Review of SM Higgs properties measured by ATLAS and CMS: couplings, spin, mass

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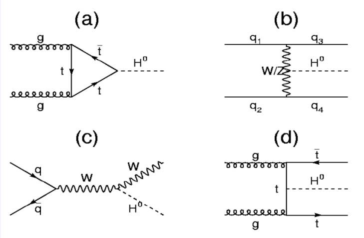
CHARGED 2014

Uppsala

Higgs boson in the SM

- Result of spontaneous symmetry breaking
- Mass to gauge bosons + unitarity at high energy
- Mass to fermions through Yukawa

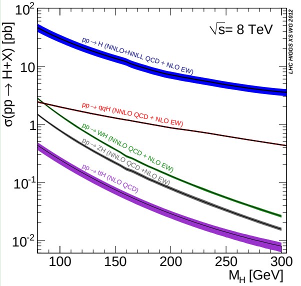
Production @ LHC

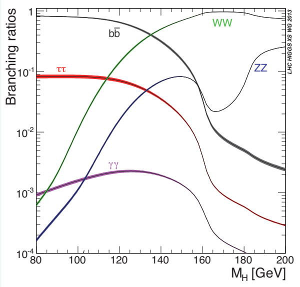


- **a:** Gluon fusion
- **c:** W/Z associated
- **b:** VBF
- **d:** $t\bar{t}$ associated

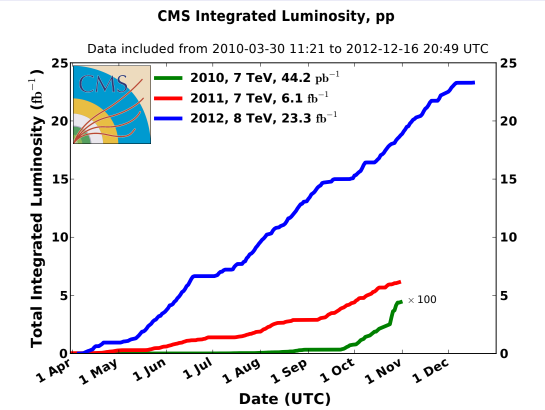
cross-section and BR

- **Mass is a free parameter of the SM**
- Couples to gauge bosons and elementary fermions
- Coupling strength proportional to mass
- total XS × BR: few fb - few pb
- [CERN Yellow report]

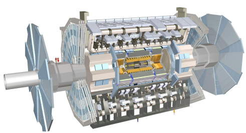


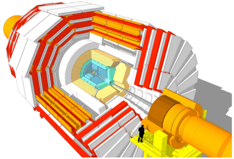


The collider and detectors



- proton-proton collisions @ 7 TeV in 2010 and 2011
- pp collisions @ 8 TeV in 2012
- Up to 15/30 interactions per beam collision in 2011/2012
- 5.08 +21.3 fb^{-1} (ATLAS)
- 5.55 + 21.79 fb^{-1} (CMS)
- $O(10^5)$ decays of $H(125) \to b\bar{b}$
- $O(10^3)$ decays of $H(125) \to \gamma\gamma$





Mass measurement

Motivation

- Mass of the boson is the last free parameter in the Standard Model
- Fundamental position in the SM:
  - Calculation of the H production and decay rates
  - Precise knowledge necessary to test the coupling structure

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Overview

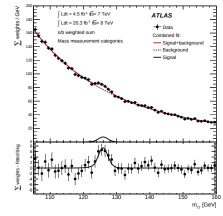
- Exploit **H → ZZ → 4l** and **H** → $\gamma\gamma$ channels
- full mass reconstruction, clean signal, excellent resolution
- Model independent measurement
  - Fit of a peak over smooth background
  - No assumption on production or decay yields
- Improved analyses of Run I data ⇒ twice better precision
- [Phys.Rev.D.90,052004(2014)](ATLAS), [CMS-PAS-HIG-14-009](CMS)

Extracting mass for individual channels

Phys.Rev.D.90,052004(2014), CMS-PAS-HIG-14-009

$H \to \gamma\gamma$

- split into several $(10 - 20)$ categories
- fit $m_{\gamma\gamma}$ distributions simultaneously
- signal shape model determined from MC
- background modeled by smooth function
- bias from choice of background model studied with MC



