





Higgs Combination

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Introduction

- After the discovery, emphasis at LHC shifted towards measurement of properties of the new particle
- Statistical uncertainty reduced by combining two experiments

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[hep-ex]

arXiv:1606.02266v1

Higgs mass paper PRL 114 (2015) 191803



Higgs coupling paper arXiv:1606.02266

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN) With the second seco

Combined ATLAS and CMS measurements of the Higgs boson production and decay rates, as well as constraints on its couplings to vector bosons and fermions, are presented. The combination is based on the analysis of five production processes, namely gluon fusion, vector boson fusion, and associated production with a W or a Z boson or a pair of top quarks, and of the six decay modes $H \rightarrow ZZ$, WW, $\gamma\gamma$, τ , bh, and $\mu\mu$. All results are reported assuming a value of 125.09 GeV for the Higgs boson mass, the result of the combined measurement by the ATLAS and CMS experiments. The analysis uses the CERN LHC proton-proton collision data recorded by the ATLAS and CMS experiments of 12011 and 2012, corresponding to integrated luminosities per experiment of approximately 5 fb⁻¹ at $\sqrt{s} = 7$ TeV and 20 fb⁻¹ at $\sqrt{s} = 8$ TeV. The Higgs boson mass, and decay rates measured by the two experiments are combined within the context of three generic parameterisations: two based on cross sections and branching fractions, and one on ratios of coupling modifiers. Several interpretations of the measurements tilt who remodel-dependent parameterisations rare of the 20 fb⁻¹ at 0.11. The combined signal yield relative to the Standard Model prediction is measured to this 04 ± 01.11 the combined reasons for the vector boson fusion production process and for the $H \rightarrow \tau \tau$ decay of 5.4 and 5.5 standard work of predictions for all parameterisations considered.





Combination Input

Based on the inputs to the separate CMS and ATLAS combinations: the main **five decay channels + ttH analyses**

	Untagged	VBF	VH	ttH
Н→үү	✓	✓	✓	✓
H→ZZ→4I	✓	✓	✓	✓
H→WW→2l2v	✓	✓	✓	✓
Η→ττ	✓	✓	✓	✓
H→bb			✓	✓
Н→μμ	✓	✓		

- $H \rightarrow \mu \mu$ only included for one particular result
- Each analysis targeting a particular production/decay mode may also consider contributions from other processes that are not specifically targeted, e.g.
 H→WW entering H→ττ analysis, single-top + Higgs production in ttH

Statistics

• Workhorse of the combination is the **profile likelihood ratio**, Λ

 $\vec{\alpha} = \text{Set of POIs at some}$ fixed values to be tested $\vec{\theta} = \text{Nuisance parameters}$ $\Lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}, \vec{\theta}(\vec{\alpha}))}{L(\vec{\alpha}, \vec{\theta})}$ Values of $\vec{\theta}$ that maximise the likelihood given the fixed values of $\vec{\alpha}$ being tested (conditional estimate)
Values of $\vec{\alpha}$ and $\vec{\theta}$ that globally maximise the likelihood (unconditional estimate)

- Exploit the **asymptotic limit**:
 - Test statistics $q(\vec{\alpha}) = -2 \ln (\Lambda(\vec{\alpha}))$ is assumed to follow a χ^2 distribution with $\vec{\alpha}$ degrees of freedom
 - To determine a confidence-level (CL) interval for a single parameter α , we only need to find the values of α where $q(\alpha) = \text{the } \chi^2$ critical value for that CL, e.g. 1D 68% CL at $q(\alpha) = 1.00$

Technical Challenges

- Fit convergence: ~4300 nuisance parameters
 - Minuit handles such fits surprisingly well, few tricks used to reduce the time needed for convergence
- Memory usage: ~4-5GB needed for combination
- Fitting time:
 - **0.5-1 hours per combined fit** thanks to significant low-level optimizations in the likelihood evaluation
 - Each best-fit value + uncertainties from scan of ~ 40 points
 - Total number of fits = 150 (POIs) * 40 (points) * 2 (observed, asimov)
 - + ~10 2D scans requiring 1600 fits each
 - Total CPU time ~ 12000 hours

