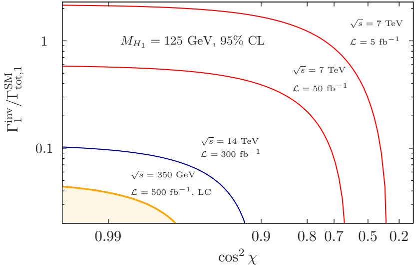
- bounds are determined by measurement of twin ratios

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

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

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

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



- 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:

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

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

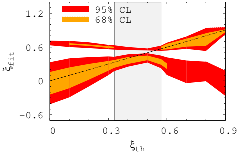
Significant and observable deviations also in Higgs self-couplings [Gröber, Mühlleitner]

MCHM5

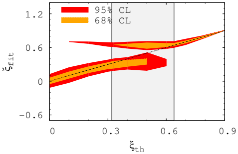
[Bock, Lafaye, Plehn, MR, D. Zerwas, P.M. Zerwas]

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

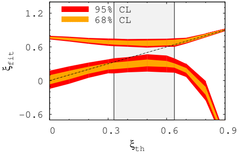
$m_H = 120$ GeV



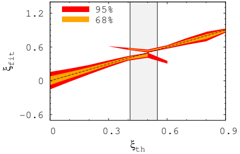
$m_H = 160$ GeV



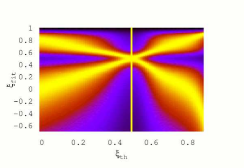
$m_H = 200$ GeV



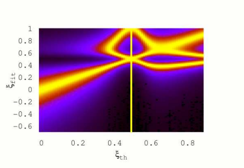
$\mathcal{L} = 300\ \text{fb}^{-1}$



Gluon fusion $H \to \gamma\gamma$



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



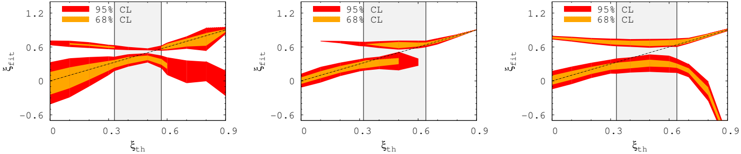
Not a true degeneracy
$\to$ Each (smeared) toy experiment has unique solution

MCHM5

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

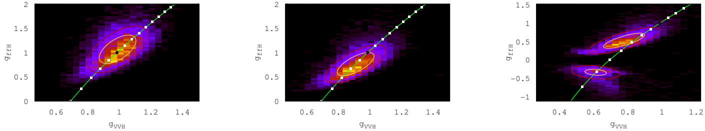
Secondary solutions appear (sign of $f\bar{f}H$ coupling)

$m_H = 120$ GeV $\quad m_H = 160$ GeV $\quad m_H = 200$ GeV



Independent fit of common vector and fermion couplings

$\xi_{\rm th} = 0 \quad \xi_{\rm th} = 0.2 \quad \xi_{\rm th} = 0.6$



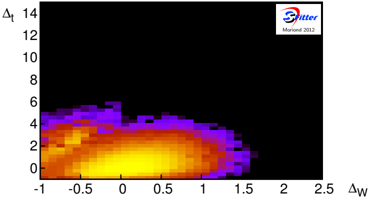
Not a true degeneracy
$\rightarrow$ Each (smeared) toy experiment has unique solution

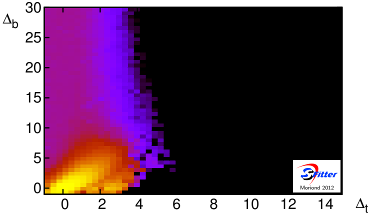
Top-associated Higgs Subjets

Add additional measurement for $t\bar{t}H$, $H \to b\bar{b}$ using subjet techniques

[Plehn, Salam, Spannowsky]

extrapolated to 7 TeV
SM hypothesis





$\Rightarrow$ Secondary solution strongly suppressed
$\to$ large g_t disfavoured by new measurement