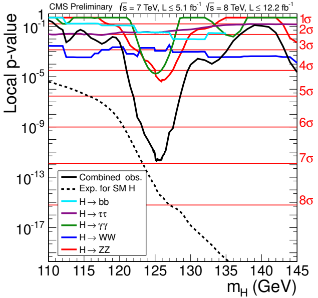
Higgs Fits

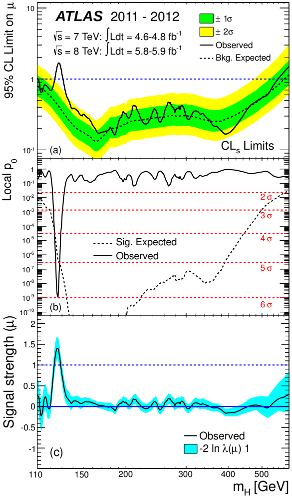
Michael Rauch | Advances in Computational Particle Physics | Sep 17, 2014

INSTITUTE FOR THEORETICAL PHYSICS

Found a Resonance

Resonance at $\sim$ 126 GeV found





Assuming SM is correct, full theory:

$\Rightarrow$ Job done

- must be Higgs
  (only missing but expected particle)
- mass only remaining unknown parameter
- couplings and quantum numbers fixed by theory prediction

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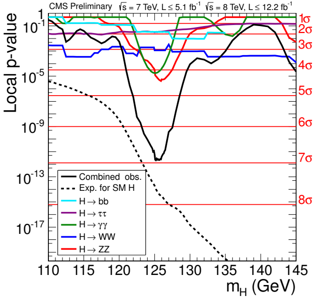

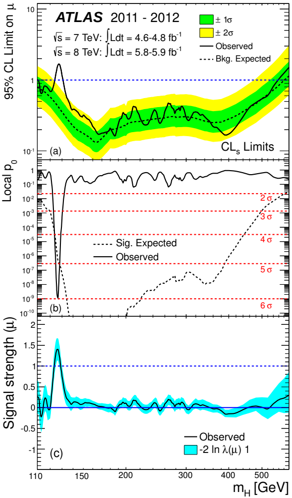

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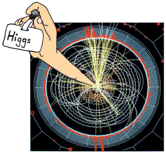
↔ test predictions

Properties of the Resonance



Characterize resonance [see e.g. Englert *et al.* , Artoisenet *et al.*]
[Zeppenfeld *et al.* ; Choi *et al.* ; Godbole *et al.* ; Hagiwara, Mawatari, Li;
Englert *et al.* ; Ellis *et al.* ; Frank, MR, Zeppenfeld; Alves; Boughezal *et al.* ; . . .]

- Spin
  - spin-1 excluded by observing $H \to \gamma\gamma$ [Landau, Yang]
  - spin-2 disfavoured by exp. measurements ($\gtrsim 3\sigma$ in ATLAS/CMS)
  - $\Rightarrow$ spin-0 ✓
- CP
  most general structure of $HV^\mu V^\nu$ vertex: [Zeppenfeld *et al.*]

  $$T^{\mu\nu} = a_1 g^{\mu\nu} + a_2 (p_1 \cdot p_2 g^{\mu\nu} - p_2^\mu p_1^\nu) + a_3 \varepsilon^{\mu\nu\rho\sigma} p_{1,\rho} p_{2,\sigma}$$

  a_3: CP-odd coupling – disfavoured by experiments

  $\leftrightarrow$ CP-odd Higgs (e.g. A^0 in 2HDM) a_3 contribution loop-induced
  CP-mixed Higgs: a_1 coupling to WW, ZZ proportional to CP-even admixture
  (up to loop effects)
  $\Rightarrow$ constrain CP-odd admixture [Djouadi, Moreau]
- Couplings
  $\to$ requires operator basis

Parametrizing Higgs Couplings

Discrete quantum numbers (CP-even scalar) those of SM Higgs
Measured rates in reasonable agreement with SM expectation

- $\Rightarrow$ Constraints on new-physics models [$\rightarrow$ next talk by Maggie]
- $\Rightarrow$ SM(-Higgs) + X
  - Effective Lagrangian – dimension-6 operators
    [Buchmüller, Wyler; Grzadkowski *et al.* ; Giudice *et al.* ; Contino *et al.* ; Passarino; Gonzalez Garcia *et al.*]
  - Renormalizable Lagrangian + non-decoupling dimension-6 operators
    [Zeppenfeld *et al.* ; Duehrssen *et al.* ; Lafaye, Plehn, MR, Zerwas; LHC HXSWG]

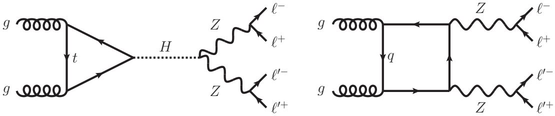
  Assumptions:
  - single narrow resonance at $\sim$ 126 GeV
  - width negligible
    $\Rightarrow (\sigma \cdot \mathrm{BR})(ii \rightarrow H \rightarrow ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$
  - tensor structure identical to SM

Generalized 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 $x = W, Z, t, b, \tau$
  $g_{xxH} \equiv g_x \longrightarrow g_x^{\text{SM}} \ (1 + \Delta_x) \equiv g_x^{\text{SM}} \ \kappa_x$ ($\rightarrow \Delta = -2$ means sign flip)
- For loop-induced Higgs couplings $x = \gamma, g$
  $$g_x \longrightarrow g_x^{\text{SM}} \left(1 + \Delta_x^{\text{SM}} + \Delta_x\right) \equiv \kappa_x g_x^{\text{SM}}$$
  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 $\frac{g_x}{g_y} = \frac{g_x^{\text{SM}}}{g_y^{\text{SM}}}(1 + \Delta_{x/y}) \equiv \frac{g_x^{\text{SM}}}{g_y^{\text{SM}}}\lambda_{xy}$
- Neglecting couplings only available from high-luminosity analyses
  (g_μ, $g_{HZ\gamma}^{\text{eff}}$, g_{HHH}, g_{HHHH})
- Electro-weak corrections not yet relevant
  for later consistency: QCD corrections scale with couplings, EW ones not
- Total width not directly measurable at LHC
  Additional decays into “invisible” final states possible
  $\rightarrow$ can be compensated by global scaling of couplings
  $$(\sigma \cdot BR)(ii \rightarrow H \rightarrow ff) = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} (\sigma \cdot BR)_{\text{SM}}$$