Higgs mass

and 95% CL contours

[GeV] ATLAS+CMS combination on m, = 173.34 GeV 80.5 fit w/o M_w and m, measurements σ = 0.76 GeV - σ = 0.76 ⊕ 0.50_{then} GeV fit w/o M_w , m, and M_H measurements mass measurement with direct M,,, and m, measurements 80.45 high-resolution channels: $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ \rightarrow 4I$ 80.4 Self-consistency test of SM M_w world comb. $\pm 1\sigma$ 80.35 M_w = 80.385 ± 0.015 GeV parameters 80.3 Precise calculation XS•BR 1=125.14 GeV 80.25 150 160 170 180 190 140 m, [GeV] ATLAS and CMS **⊢**•–|Total Syst. Stat. LHC Run 1 Total Stat. Syst. **m**_н= ATLAS $H \rightarrow \gamma \gamma$ 126.02 ± 0.51 (± 0.43 ± 0.27) GeV 124.70 ± 0.34 (± 0.31 ± 0.15) GeV **CMS** $H \rightarrow \gamma \gamma$ 125.09 ± 0.24 (± 0.21 ± 0.11) GeV 124.51 ± 0.52 (± 0.52 ± 0.04) Ge ATLAS $H \rightarrow ZZ \rightarrow 4l$ **CMS** $H \rightarrow ZZ \rightarrow 4l$ 125.59 ± 0.45 (± 0.42 ± 0.17) GeV Statistical uncertainty still ATLAS+CMS yy 125.07 ± 0.29 (± 0.25 ± 0.14) GeV dominates and can be ATLAS+CMS 41 125.15 ± 0.40 (± 0.37 ± 0.15) GeV ATLAS+CMS yy+4l further reduced in future $125.09 \pm 0.24 (\pm 0.21 \pm 0.11)$ GeV 123 126 124 125 127 128 129 m_H [GeV]

m. world comb. ± 10

Higgs rates & couplings

F

K

Signal parameterization

Signal strengths, µ

Parameters scale cross sections and **BRs relative to SM**

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\rm SM}} \qquad \mu^f = \frac{{\rm BR}^f}{{\rm BR}_{\rm SM}^f}.$$

Scaling of generic i \rightarrow H \rightarrow f process

$$\mu_i^f \equiv \frac{\sigma_i \cdot \mathbf{BR}^f}{(\sigma_i \cdot \mathbf{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

Couplings,
$$\kappa$$

Parameters scale cross sections and
partial widths relative to SM
 $\kappa_j^2 = \sigma_j / \sigma_j^{SM}$ $\kappa_j^2 = \Gamma_j / \Gamma_j^{SM}$
 $\sigma_i \cdot BR^f = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$,
Total width determined as
 $\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - BR_{BSM}}$
Where
 $\kappa_H^2 = \sum_j BR_{SM}^j \kappa_j^2$

Higgs production processes

Usual suspects:





H

W/Z

Κz

W/ZK

Rare processes:



Overall signal strength

Assumptions

- SM ratios of all cross sections and BRs
- 7/8 TeV ratios as in SM

 $\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07} \text{ (stat)} {}^{+0.04}_{-0.04} \text{ (expt)} {}^{+0.03}_{-0.03} \text{ (thbgd)} {}^{+0.07}_{-0.06} \text{ (thsig)}$

- For this, and other key measurements, break uncertainty down into 4 components:
 - statistical, experimental, background theory, signal theory
- All ~4300 NPs assigned to one of these groups
- Each component determined by fixing successive group of NPs to best-fit values θ̂ and repeating NLL scan



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- Useful for extrapolating results to higher luminosity and understanding what sources may limit future precision
- Signal theory uncertainty as large as statistical uncertainty
- However dominant parts will be reduced for Run 2:
 - N3LO ggH scale: 8% → 2-3%
 - New PDF4LHC: 7% → 2%



Signal strengths in each prod./decay



2.9

4.2

2.0

5.0

3.7

- ', Beijing)

2.3

3.5

4.4

5.5

2.6

VBF

WH

ZH

VH

ttH

 $H \rightarrow \tau \tau$

 $H \rightarrow bb$

Decay channel

H→ττ decay	y mode and	VBF process		
established through combination				

Signal strength ratios

- Assumptions: only the 7/8 ratios as in SM
- Normalize the rate for any particular channel to a reference process using ratios of cross sections and branching ratios
- Motivation:
 - No assumptions on relative cross sections or BRs
 - Measured values independent of SM prediction and inclusive theory uncertainties
 - Cancellation of common systematic uncertainties in ratios
- Choose reference process as one measured with the smallest systematic uncertainty: gg→H→ZZ

$$\sigma_i \cdot \mathrm{BR}^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}\right)$$



