Karlsruher Institut für Technologie

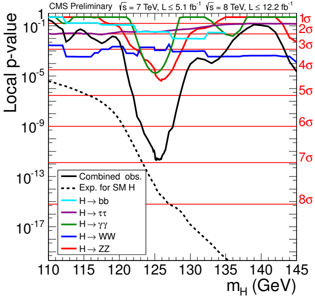
Current status of Higgs physics

Michael Rauch | Sep 8, 2014

INSTITUTE FOR THEORETICAL PHYSICS

Found a Resonance

Resonance at $\sim$ 126 GeV found

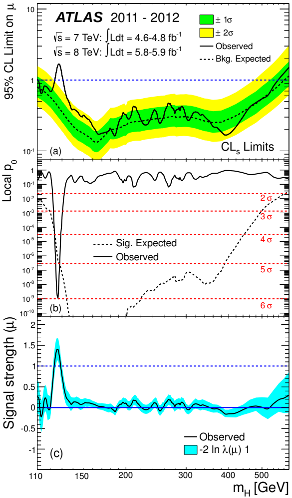


Assuming SM is correct, full theory:

⇒ Job done

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

↔ test predictions

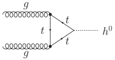


Higgs Production Channels

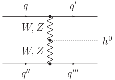
Where have we been looking?

Main production channels of Higgs boson:

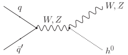
- gluon gluon fusion



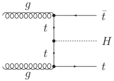
- vector boson fusion

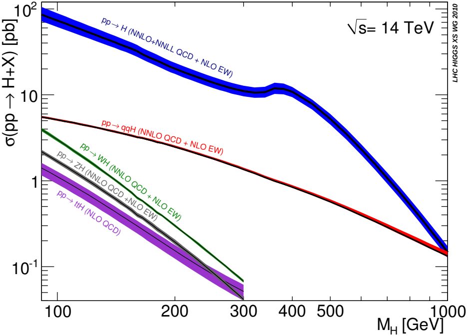


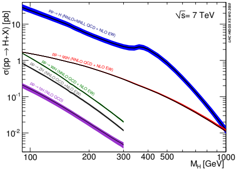
- associated production with gauge bosons



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



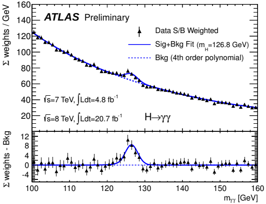


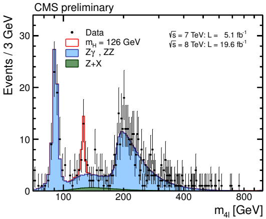


Higgs decay modes

- $H \to \gamma\gamma$
  - 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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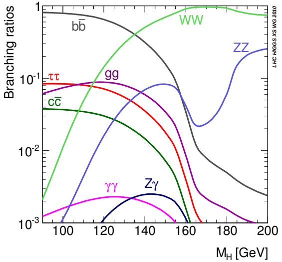


$\to$ 126 GeV ideal value for testing different modes

Properties of the Resonance

Characterize resonance [see e.g. Englert *et al.* , Artoisenet *et al.*]

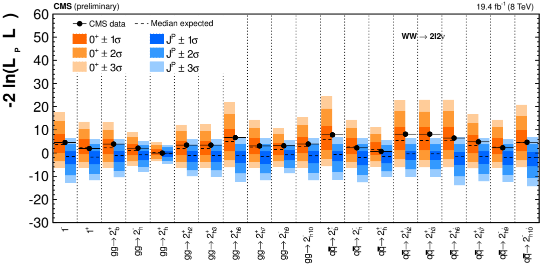
- Spin [Zeppenfeld *et al.* ; Choi *et al.* ; Godbole *et al.* ; Hagiwara, Mawatari, Li; Englert *et al.* ; Ellis *et al.* ; Frank, MR, Zeppenfeld; Alves; Boughezal *et al.* ; . . .]
  - spin-1 excluded by observing $H \to \gamma\gamma$ [Landau, Yang]
  - spin-2 disfavoured by exp. measurements ($\gtrsim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