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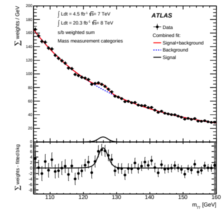
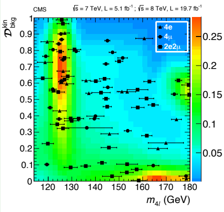


$H \rightarrow ZZ \rightarrow 4l$

- using matrix element approach to build discriminants against ZZ background
- mass is obtained via parameter estimation with multi-dimensional unbinned likelihoods



Results of 2D fits in $(\mu \times m_H)$ plane

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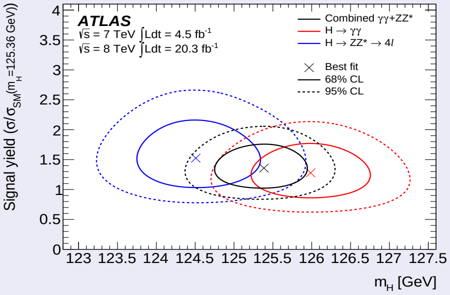
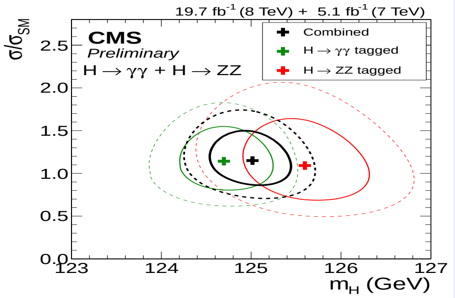
- fix the relative signal yields between $\gamma\gamma$ and ZZ
- let the overall signal strength $(\mu = \sigma/\sigma_{\rm SM})$ and mass float
- Fixed σ_{SM} at ATLAS, mass dependent in CMS

ATLAS



CMS



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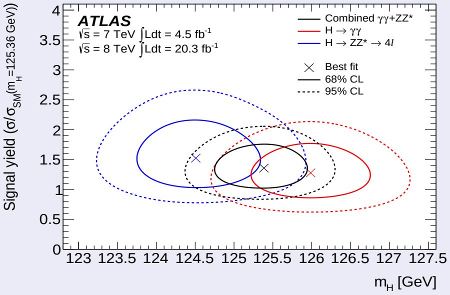

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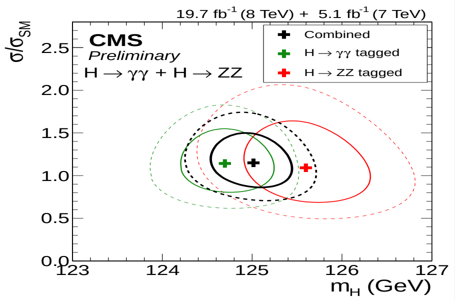


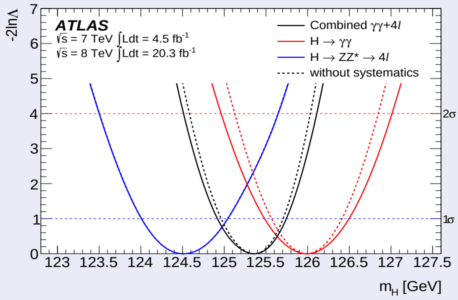
- All results compatible within 1-2σ
- No dependence of m_H on μ

Mass combination

Phys.Rev.D.90,052004(2014), CMS-PAS-HIG-14-009

- Assume single state with mass m_H
- production and decay ratios can float in the fit
- separate μ per decay (both) and production tag (only $\gamma\gamma$ at CMS)

ATLAS



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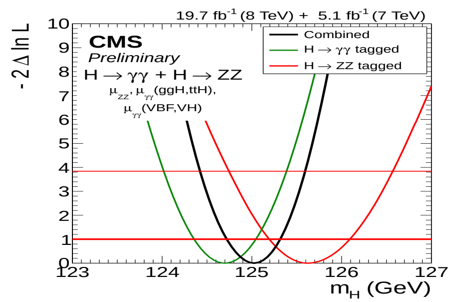

