

# Combinations of results of Higgs boson production at the LHC (production rates, couplings)

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on behalf of the ATLAS and CMS collaborations

## Combinations

- **No current combination** of CMS and ATLAS results with the full run 1 dataset  $\rightarrow$  scheduled for **Fall 2014**
- **In this talk:** Combinations of results in various search channels for the **two experiments separately**

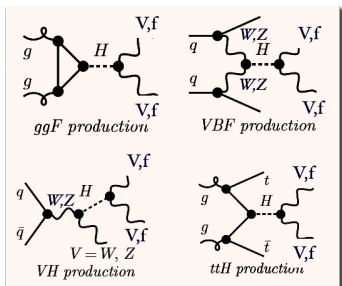
### • ATLAS:

- Combinations of coupling measurements using  $25 \text{ fb}^{-1}$  of pp-collisions - *March 2014* comparison with older CMS results
- Constraints on New Phenomena - *March 2014*

### • CMS:

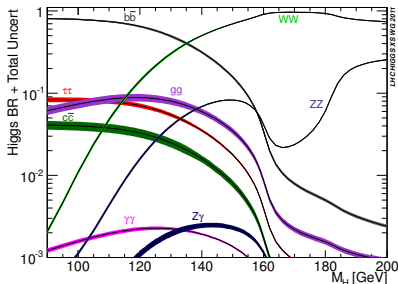
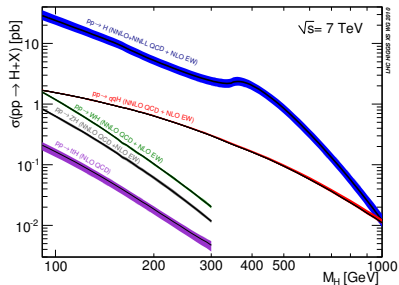
- Final Results from  $H \rightarrow ZZ \oplus WW$  - *December 2013*
- Constrains on the Higgs boson width,  $H \rightarrow ZZ \rightarrow 4\ell$ ,  $H \rightarrow ZZ \rightarrow 2\ell 2\nu$  - *March 2014*

# Overview



	$H \rightarrow \gamma\gamma$	$H \rightarrow WW$	$H \rightarrow ZZ$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau\tau$
$ggF$	⊗/⊙	⊗/⊙	⊗/⊙		⊗/⊙
$VBF$	⊗/⊙	⊗/⊙	⊗/⊙	⊙	⊗/⊙
$VH$	⊗/⊙	⊗/⊙	⊗/⊙	⊗/⊙	⊗/⊙
$ttH$	⊗/⊙	⊙	⊙	⊗/⊙	⊙

⊗ = ATLAS, ⊙ = CMS



# Mass of the Higgs-Boson

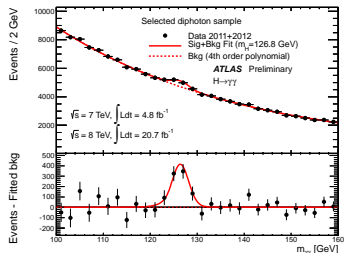
## ATLAS:

- $m_H^{\gamma\gamma+4\ell} = 125.5 \pm 0.2(\text{stat})_{-0.6}^{+0.5}(\text{sys}) \text{ GeV}$
- $\Delta m_H = 2.4_{+0.6}^{-0.7}(\text{stat}) \pm 0.6(\text{sys}) \text{ GeV}$
- Energy scale calibration  $\oplus$  systematics under **re-evaluation** (To be published soon)

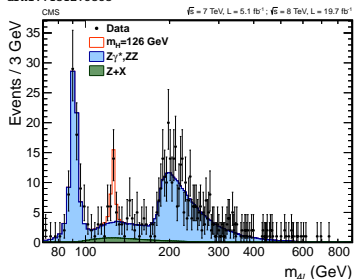
## CMS:

- $m_H^{\gamma\gamma+4\ell} = 125.7 \pm 0.3(\text{stat}) \pm 0.3(\text{sys}) \text{ GeV}$
- $\Delta m_H \approx 0.2 \text{ GeV}$
- extracted from CMS-PAS-HIG-13-002, March 2013
- **Combination of ATLAS and CMS mass planned soon**

Phys. Lett. B 726 (2013)



arXiv:1312.5353



# Combination of coupling measurements

## Signal strength:

- Combination of 5 decay channels
- $\mu_{ATLAS} = 1.30 \pm 0.12(\text{stat})^{+0.14}_{-0.11}(\text{sys})$   
 $\mu_{CMS} = 0.8 \pm 0.14$
- Standard-Model expectation  $\approx 1.8 \sigma$  below measurement
- Greatest SM deviation from  $H \rightarrow \gamma\gamma$  with  $\approx 2 \sigma$