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

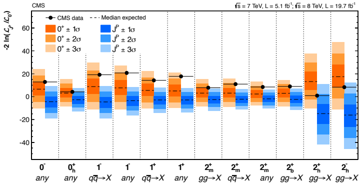
  a_3: CP-odd coupling – disfavoured by experiments

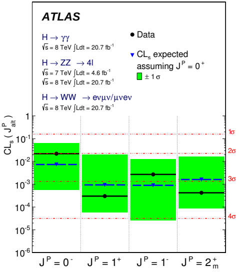
  $\leftrightarrow$ CP-odd Higgs (e.g. A^0 in 2HDM) a_3 contribution loop-induced
  CP-mixed Higgs: a_1 coupling to WW, ZZ proportional to CP-even admixture (up to loop effects)
  $\Rightarrow$ constrain CP-odd admixture [Djouadi, Moreau]

Spin and CP-Properties



other Spin-CP combinations disfavoured at 3 σ level





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  (up to loop effects)
  $\Rightarrow$ constrain CP-odd admixture [Djouadi, Moreau]
- Couplings

  $\rightarrow$ requires operator basis

Parametrizing Higgs Couplings

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

$\Rightarrow$ 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
  $\Rightarrow (\sigma \cdot \mathrm{BR})(ii \to H \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$
- tensor structure identical to SM

Parametrization

Definition of scaling factors:

- scale SM Higgs couplings to particle i with additional factor κ_i
  $\rightarrow g_i = \kappa_i \cdot g_i^{\mathrm{SM}} \quad \equiv c_i \cdot g_i^{\mathrm{SM}} \equiv (1 + \Delta_i) \cdot g_i^{\mathrm{SM}}$
- 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

$\rightarrow$ two options, κ_γ as example:

- $\kappa_\gamma = \kappa_\gamma(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H)$
  $\kappa_\gamma^2 = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma^{ij}_{\gamma\gamma}(m_H)}{\sum_{i,j} \Gamma^{ij}_{\gamma\gamma}(m_H)}$ fully determined from other parameters
  (analogously for cross sections: $\Gamma \rightarrow \sigma$)
- additional free parameter, to be determined

Parametrization (cont.)

- total width $\Gamma_H = \kappa_H^2 \, \Gamma_H^{\text{SM}} \quad = \Gamma_H(\Delta_i) + \Delta\Gamma \, \Gamma_H^{\text{SM}}$

  again two choices:

  - derived assuming no additional decay modes $\kappa_H^2(\kappa_i, m_H)$
  - Higgs can decay into BSM particles (invisible & unobserved decay modes, $\text{BR}_{\text{inv,undet}}$)
    $\rightarrow$ additional free parameter

Total width not directly measurable at LHC without assumptions

Additional decays into "invisible" final states possible
$\rightarrow$ can be compensated by global scaling of couplings

$$(\sigma \cdot BR)(ii \rightarrow H \rightarrow ff) = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} (\sigma \cdot BR)_{\text{SM}}$$

$\leftrightarrow$ Direct measurements of $\sigma_{\text{VBF, ZH}} \cdot BR(H \rightarrow \text{invisible})$

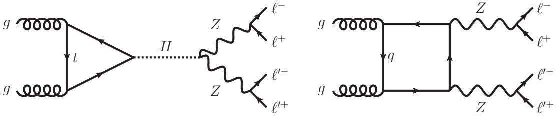
[Eboli, Zeppenfeld; Choudhury, Roy; Godbole, Guchait, Mazumdar, Moretti, Roy; Englert, Spannowsky, Wymant]

Does not account for decays into "unobserved" decay modes (e.g. light quarks)

$\leftrightarrow$ indirect determination from off-shell interference [Caola, Melnikov]

Higgs Width from Off-shell Measurements

Consider process $(pp \to) gg \to \ell^+\ell^-\ell'^+\ell'^-$:

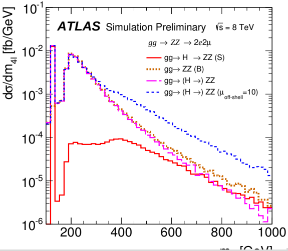


Contributions from Higgs resonance and continuum diagrams

- 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
  $c_1 \kappa^2 + c_2 \kappa^4$