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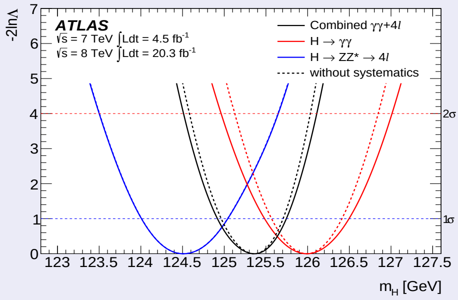
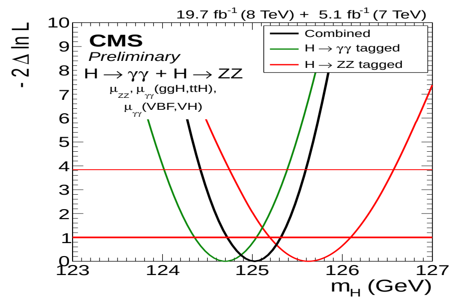


$$m_H = 125.36 \pm 0.37 \pm 0.18 \text{ GeV}$$

CMS



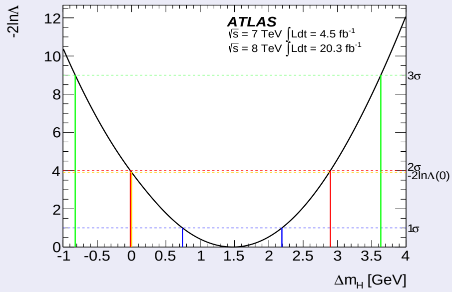
$$m_H = 125.03^{+0.26}_{-0.27}\ ^{+0.13}_{-0.15} \text{ GeV}$$

Compatibility of measurements in 2 channels

Phys.Rev.D.90,052004(2014), CMS-PAS-HIG-14-009

- Using test statistics $q(m_H^{\gamma\gamma} - m_H^{4l})$
- 2 degrees of freedom ($m_H^{\gamma\gamma}$ and Δm), $m_H^{\gamma\gamma}$ is profiled

ATLAS



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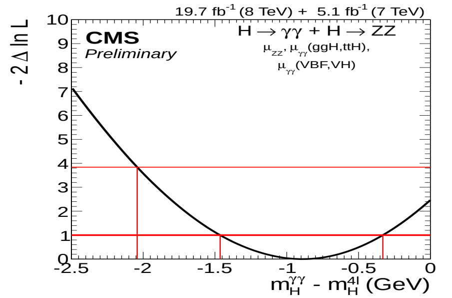

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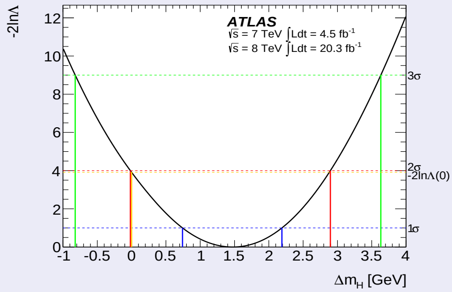
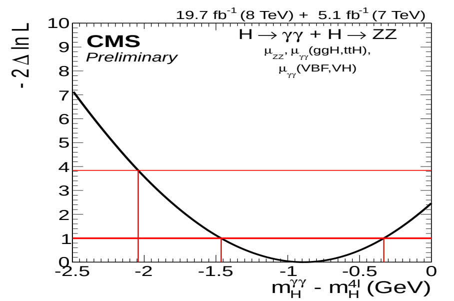


$\mathbf{\Delta m_H = 1.47 \pm 0.72}$ **GeV** $\mathbf{(1.98\sigma)}$

CMS

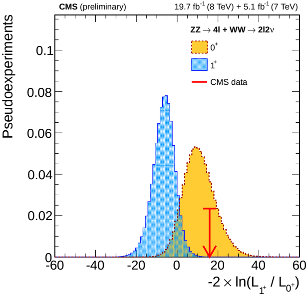


$\mathbf{\Delta m_H = -0.87^{+0.54}_{-0.59}}$ **GeV** $\mathbf{(1.6\sigma)}$

Spin and CP of the H boson

- **SM:** H boson is scalar ($J^P = 0^+$)
- testing compatibility of data with $J^P = 0^+, 0^-, 1^{+/-}, 2^{+/-}$
- various models for non-SM spin and parity
- exploiting kinematical observables in $\gamma\gamma$, $ZZ \to 4l$ and $WW \to l\nu l\nu$ channels
- **first measurements of anomalous couplings**