Higgs Width from Off-shell Measurements

Consider process $(pp \to)gg \to \ell^+\ell^-\ell'^+\ell'^-$: [Caola, Melnikov]

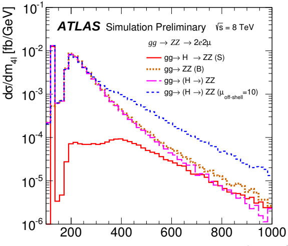


Contributions from Higgs resonance and continuum diagrams

- at Higgs peak:
  basically no interference between both diagrams
  contribution given by

$$|\mathcal{M}_{\text{prod}}|^2 \; |\mathcal{M}(H \to 4\ell)|^2 \; \frac{1}{(m_{4\ell}^2 - M_H^2)^2 + (M_H \Gamma_H)^2} \propto \frac{\kappa_g^2 \kappa_Z^2}{\Gamma_H / \Gamma_H^{\text{SM}}} \overset{\kappa_i \equiv \kappa}{\propto} \frac{\kappa^4}{\Gamma_H / \Gamma_H^{\text{SM}}}$$

- at large 4-lepton invariant mass:
  large destructive interference between (off-shell) Higgs and continuum diagram
  [Glover, van der Bij; . . .]
  contribution of Γ_H in term above becomes irrelevant for $m_{4\ell}^2 - M_H^2 \gg M_H \Gamma_H$
  $\Rightarrow$ interference changes proportional to
  $c_1 \kappa^2 + c_2 \kappa^4$



Higgs Width from Off-shell Measurements

[Caola, Melnikov]

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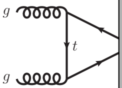

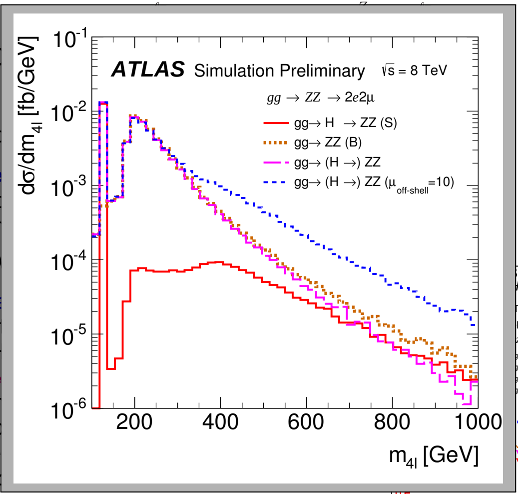

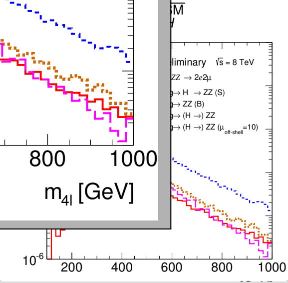

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  $\Rightarrow$ interfere

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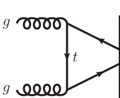

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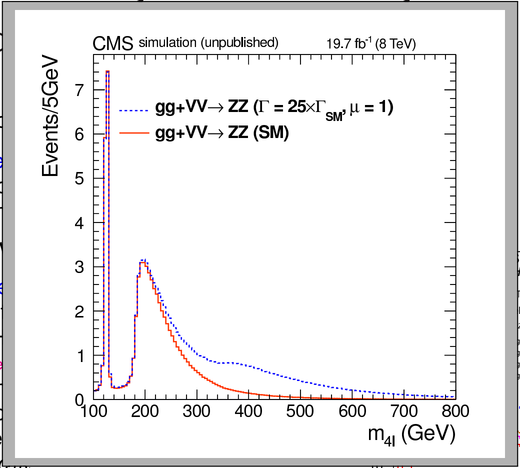
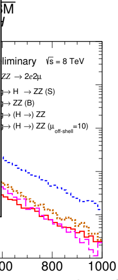
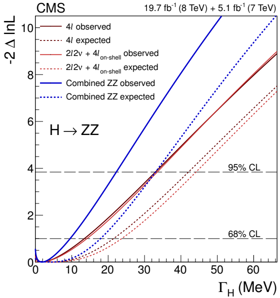




Higgs Width from Off-shell Measurements (cont.)

Compare results from on-shell and off-shell Higgs region
$\Rightarrow$ determine Γ_H



ATLAS: $\Gamma_H < 20 - 32$ MeV
(29 – 50 MeV exp.) @95% CL

CMS: $\Gamma_H < 22$ MeV
(33 MeV exp.) @95% CL

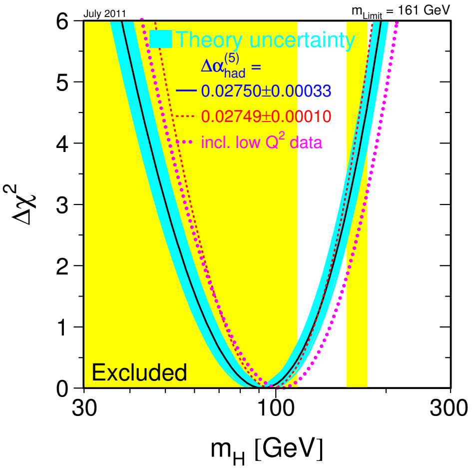
$(\Gamma_H^{SM} = 4.1 \text{ MeV})$

Limitations:

- higher-order corrections to continuum diagram unknown
  $\leftrightarrow$ large K-factor ~ 2 expected ($\rightarrow$ range in ATLAS results)
- new-physics effects can modify on-shell and off-shell region differently
  e.g. dim-6 operators like $Z_\mu Z^\mu \Box H$
  or additional scalars contributing in the loop [Gainer *et al.* ; Englert, Spannowsky]

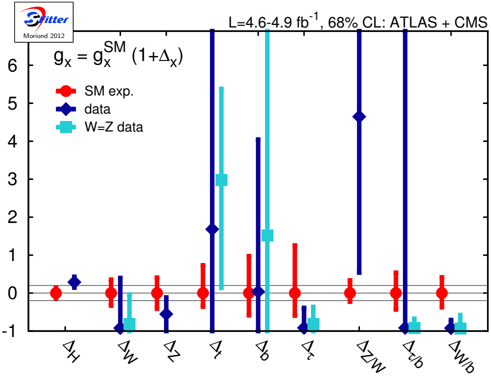
$\Rightarrow$ not model-independent

Higgs Coupling Results



- Large part of SFB ...
  (before December 2011)
  [LEPEWWG Juli 2011]

Higgs Coupling Results



- Two years 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.* ; Mühlleitner *et al.* ; Giardino *et al.* ; Ellis *et al.* ; Farina *et al.* ; Bechtle *et al.* ; . . .]

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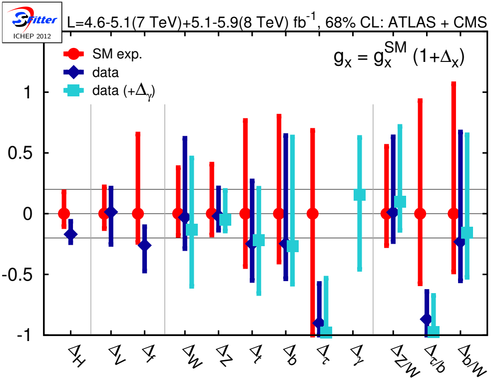

- Discovery ...
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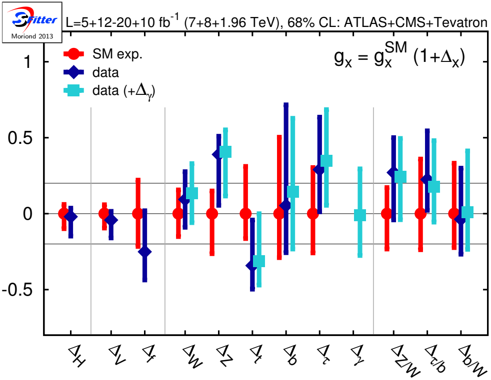

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- Δ_V-Δ_f also well determined

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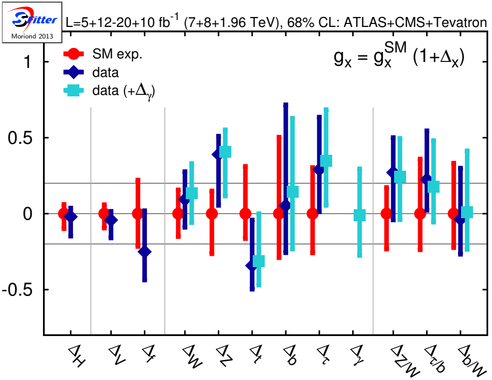

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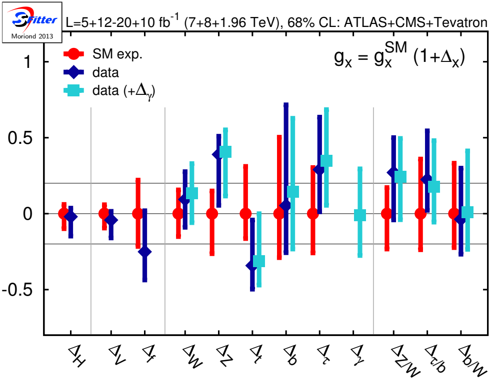

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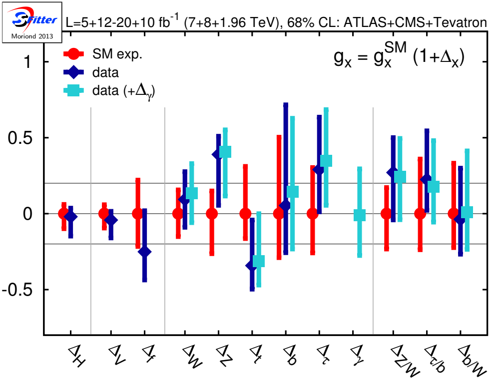

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Standard Model-like Higgs

- best-fit point from Markov-chain Monte Carlo
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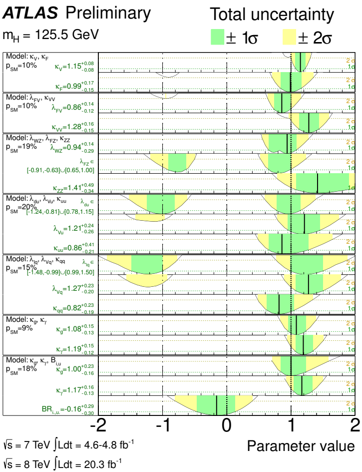
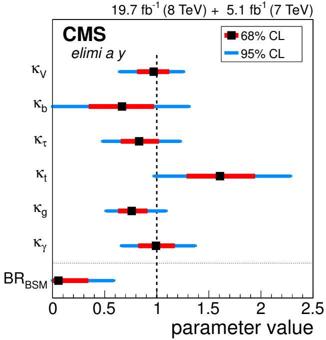
[see also Carmi *et al.* ; Asatov *et al.* ; Mühlleitner *et al.* ; Giardino *et al.* ; Ellis *et al.* ; Farina *et al.* ; Bechtle *et al.* ; . . .]