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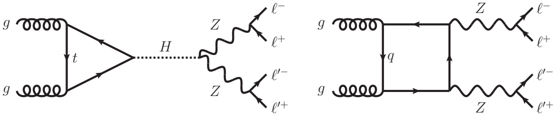

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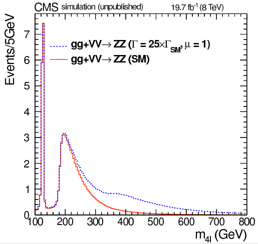
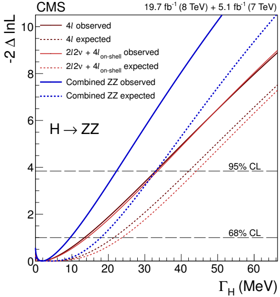


Higgs Width from Off-shell Measurements (cont.)

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

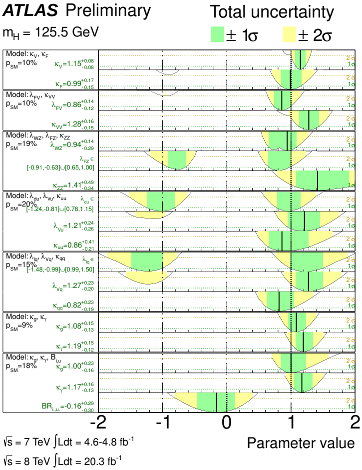
$(\Gamma_H^{\mathrm{SM}} = 4.1$ MeV)

Limitations:

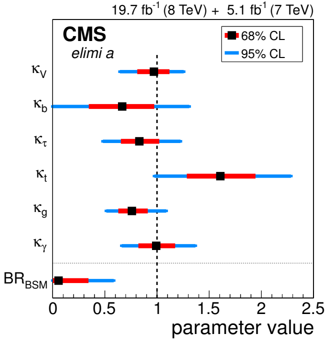
- higher-order corrections to continuum diagram unknown
  $\leftrightarrow$ large K-factor ~ 2 expected ($\rightarrow$ range in ATLAS results)
- new-physics effects can modify on-shell and off-shell region differently
  e.g. dim-6 operators like $Z_\mu Z^\mu \Box H$
  or additional scalars contributing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

$\Rightarrow$ not model-independent

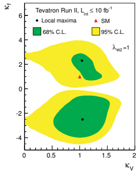
Experimental Results . . .



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

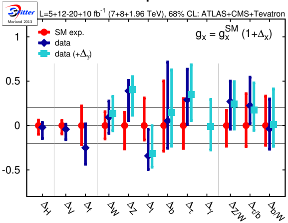


$$\mu = 1.00 \pm 0.09\ (\text{stat.})^{+0.08}_{-0.07}\ (\text{theo.}) \pm 0.07\ (\text{syst.})$$

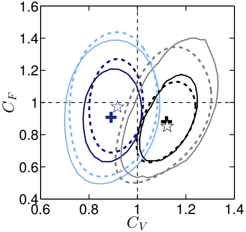


. . . and Theory Fit Combinations

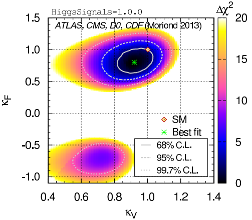
Moriond/Aspen 2013 results



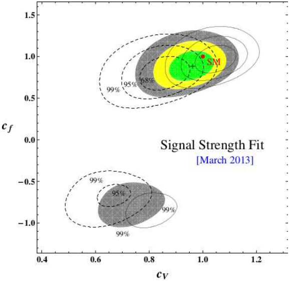
[Plehn, MR, Klute, Lafaye, Zerwas]



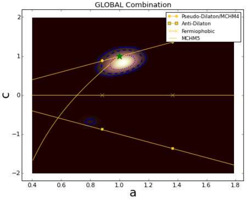
[Belanger *et al.*]



[HiggsSignals]



[Djouadi, Moreau]



[Ellis, You]

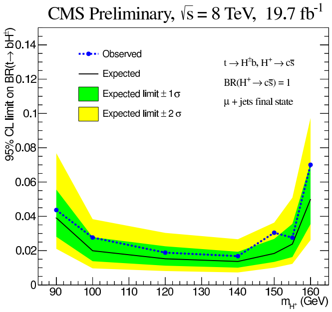
[for earlier fits see also
Carmi *et al.* ; Azatov *et al.* ;
Mühlleitner *et al.* ; Giardino *et al.* ;
Ellis *et al.* ; Farina *et al.* ; . . .]