Signal strength ratios

- Largest disagreement in σ_{ttH}/σ_{ggF} (~3σ)
 - mainly due to the multilepton categories
- In this parameterization, the high values found for the production cross section ratios for the ZH and ttH processes induce a low value for the $H \rightarrow bb$ decay branching fraction because the $H \rightarrow bb$ decay mode does not contribute to the observed excesses.
- BR_{bb}/BR_{ZZ} (2.5σ)
 - Anti-correlated with above excess

$$\sigma_i \cdot \mathrm{BR}^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}\right)$$



Ratio of rates \rightarrow Ratio of couplings

Re-fit fewer couplings to actual particles as ratios to Z and gluon, $\lambda_{ij} = \kappa_i / \kappa_j$



Allowing for BSM loop/decay contributions

- Use effective couplings for ggH (κ_g) and H $\rightarrow \gamma\gamma$ (κ_γ)
- Consider two scenarios:
 - BR_{BSM} = o
 - BR_{BSM} floating, but $\kappa_w, \kappa_Z < 1$
- Care needed with BR_{BSM}: not just Higgs decays to new particles but also non-SM BRs to unmeasured final states, e.g. gg and cc





No BSM loop/decay contributions



- Resolve ggH (κ_g) and H $\rightarrow \gamma\gamma$ (κ_γ) loops
- Includes H→µµ analyses for reduced coupling vs. particle mass



2D scans of κ_V , κ_F

- Commonly-presented model in which
 - **K**_V=K_W=K_Z
 - $\kappa_{F} = \kappa_{t} = \kappa_{b} = k_{\tau}$
- Perform additional scans in a model with separate κ_V^{f} , κ_F^{f} per decay-mode
 - 10 parameter fit for 5 channels
- Here the best-fit is restricted to quadrant where κ_v>0, κ_F>0
- All channels compatible with $\kappa_V = \kappa_F = 1$



2D scans of κ_V , κ_F

• Most channels nearly degenerate in relative sign of κ_{V} and κ_{F}



2D scans of κ_V , κ_F

• Most channels nearly degenerate in relative sign of κ_V and κ_F



Fermion Couplings

- In MSSM / 2HDM Type II [κ_v, κ_d, κ_u], ratio of down-type (b, τ, μ) and uptype (t) fermion couplings is tested with ~10% precision
- No enhancement observed wrt SM, i.e. consistent with alignment limit



- In 2HDM Lepton-Specific [$\kappa_v, \kappa_{\mu}, \kappa_{q}$], ratio of lepton (τ, μ) and quark couplings (t, b) would be enhanced at large tan β
- Also good agreement with SM



Summary

- Run 1 Higgs mass precision < 0.2%
- A comprehensive combined measurement of ATLAS and CMS Higgs boson couplings has been performed
 - Precision usually better by ~1/√2 wrt single experiment
- Strong picture of overall consistency with SM expectations
 - Results given in a range of models based on either signal strength or coupling modifiers
- H→ττ decay mode and VBF process established through combination

Backup

Correlation Matrix



Mingshui Chen (IHEP, Beijing)

Correlation Matrix



Coupling Parameterization

			Effective	Resolved
Production	Loops	Interference	scaling factor	scaling factor
$\sigma(ggF)$	\checkmark	t–b	κ_q^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\text{VBF})$	_	_	·	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	_	_		κ_W^2
$\sigma(qq/qg \rightarrow ZH)$	_	_		κ_Z^2
$\sigma(gg \to ZH)$	\checkmark	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	_	-		κ_t^2
$\sigma(gb \to tHW)$	_	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qq/qb \rightarrow tHq)$	_	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
σ (bbH)	_	-		κ_b^2
Partial decay width				
ΓΖΖ	_	_		κ _Z ²
Γ^{WW}	_	_		κ_W^2
$\Gamma^{\gamma\gamma}$	\checkmark	t–W	κ_{γ}^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{ au au}$	_	_		κ_{τ}^2
Γ^{bb}	_	_		κ_{h}^{2}
$\Gamma^{\mu\mu}$	_	_		κ_{μ}^{2}
Total width ($B_{BSM} =$	0)			
				$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_a^2 +$
Γ_H	\checkmark	_	κ_{H}^{2}	$0.06 \cdot \kappa_{\tau}^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$
			**	$0.0023 \cdot \kappa_{\gamma}^2 + 0.0016 \cdot \kappa_{(Z_{\gamma})}^2 +$
				$0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_u^2$

8/22/16

Ratio of couplings