Example test statistics:



- **Test statistics:**
$$q = -2\ln\frac{\mathcal{L}(J^P_{\mathrm{alt}})}{\mathcal{L}(J^P{=}0^+)}$$
- **exclusion level $1-\alpha$:**
$$\mathrm{CL}_s = \frac{P(q{>}q_{\mathrm{obs}}|J^P_{\mathrm{alt}}{+}\mathrm{bkg})}{P(q{>}q_{\mathrm{obs}}|0^+{+}\mathrm{bkg})} < \alpha$$

Spin 0 hypotheses and measurements

Amplitude parametrization:

$$A(X_{J=0} \to V_1 V_2) \sim v^{-1} \left(\left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* + \sum_{V_1 V_2} \left(a_2^{V_1 V_2} f_{\mu\nu}^{*(V_1)} f^{*(V_2),\mu\nu} + a_3^{V_1 V_2} f_{\mu\nu}^{*(V_1)} \tilde{f}^{*(V_2),\mu\nu} \right) \right)$$

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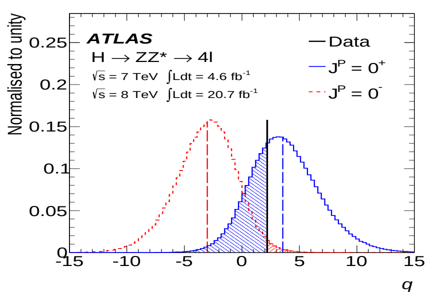
a_i's can in general be complex (loop contributions from light particles)

Spin 0 hypotheses testing

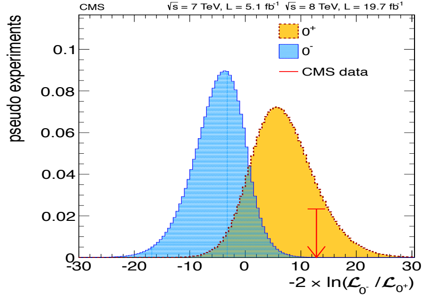
- Using $ZZ \to 4l$ channel
- [Phys.Lett.B726(2013),120-144](ATLAS), [Phys.Rev.D89(2014)092007](CMS)

ATLAS



CL_s = 97.8%

CMS



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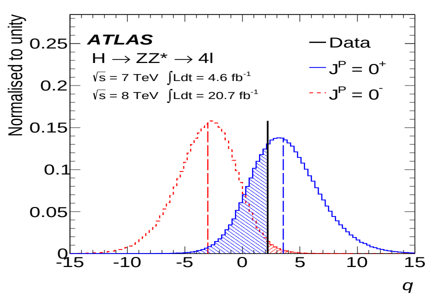

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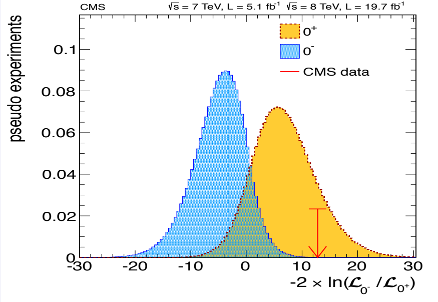

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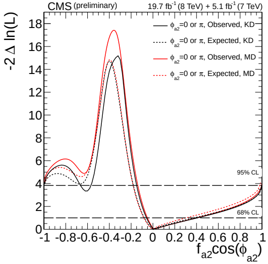
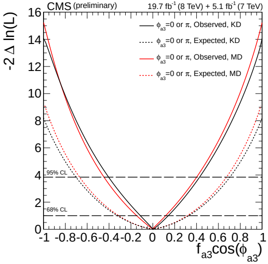
CMS also excluded scalar decoupled from EWSB(0_h^+) with **CL_s=95.5%**