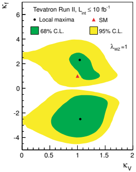
Results from Experimental Groups



$$\mu = 1.30 \pm 0.12\ (\text{stat})^{+0.14}_{-0.11}\ (\text{sys})$$



$$\mu = 1.00 \pm 0.09\ (\text{stat.})^{+0.08}_{-0.07}\ (\text{theo.}) \pm 0.07\ (\text{syst.})$$



2HDM interpretation

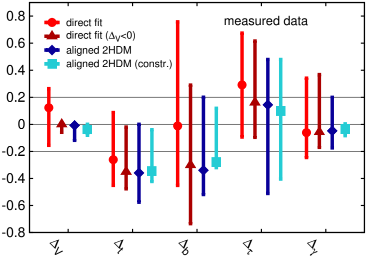
Δ not only scaling factors

$\Rightarrow$ Interpretation of Δ in terms of 2HDM

[Lopez-Val,Plehn,MR]

Yukawa-aligned 2HDM – 5 relevant parameters: $\sin\alpha$, $\tan\beta$, γ_b, γ_τ, M_H

$1+\Delta_V$	$\sin(\beta-\alpha)$
$1+\Delta_t$	$\frac{\cos\alpha}{\sin\beta}$
$1+\Delta_b$	$-\frac{\sin(\alpha-\gamma_b)}{\cos(\beta-\gamma_b)}$
$1+\Delta_\tau$	$-\frac{\sin(\alpha-\gamma_\tau)}{\cos(\beta-\gamma_\tau)}$
$1+\Delta_\gamma^{\text{tot}}$	$f(\sin\alpha,\tan\beta,\gamma_b,\gamma_\tau,M_H)$



Direct mapping between 2HDM parameters and Δ possible

Constraints:

- $|1+\Delta_V|<1$
  due to sum rule $\sum_i g^2_{VVh_i^0} = g^2_{VVH_{\text{SM}}}$
  $\rightarrow$ BSM loop corrections
- $\Delta_W = \Delta_Z$
  Breaking possible by adding Higgs triplet
  $\rightarrow$ custodial symmetry breaking
  $\leftrightarrow$ strong experimental constraints
- no invisible decays
  $\rightarrow$ add dark singlet
- ignore model-specific exp. limits

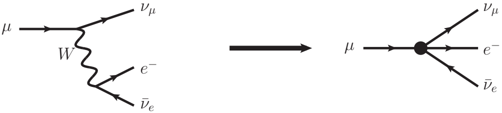
$\rightarrow$ Good agreement between constrained Δ fit and 2HDM interpretation

$\Rightarrow$ can serve as consistent model for fully flexible fit of Higgs couplings

Effective Field Theory

Assumption: new physics is heavy

Classic example: μ decay $\rightarrow$ Fermi theory (t-channel W integrated out)



$$G_F = \frac{\sqrt{2}}{8}\frac{g^2}{m_W^2}$$

$\Rightarrow$ Effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4}\sum_i \frac{f_i^{(d)}}{\Lambda^{d-4}}\mathcal{O}_i^{(d)}$$

- operators $\mathcal{O}$ contain SM fields only
- respect SM gauge symmetries
- suppressed by $1/\Lambda^{d-4}$ (Λ: scale of new physics)
  $\rightarrow$ keep only leading order (lowest dimension $d = 6$)
- building blocks:
  - Higgs field Φ
  - (covariant) derivative ∂^μ, D^μ
  - field strength tensors $G^{\mu\nu}$, $W^{\mu\nu}$, $B^{\mu\nu}$
  - fermion fields ψ

Effective Operators for Higgs

Relevant operators for Higgs physics

[Buchmuller, Wyler; Hagiwara *et al.* ; Grzadkowski *et al.* ; Corbett *et al.* ; Pomarol *et al.* ; . . .]

[recent reviews: Wackeroth (ed.), MR *et al.* ; Englert, Freitas, Mühlleitner, Plehn, MR, Spira, Walz]

Higgs–gluon	$\mathcal{O}_{GG} = \phi^\dagger \phi \, \mathrm{tr}\{G^2\}$	SM Higgs phenomenology
Higgs–vector boson (1)	$\mathcal{O}_{\phi 1} = (D\phi)^\dagger \phi \phi^\dagger (D\phi)$ $\mathcal{O}_{\phi 4} = (D\phi)^\dagger (D\phi) \phi^\dagger \phi$	custodial symmetry violation
Higgs–vector boson (2)	$\mathcal{O}_{WW} = \phi^\dagger W^2 \phi, \quad \mathcal{O}_{BB}$ $\mathcal{O}_{BW} = \phi^\dagger BW\phi$ $\mathcal{O}_{W} = (D\phi)^\dagger W (D\phi), \quad \mathcal{O}_{B}$	SM Higgs decays $h \to \gamma\gamma, \gamma Z$ custodial symmetry violation
Higgs–fermion (1)	$\mathcal{O}_{LR} = (\phi^\dagger \phi)(\bar{L}\phi R)$ $\mathcal{O}_{LL1} = \phi^\dagger (i \overleftrightarrow{D} \phi)(\bar{L}\gamma L), \quad \mathcal{O}_{RR1}$ $\mathcal{O}_{LL3} = \phi^\dagger (i \overleftrightarrow{D}^a \phi)(\bar{L}\gamma \tau^a L)$	corrections to Yukawa couplings neutral current contributions neutral/charged current contributions
Higgs–fermion (2)	$\mathcal{O}_{\phi B} = \phi \bar{L} (\sigma B) R, \quad \mathcal{O}_{\phi W}, \quad \mathcal{O}_{\phi G}$	electric/magnetic moments
Higgs self-coupling	$\mathcal{O}_{\phi 2} = \frac{1}{2} \lvert \partial(\phi^\dagger \phi) \rvert^2$ $\mathcal{O}_{\phi 3} = \frac{1}{3} \lvert \phi^\dagger \phi \rvert^3$	weak boson fusion, decays $h \to VV$ Higgs self-interactions