Charged Higgs

Limits on charged Higgs production

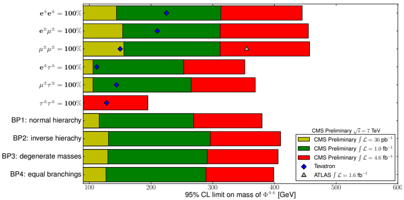
singly charged

only $t\bar{t}$, $t \to H^+ b$ at the moment



doubly charged

$H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$



Supersymmetric Models

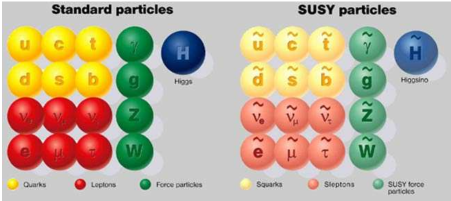
Symmetry between bosons and fermions:

$$Q\,|\text{boson}\rangle = |\text{fermion}\rangle\,; \qquad Q\,|\text{fermion}\rangle = |\text{boson}\rangle$$

Q: Supersymmetry Operator

Simplest model:
Minimal Supersymmetric Standard Model (MSSM)

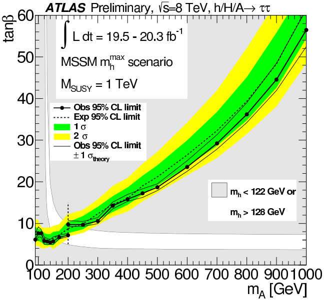
- Supersymmetric partner to each Standard Model particle
- Two Higgs doublets $\Rightarrow$ 5 Higgs bosons (h^0,H^0,A^0,$H^\pm$)
- Particles with same quantum numbers mix
  (e.g. Zino, Photino, 2 Higgsino $\to$ 4 Neutralino)

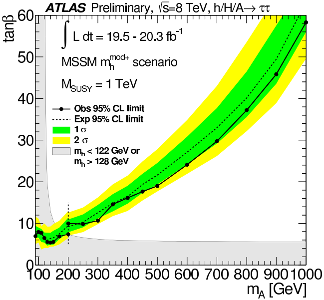


Supersymmetric Models

Higgs sector of the MSSM:

- at leading order described by two parameters:
  m_A (CP-odd Higgs) and $\tan\beta$ (ratio of Higgs doublet vevs)
- typically 1 SM-like Higgs boson (h^0)
  $M_{h^0} \lesssim 140$ GeV ($\lesssim M_Z$ at tree-level + loop corrections) $\Rightarrow$ 125 GeV fine
  $\leftrightarrow$ significant loop corrections needed $\rightarrow$ large mass splitting for top partners
- $\tan\beta$ can be large
  $\rightarrow$ bbh^0 and $\tau\tau h^0$ couplings enhanced: $\sim \tan\beta$
  $\rightarrow$ limits from non-observation



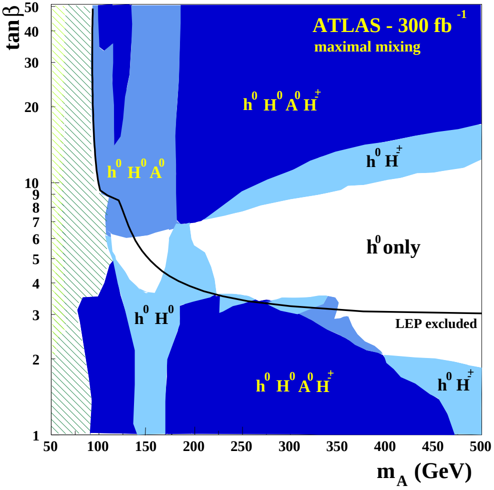


$\leftrightarrow$ SUSY models with extended Higgs sectors (e.g. NMSSM)