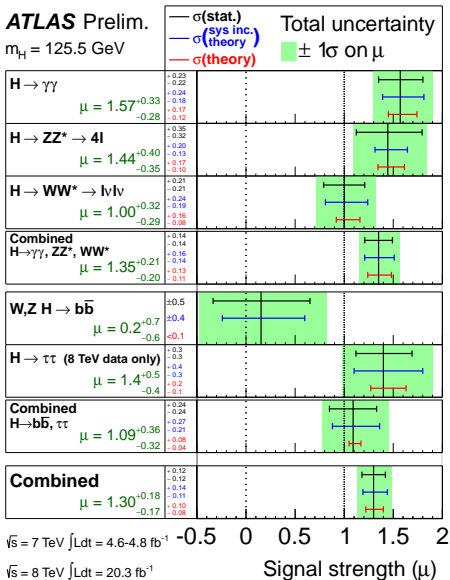
## Numbers from CMS:

$H \rightarrow b\bar{b}$	$1.0 \pm 0.5$	arXiv:1310.3867
$H \rightarrow \tau\tau$	$0.78 \pm 0.27$	arXiv:1301.5041
$H \rightarrow \tau\tau \oplus b\bar{b}$	$0.83 \pm 0.24$	arXiv:1401.6527
$H \rightarrow WW$	$0.72^{+0.20}_{-0.18}$	arXiv:1312.1129
$H \rightarrow ZZ$	$0.93^{+0.26}_{-0.23}(\text{stat})^{+0.13}_{-0.09}(\text{syst})$	arXiv:1312.5353
$H \rightarrow \gamma\gamma$	$0.77 \pm 0.27$	CMS-PAS-HIG-13-005

ATLAS-CONF-2014-009

**ATLAS Prelim.**

$m_H = 125.5 \text{ GeV}$

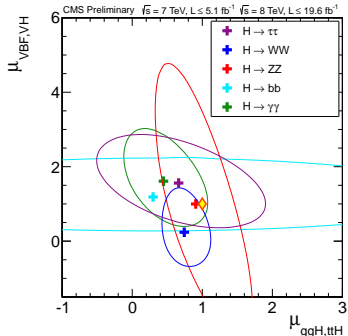


# Combination of coupling measurements

## Signal strength by production processes:

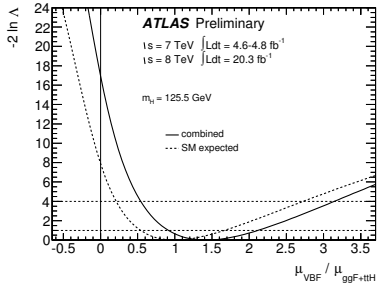
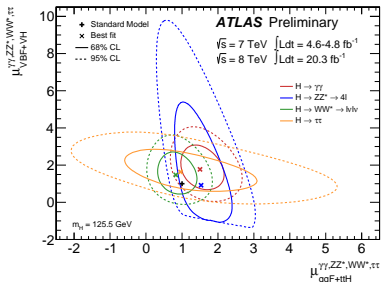
- $\frac{\mu_{\text{VBF+VH}}}{\mu_{\text{ggF+ttH}}} = 1.4^{+0.5}_{-0.4}(\text{stat})^{+0.4}_{-0.3}(\text{sys})$
- Good agreement with the SM expectation ( within  $1\sigma$  )
- From Likelihood fit for the ratio  $\frac{\mu_{\text{VBF}}}{\mu_{\text{ggF+ttH}}}$  :  $\Rightarrow$  evidence for VBF Higgs production at  $4.1\sigma$  level
- **Main contribution to systematic uncertainty comes from theoretical prediction for the ggF contributions**

CMS-PAS-HIG-13-005



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ATLAS-CO NF-2014-009



LHC Higgs Combinations

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# Combination of coupling measurements

## Coupling Fit under the “Only SM contributes to the total width” assumption:

- Fit parameters:

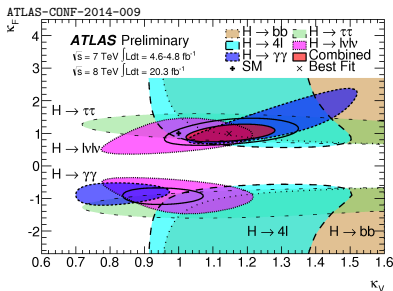
$$\kappa_V = \kappa_W = \kappa_Z \quad \text{with } \kappa = \frac{g}{g_{SM}}$$