$\leftrightarrow$ equations of motion

$\to$ different operators may lead to same physics

$\leftrightarrow$ electro-weak precision observables from LEP

$\to$ some operators strongly constrained

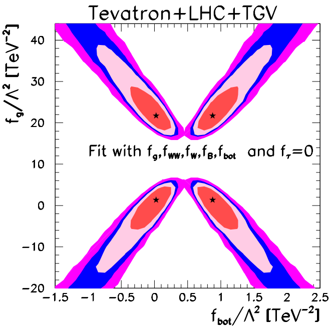
$\to$ relevant operator basis

$$\mathcal{O}_{GG}, \quad \mathcal{O}_{WW}, \quad \mathcal{O}_{BB}; \quad \mathcal{O}_{\phi 2}, \quad \mathcal{O}_{\phi 3}; \quad \mathcal{O}_{LR}(f)$$

EFT in Higgs Sector

[Corbett, Eboli, Gonzalez-Fraile, Gonzalez-Garcia]

Allowed regions at 68%, 90%, 95% und 99% CL using ATLAS, CMS and Tevatron data as well as indirect constraints



stars: global minima
marginalization over undisplayed parameters

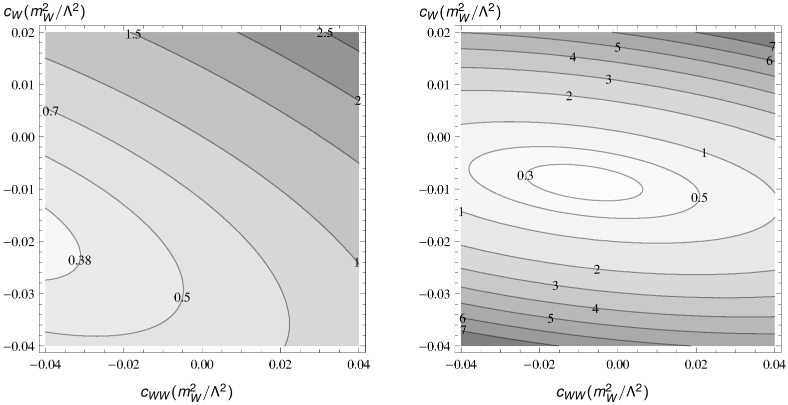
From Coupling Factors to Distributions

$\rightarrow$ need distributions to disentangle different operator structures contributing to the same Higgs vertex

[Biekötter, Knochel, Krämer, Liu, Riva; see also e.g. Ellis, Sanz, You]

$\sigma/\sigma_{\text{SM}}$ ($pp \rightarrow WH$)

incl. c.s. | $p_T > 200$ GeV



Future Precision

What to expect for Higgs couplings in the future?

[Snowmass report; Englert, Freitas, Mühlleitner, Plehn, MR, Spira, Walz]

Scenarios:

- LHC / high-luminosity (HL) LHC: 14 TeV, $\int \mathcal{L}$ = 300 / 3000 fb^{-1}
- e^+e^- linear collider (LC)/ HL-LC:
  250+500 GeV/250+500 GeV+1 TeV, $\int \mathcal{L}$ = 250+500 fb^{-1}/1150+1600+2500 fb^{-1}
  (other e^+e^- collider scenarios comparable in first approximation)

coupling	LHC	HL-LHC	LC	HL-LC	HL-LHC + HL-LC
hWW	0.09	0.08	0.011	0.006	0.005
hZZ	0.11	0.08	0.008	0.005	0.004
htt	0.15	0.12	0.040	0.017	0.015
hbb	0.20	0.16	0.023	0.012	0.011
$h\tau\tau$	0.11	0.09	0.033	0.017	0.015
$h\gamma\gamma$	0.20	0.15	0.083	0.035	0.024
hgg	0.30	0.08	0.054	0.028	0.024
h_{invis}	—	—	0.008	0.004	0.004

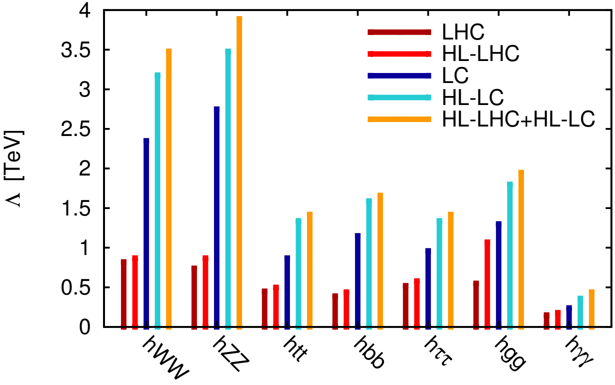
deviations on Higgs couplings, accuracy at 68% CL

Effective New Physics Scales

[Englert, Freitas, Mühlleitner, Plehn, MR, Spira, Walz]

Effective new-physics scales Λ^* extracted from coupling measurements

$\Delta_V = -\frac{v^2}{2\Lambda^2} f'_{\phi 2} \quad \rightarrow \quad 2\frac{v^2}{2\Lambda_*^2[V_m]}$, etc.