Discovery Potential

Discovery potential for supersymmetric Higgs bosons

[ATLAS 2009]



Composite Higgs Boson

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[Kaplan, Georgi; Dimopoulos *et al.* ; Dugan *et al.*]

- bound state from a strongly interacting sector not much above weak scale
- light composite Higgs:
  Pseudo-Goldstone boson of strongly interacting sector

  $$\text{Global symmetry of strong sector } \mathcal{G} \xrightarrow{\text{spontaneously broken at scale } f} \text{sub-group } \mathcal{H}_1$$

  $\mathcal{G}/\mathcal{H}_1$ contains Higgs as Goldstone boson
- interpolation between SM and Higgsless models
  define parameter

  $$\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong interaction scale})^2}$$

  $\xi = 1$ ($f \to \infty$): SM limit, strong sector decouples
  $\xi = 0$ ($f = v$): "Technicolor" limit, "Higgs" boson decouples

Composite Higgs Boson

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- Low-energy description:
  strongly interacting light Higgs (SILH) Lagrangian for $\xi \ll 1$
  ($\leftarrow$ electro-weak precision tests)
- Explicit models: Minimal Composite Higgs Models (MCHM) based on SO(5)/SO(4) coset, e.g.
  - MCHM4 (fermions in spinorial represenation of SO(5)):

    Scaling of all couplings with $\sqrt{1-\xi}$
  - MCHM5 (fermions in fundamental representation of SO(5)):

    Scaling:

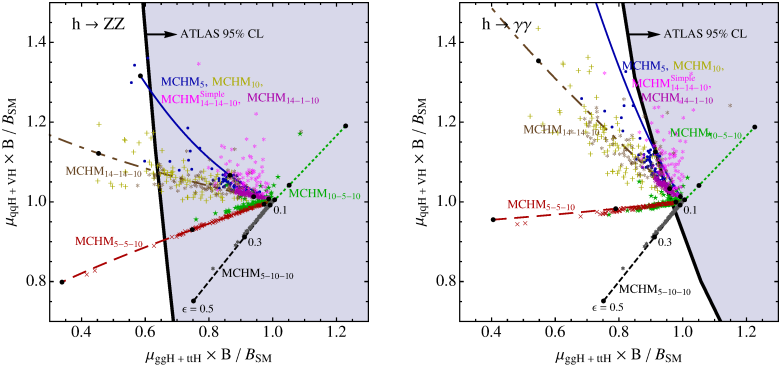
    $g_{VVH} = g_{VVH}^{\mathrm{SM}} \cdot \sqrt{1-\xi}$

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

Composite Higgs Boson

[Carena, Da Rold, Ponton]

considering many different fermion representations
+ effects from first strong-sector resonance
($\epsilon \equiv \xi$)



⇒ Parameter space reduced by measurements

↔ no global fit by exp. groups yet

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)

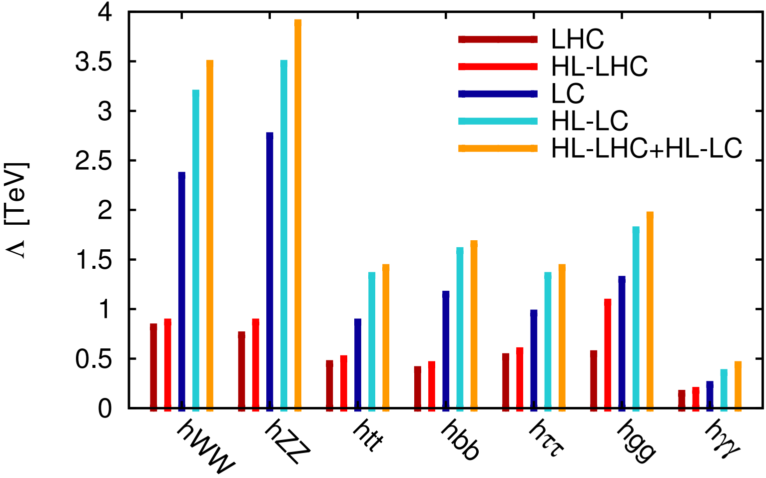
coupling	LHC	HL-LHC	LC	HL-LC	HL-LHC + HL-LC
hWW	0.09	0.08	0.011	0.006	0.005
hZZ	0.11	0.08	0.008	0.005	0.004
htt	0.15	0.12	0.040	0.017	0.015
hbb	0.20	0.16	0.023	0.012	0.011
$h\tau\tau$	0.11	0.09	0.033	0.017	0.015
$h\gamma\gamma$	0.20	0.15	0.083	0.035	0.024
hgg	0.30	0.08	0.054	0.028	0.024
h_{invis}	—	—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