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$$

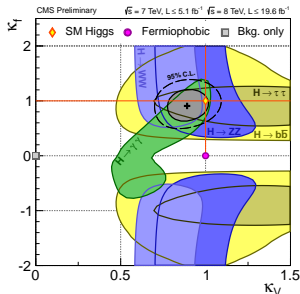
- best-fit values:

$$\kappa_V = 1.15 \pm 0.18, \kappa_F = 0.99^{+0.17}_{-0.15}$$

- Relatively large** values of  $\kappa_V \Leftrightarrow$  reflect the large  $\mu$  values for the **bosonic modes**



CMS-PAS-HIG-13-005



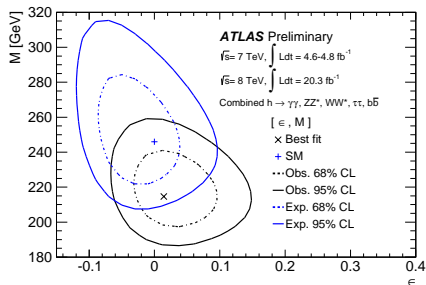
## Mass Scaling of Couplings:

- Couplings scale factors:

$$\kappa_{f,i} = v \frac{m_{f,i}^\epsilon}{M^{1+\epsilon}} \quad \kappa_{V,j} = v \frac{m_{V,j}^{2\epsilon}}{M^{1+2\epsilon}}$$

with  $v \approx 246$  GeV

- Best fit** is **compatible** with the **SM** expectation at the  $1.5\sigma$  level  
 $\Leftrightarrow$  **no evidence** for any unexpected mass dependency of the Higgs Boson coupling





## 2HDM(s):

- 2HDM in general: Add an additional Higgs-doublet to SM Higgs sector

5 States: 2 neutral CP-Even:  
 $h \oplus H$ , 1 neutral CP-odd  $A$  and two charged  $H^\pm$  Higgs-Bosons

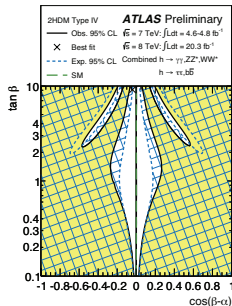
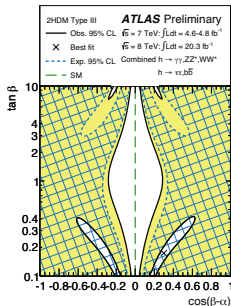
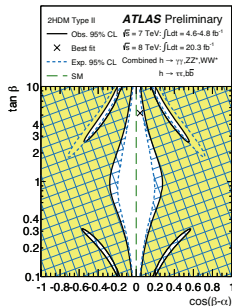
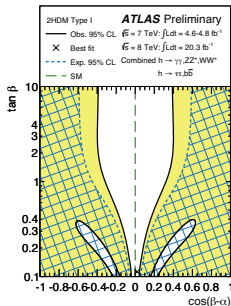
- Couplings:

$$\frac{g_{hVV}^{2HDM}}{g_{hVV}^{SM}} = \sin(\beta - \alpha)$$

$$\frac{g_{HVV}^{2HDM}}{g_{HVV}^{SM}} = \cos(\beta - \alpha)$$

where  $h$  is the light (CP-even, neutral) Higgs

$\tan(\beta) = \frac{v_2}{v_1}$  and  $\alpha$  is the **mixing angle** of the two neutral, CP-even states.



## Higgs Portal to Dark Matter:

- Put limit on WIMP coupling to SM-Higgs Boson.

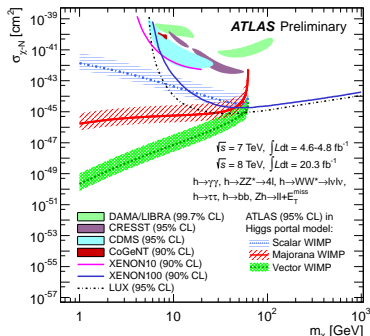
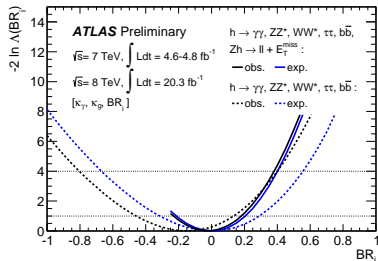
Higgs-Couplings to non-WIMP's assumed to be as predicted by the SM

- Parametrization:

$$\kappa_h^2 = \frac{\Gamma_h}{\Gamma_{h,SM}} = \sum_i \kappa_i^2 / (1 - BR_i)$$

$$\sum_i \kappa_i^2 = 0.0023\kappa_\gamma^2 + 0.085\kappa_g^2 + 0.91$$

- Lower plot: Upper Limits on WIMP-nucleon scattering cross section  $\sigma_{\chi-N}$