Conclusions

- Great confidence that “a Higgs particle” has been found
  $\rightarrow$ spin-1 / spin-2 alternatives excluded
  $\Rightarrow$ Look for deviations in couplings
- Models:
  - SM plus free Higgs couplings
    assumes operator structure equal to SM
  - Effective Field Theory with dimension-6 operators
    allows for different operator structure
    $\rightarrow$ differential distributions (not used yet)

  good agreement with SM expectation
- Future:

  Prospects for LHC (300 or 3000 fb^{-1}) look good
  Limited by exp. systematics and theory errors

  high-precision analysis at lepton collider possible
  $\rightarrow$ per mill range for many couplings

$\Rightarrow$ Precise test of new-physics contributions possible

Karlsruher Institut für Technologie

Backup

SFitter

Algorithms:

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

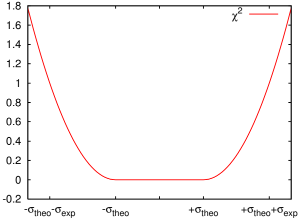
[Lafaye, Plehn, MR,Zerwas]

[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:

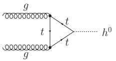
- fully-dimensional log-likelihood map
- one- and two-dimensional distributions via
  - marginalization (Bayesian)
  - profile likelihood (Frequentist)
- list of best points

Higgs Production Channels

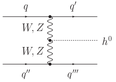
Where have we been looking?

Main production channels of Higgs boson:

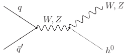
- gluon gluon fusion



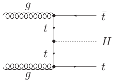
- vector boson fusion

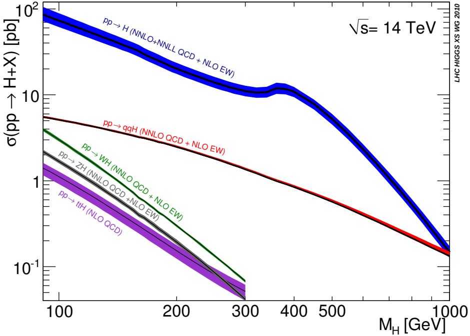


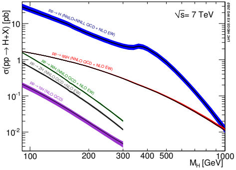
- associated production with gauge bosons



- associated production with top-quark–anti-quark pair



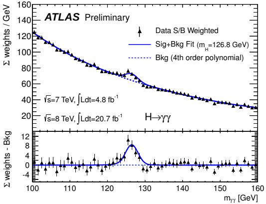


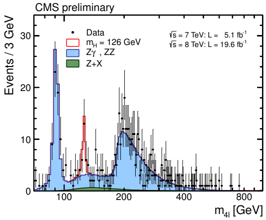


Higgs decay modes

- $H \to \gamma\gamma$
  - loop-induced coupling by (mainly) W and t
  - small branching ratio ($\lesssim 0.2\%$)
  - clear peak, background can be subtracted via sidebands
  - Higgs mass measurement up to 100 MeV
- $H \to ZZ$
  - "Golden Channel" due to four-lepton final state
- $H \to WW$
- $H \to \tau\bar{\tau}$
  - need to reconstruct invariant mass of the two taus $\to$ most sensitivity from vector-boson fusion
- $H \to b\bar{b}$
  - main decay mode for light Higgs bosons
  - hard to extract from QCD backgrounds
  - WH/ZH production with boosted kinematics plus possibly jet substructure analysis looks promising

[Butterworth, Davison, Rubin, Salam]





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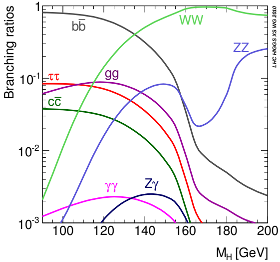
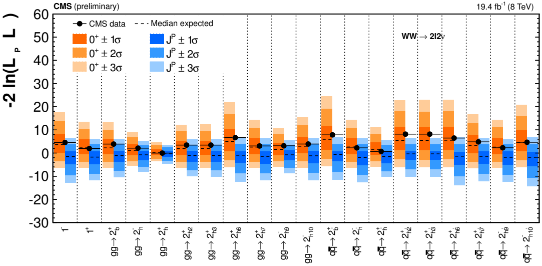
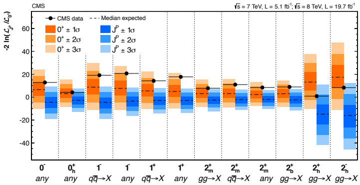


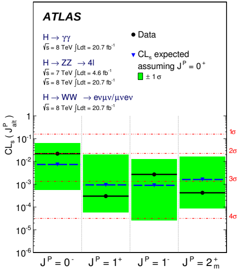
$\to$ 126 GeV ideal value for testing different modes

Spin and CP-Properties



other Spin-CP combinations disfavoured at 3 σ level





Parametrization

Definition of scaling factors:

- scale SM Higgs couplings to particle i with additional factor κ_i
  $\rightarrow g_i = \kappa_i \cdot g_i^{\text{SM}} \quad \equiv c_i \cdot g_i^{\text{SM}} \equiv (1 + \Delta_i) \cdot g_i^{\text{SM}}$
- 5 relevant couplings at tree-level: W, Z, t, b, τ
- κ for 2nd-generation fermions equal to corresponding 3rd-generation one
  (i.e. $\kappa_c \equiv \kappa_t$, unless explicitly stated otherwise)
- loop-induced couplings: gg, $\gamma\gamma$, $Z\gamma$
  - deviations induced by changes in tree-level couplings
  - new physics contribution can appear at same loop-order as SM
    $\rightarrow$ allow for additional contributions

slight difference: [SFitter; Cacciapaglia *et al.*]

κ_γ does not disentangle effects
from changes in tree-level couplings and new-physics contributions in loops

$\Rightarrow$ Define e.g. $\kappa_\gamma = 1 + \Delta_\gamma^{\text{SM}} + \Delta_\gamma$

Parametrization (cont.)