Composite Higgs Scenarios

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

Future precision for composite Higgs scenarios

expressed in terms of strong-sector scale f and $\xi = \frac{v}{f}$

ξ	LHC	HL-LHC	LC	HL-LC	HL-LHC+HL-LC
MCHM4	0.076	0.051	0.008	0.0052	0.0052
MCHM5	0.068	0.015	0.0023	0.0019	0.0019
f [TeV]					
MCHM4	0.89	1.09	2.82	3.41	3.41
MCHM5	0.94	1.98	5.13	5.65	5.65

$\Rightarrow$ Testing up to high mass values possible

Conclusions

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- Great confidence that "a Higgs particle" has been found
  $\rightarrow$ spin-1 / spin-2 alternatives excluded
  $\Rightarrow$ Look for deviations in couplings
- Model: SM plus free Higgs couplings
  assumes operator structure equal to SM
  good agreement with SM expectation
- Results putting constraints on BSM models
  $\rightarrow$ next talk
- 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

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 . . .

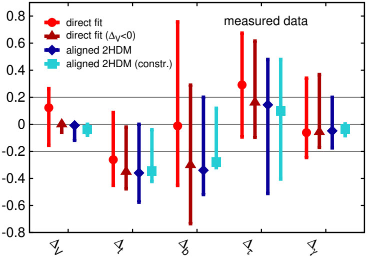
2HDM interpretation

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

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



Direct mapping between 2HDM parameters and Δ possible

Constraints:

- $|1+\Delta_V| < 1$
  due to sum rule $\sum_i g^2_{VVh_i^0} = g^2_{VVH_{SM}}$
  $\rightarrow$ 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

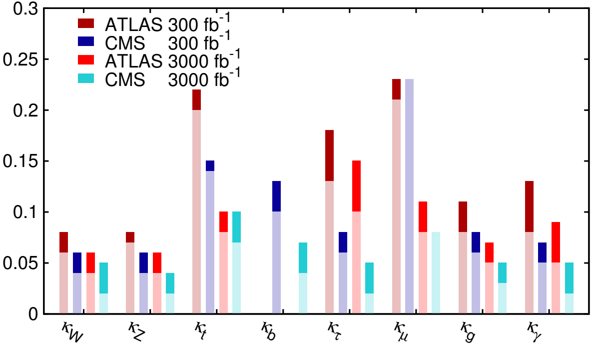
$\rightarrow$ Good agreement between constrained Δ fit and 2HDM interpretation
$\Rightarrow$ can serve as consistent model for fully flexible fit of Higgs couplings

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./$\sqrt{L}$

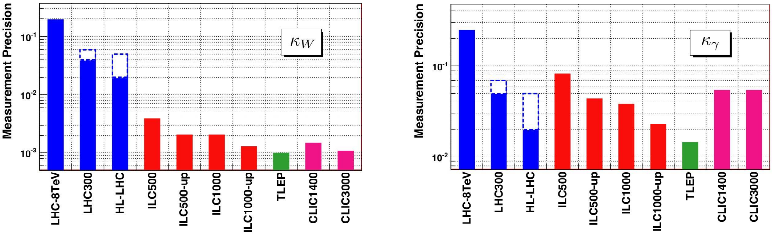
cf. expected deviation in BSM models: $\mathcal{O}(5-10\%)$ [Gupta, Rzehak, Wells]

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
→ per mill range for many

→ allows testing for BSM physics