# Final Run 1 $H \rightarrow WW \oplus ZZ$ Results - CMS

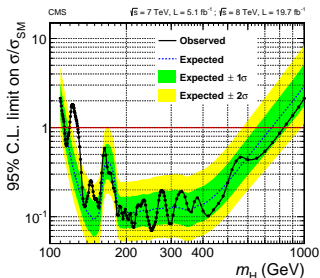
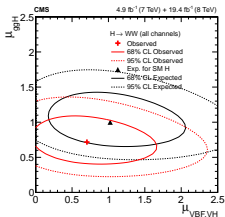
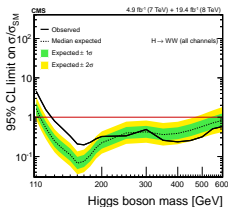
A view towards future combination:

**WW** arXiv:1312.1129:

- Observed significance is  $4.3\sigma$  for  $m_H = 125.6$  GeV
- Observed  $\mu = 0.72^{+0.20}_{-0.18}$  for  $m_H = 125.6$  GeV
- Analysis split in 0,1 and  $\geq 2$  jets

**ZZ** arXiv:1312.5353:

- Observed significance is  $6.8\sigma$  for  $m_H = 125.6$  GeV
- Observed  $\mu = 0.93^{+0.26}_{-0.23}(\text{stat})^{+0.13}_{-0.09}(\text{sys})$  for  $m_H = 125.6$  GeV

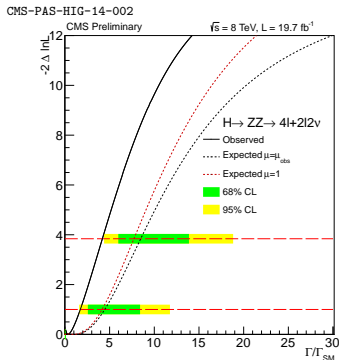
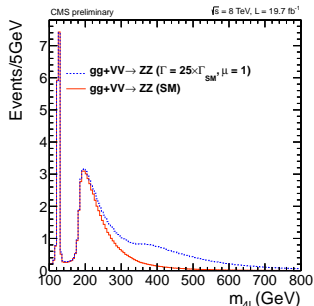


Both ATLAS and CMS haven't published the final  $H \rightarrow \gamma\gamma$  result yet

# Constraints on the Higgs boson width - CMS

- Combined  $H \rightarrow ZZ \rightarrow 4\ell \oplus 2\ell 2\nu$
- using  $m_{4\ell}$  for the  $4\ell$  analysis, the  $2\ell 2\nu$  analysis makes use of  $m_T$

$$m_T^2 = \frac{\left[ \sqrt{p_{T,\ell\ell}^2 + m_{\ell\ell}^2} + \sqrt{E_T^{miss} + m_{\ell\ell}^2} \right]^2 - \left[ p_{T,\ell\ell}^{\vec{}} + E_T^{miss\vec{}} \right]^2}{2}$$



	$4\ell$	$2\ell 2\nu$	Combined
Expected 95% CL limit, $r$	11.5	10.7	8.5
Observed 95% CL limit, $r$	6.6	6.4	4.2
Observed 95% CL limit, $\Gamma_H$ (MeV)	27.4	26.6	17.4
Observed best fit, $r$	$0.5^{+2.3}_{-0.5}$	$0.2^{+2.2}_{-0.2}$	$0.3^{+1.5}_{-0.3}$
Observed best fit, $\Gamma_H$ (MeV)	$2.0^{+9.6}_{-2.0}$	$0.8^{+9.1}_{-0.8}$	$1.4^{+6.1}_{-1.4}$

with  $r = \Gamma_H / \Gamma_H^{SM}$ ,  $\Gamma_H^{SM} = 4.15 \text{ MeV}$

- **Results** from Higgs Combinations are in **very good agreement** with the **SM expectations!**
- Higgs **couplings estimated** using all “main” decay channels by **ATLAS and CMS**
- Many **results** are in the **pipeline** (Final  $H \rightarrow WW \oplus ZZ \oplus \gamma\gamma$  from ATLAS,  $H \rightarrow \gamma\gamma$  from CMS)
- Search goes on towards **BSM physics** → can make use of **precise Higgs measurements** to put **limits on BSM** scenarios
- Expect final CMS and ATLAS combination in **Fall 2014**

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# Evidence for the direct decay to Fermions - CMS

- Combination of  $VH \rightarrow b\bar{b}$  and  $H \rightarrow \tau\tau$