Possible solutions:

- measure only ratios of κ_i $\quad (\lambda_{ij} = \frac{\kappa_i}{\kappa_j})$
- assume no new decay modes
- $\kappa_W \leq 1$, $\kappa_Z \leq 1$; due to $\Gamma_i > 0$
  $\Rightarrow$ lower and upper bounds on κ_i
  depends on accuracy of $\kappa_b \Rightarrow$ practical relevance?
- build lepton collider

Scenarios

Fitting all possible couplings (κ_W, κ_Z, κ_t via GF, κ_b, κ_τ, κ_γ)
(κ_t via $t\bar{t}H$ and κ_g via GF not possible at the moment – $t\bar{t}H$ not yet sensitive)

Specific scenarios defined

- Common scale factor $\boxed{\kappa}$
  $\kappa = \kappa_t = \kappa_b = \kappa_\tau = \kappa_W = \kappa_Z$
- Scaling of vector boson and fermion couplings $\boxed{\kappa_V, \kappa_f}$
  $\kappa_V = \kappa_W = \kappa_Z, \quad \kappa_f = \kappa_t = \kappa_b = \kappa_\tau$
- Probing custodial symmetry $\boxed{\kappa_Z, \lambda_{WZ}, \kappa_f}$
  $\kappa_f = \kappa_t = \kappa_b = \kappa_\tau$
- ...

Relation to full models

Coupling shifts break renormalizability

- QCD corrections factorize $\rightarrow$ still applicable
- electro-weak corrections small ($\mathcal{O}(5\%)$)

$\rightarrow$ not relevant at the present stage

Two-scale problem:

- first scale (125 GeV): light Higgs
- second scale: UV completion

$\rightarrow$ effective theory between first and second scale

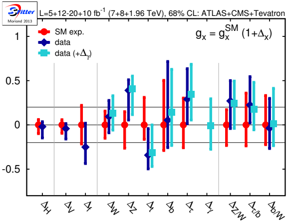
like all effective theories

if significant deviations established $\rightarrow$ look for full model

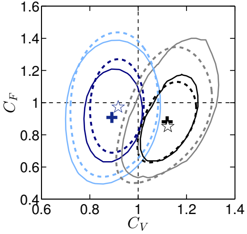
$\leftrightarrow$ Interpretation of Δ in terms of full model possible . . .

Theory Fit Combinations

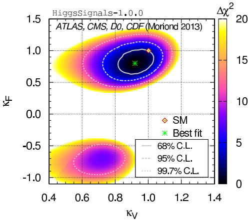
Fits using Moriond/Aspen 2013 results or later



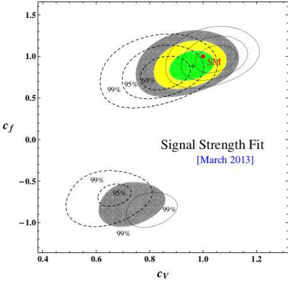
[Plehn, MR, Klute, Lafaye, Zerwas]



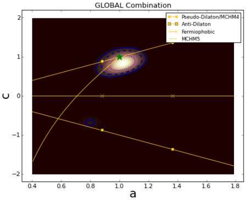
[Belanger *et al.*]



[HiggsSignals]



[Djouadi, Moreau]



[Ellis, You]

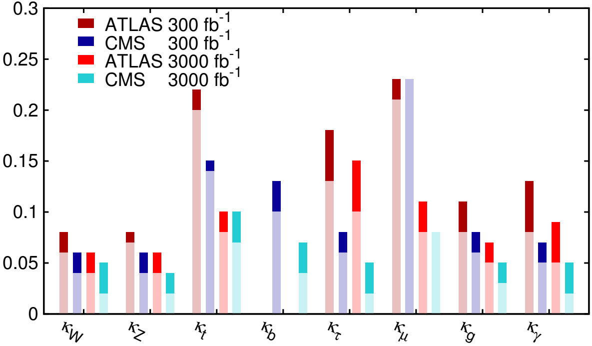
[for earlier fits see also
Carmi *et al.* ; Azatov *et al.* ;
Mühlleitner *et al.* ; Giardino *et al.* ;
Ellis *et al.* ; Farina *et al.* ; . . .]

Extrapolations – LHC

What to expect from the LHC in the future?

Precision on κ:

[ATLAS/CMS; own compilation]



dark shading:
current syst/theo unc.

light shading:
ATLAS: no theo unc.
CMS: theo unc./2,
syst unc./$\sqrt{L}$

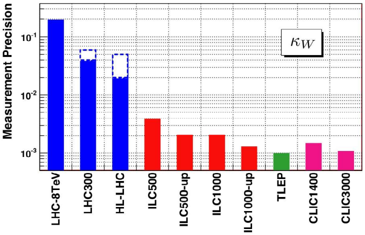
cf. expected deviation in BSM models: $\mathcal{O}(5-10\%)$ [Gupta, Rzehak, Wells]

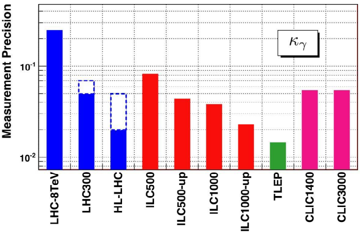
Difficult question – requires many assumptions:

- detector performance – pile-up, efficencies, . . .
- theory progress – higher-order corrections, PDFs, . . .
- new analysis channels

Coupling Precision from Lepton Colliders

[Snowmass Higgs working group report]





Significant improvements expected from lepton colliders

Again: improvement from theory side necessary
(plots assume 0.1% error on BR
$\leftrightarrow$ LHC HXSWG values in few percent range)

Combining LHC and Lepton Colliders

[Snowmass Higgs working group report]
[Input: exp. groups, Combination: SFitter]

coupling	LHC +ILC	HL-LHC +ILC	LHC +ILC Lumi-up	HL-LHC +ILC Lumi-up	HL-LHC +CLIC	HL-LHC +ILC Lumi-up +CLIC	HL-LHC +TLEP +CLIC
Γ_H	2.0 — 2.0%	1.9 — 2.0%	1.1 — 1.1%	1.1 — 1.1%	4.4 — 7.3%	0.9 — 1.0%	1.1 — 1.2%
BR_{inv}	0.8 — 0.8%	0.8 — 0.8%	0.4 — 0.4%	0.4 — 0.4%	2.2 — 3.9%	0.4 — 0.4%	0.5 — 0.5%
κ_γ	2.4 — 2.7%	1.4 — 2.5%	2.0 — 2.2%	1.3 — 2.0%	1.8 — 3.4%	1.2 — 2.0%	1.2 — 1.6%
κ_g	1.3 — 1.3%	1.2 — 1.3%	0.8 — 0.8%	0.8 — 0.8%	1.3 — 2.0%	0.6 — 0.6%	0.6 — 0.6%
κ_W	0.5 — 0.5%	0.4 — 0.5%	0.3 — 0.3%	0.3 — 0.3%	1.1 — 1.9%	0.3 — 0.3%	0.3 — 0.3%
κ_Z	0.6 — 0.6%	0.5 — 0.6%	0.3 — 0.3%	0.3 — 0.3%	1.1 — 1.9%	0.3 — 0.3%	0.3 — 0.3%
κ_μ	13.8 — 14.2%	8.0 — 9.2%	9.9 — 9.9%	7.0 — 7.8%	5.2 — 6.0%	4.6 — 4.7%	4.0 — 4.1%
κ_τ	1.5 — 1.6%	0.9 — 1.4%	0.9 — 0.9%	0.7 — 0.9%	1.3 — 2.3%	0.7 — 0.8%	0.5 — 0.6%
κ_c	1.6 — 1.6%	1.5 — 1.6%	0.9 — 0.9%	0.9 — 0.9%	1.4 — 2.1%	0.7 — 0.7%	0.7 — 0.7%
κ_b	0.8 — 0.8%	0.8 — 0.8%	0.5 — 0.5%	0.5 — 0.5%	1.1 — 1.9%	0.3 — 0.3%	0.4 — 0.4%
κ_t	2.8 — 2.9%	2.4 — 2.6%	1.9 — 1.9%	1.7 — 1.8%	3.5 — 4.5%	1.7 — 1.8%	3.2 — 3.8%
Δ_γ	2.5 — 2.8%	1.8 — 2.6%	2.0 — 2.2%	1.5 — 2.1%	2.8 — 4.6%	1.4 — 2.0%	1.7 — 2.0%
Δ_g	3.8 — 3.8%	3.3 — 3.6%	2.5 — 2.5%	2.3 — 2.4%	4.1 — 4.8%	2.1 — 2.3%	4.0 — 4.7%

range: LHC systematic & theory errors improved or at current level

Precise determination of Higgs couplings possible
$\rightarrow$ per mill range for many

$\rightarrow$ allows testing for BSM physics

Effective New Physics Scales

Effective new-physics scales Λ^* extracted from coupling measurements

$$\mathcal{O}_{LR} = (\phi^\dagger\phi)(\bar{L}\phi R)$$
$$\mathcal{O}_{\phi 2} = \tfrac{1}{2}|\partial(\phi^\dagger\phi)|^2$$
$$\mathcal{O}_{GG} = \phi^\dagger\phi\,\mathrm{tr}\{G^2\}$$
$$\mathcal{O}_{WW} = \phi^\dagger W^2\phi$$
$$\mathcal{O}_{BB} = \phi^\dagger B^2\phi$$

equations of motion:

$$\mathcal{O}_{\phi 4} = -\mathcal{O}_{\phi 2} + \frac{1}{2}\sum_{\ell,q}(y\,\mathcal{O}_{LR} + \text{h.c.}) - \frac{1}{2}\frac{\partial V(h)}{\partial h}$$
$$\mathcal{O}_B = -\frac{1}{2}\mathcal{O}_{BW} - \frac{1}{2}\mathcal{O}_{BB} - \frac{g'^2}{2}\mathcal{O}_{\phi 1} + \frac{g'^2}{4}\mathcal{O}_{\phi 2} - \frac{g'^2}{4}\sum_{\ell,q}(Y_L\mathcal{O}_{LL1} + Y_R\mathcal{O}_{RR})$$
$$\mathcal{O}_W = -\frac{1}{2}\mathcal{O}_{BW} - \frac{1}{2}\mathcal{O}_{WW} - \frac{g^2}{2}\mathcal{O}_{\phi 4} + \frac{g^2}{4}\mathcal{O}_{\phi 2} - \frac{g^2}{8}\sum_{\ell,q}\mathcal{O}_{LL3}$$

apply to get $f \to f'$ with $f'_{\phi 4} = f'_B = f'_W = 0$

fermions : $$\Delta_f = -\frac{v^2}{2\Lambda^2}\frac{f'_{LR}}{y} \quad\to\quad \frac{v^2}{2\Lambda_*^2[f]}$$

WW, ZZ : $$\Delta_V = -\frac{v^2}{2\Lambda^2}f'_{\phi 2} \quad\to\quad 2\frac{v^2}{2\Lambda_*^2[V_m]}$$

gg : $$\Delta_g = -\frac{v^2}{2\Lambda^2}\frac{4\cdot 16\pi^2}{\zeta_g}f'_{GG} \quad\to\quad \frac{4}{\zeta_g}\frac{v^2}{2\Lambda_*^2[GG]}$$

$\gamma\gamma$: $$\Delta_\gamma = -\frac{v^2}{2\Lambda^2}\frac{2\cdot 16\pi^2}{\zeta_\gamma}\frac{f'_{BB}+f'_{WW}}{2} \quad\to\quad \frac{1}{\zeta_\gamma}\frac{v^2}{2\Lambda_*^2[WW/BB]}$$