Spin 0 measurements in ZZ→ 4l

- Constraints on mixture of scalar and other spin 0 states
  CMS-PAS-HIG-14-014
- Defining effective fractions: $f_{a_i} = \frac{|a_i|^2\sigma_i}{|a_1|^2\sigma_1+|a_2|^2\sigma_2+|a_3|^2\sigma_3+\tilde{\sigma}_{\Lambda_1}/(\Lambda_1)^4}$
- Best fit assumes real phase $\phi_{a_i} = 0$ or $\phi_{a_i} = \pi$
- Similar results with different methods





$$\mathbf{f_{a_2}\cos(\phi_{a_2}) = 0.00^{+0.42}_{-0.06}}$$

$$\mathbf{f_{a_3}\cos(\phi_{a_3}) = 0.00^{+0.14}_{-0.11}}$$

$$\mathbf{f_{\Lambda_1}\cos(\phi_{\Lambda_1}) = 0.22^{+0.10}_{-0.16}}$$

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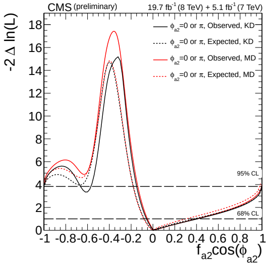

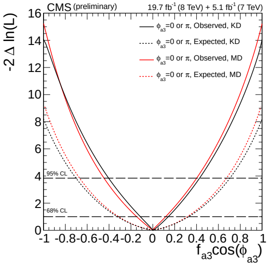

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See back-up for more results

Spin 1 hypotheses

- Landau-Yang theorem forbids spin 1 if $H \to \gamma\gamma$ decay exists BUT:
  - Different bosons for different final states
  - Multiple narrow states with different J^P

Parametrization:

$$A(X_{J=1} \to V_1 V_2) \sim b_1 \left[(\epsilon^*_{V_1} q)(\epsilon^*_{V_2} \epsilon_X) + (\epsilon^*_{V_2} q)(\epsilon^*_{V_1} \epsilon_X)\right] + b_2 \epsilon_{\alpha\mu\nu\beta} \epsilon^{\alpha}_{X} \epsilon^{*\mu}_{V_1} \epsilon^{*\nu}_{V_2} \tilde{q}^{\beta}$$

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Parametrization:

$$A(X_{J=1} \to V_1 V_2) \sim b_1 \left[(\epsilon^*_{V_1} q)(\epsilon^*_{V_2} \epsilon_X) + (\epsilon^*_{V_2} q)(\epsilon^*_{V_1} \epsilon_X)\right] + b_2 \epsilon_{\alpha\mu\nu\beta} \epsilon^{\alpha}_{X} \epsilon^{*\mu}_{V_1} \epsilon^{*\nu}_{V_2} \tilde{q}^{\beta}$$

- $V_1 V_2 \in \{ZZ, WW\}$

Spin 1 hypotheses

- Landau-Yang theorem forbids spin 1 if $H \to \gamma\gamma$ decay exists BUT:
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- ϵ_Y: polarization vector of particle Y
- $\epsilon_{\alpha\mu\nu\beta}$: Levi-Civita tensor

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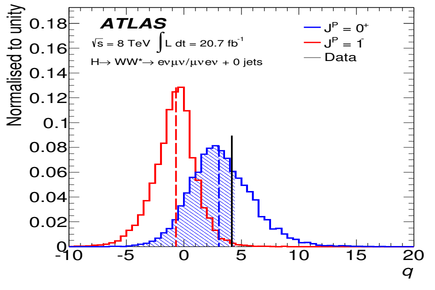
- $\epsilon_{\alpha\mu\nu\beta}$: Levi-Civita tensor
- b_1: vector coupling
- b_2: pseudovector coupling

mixture of 1^+ and 1^-states: $f_{b_2} = \frac{|b_2|^2\sigma_2}{|b_1|^2\sigma_1 + |b_2|^2\sigma_2}$

Spin 1 results

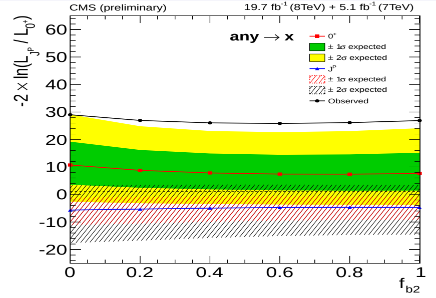
- Using $ZZ \to 4l$ and $WW \to l\nu l\nu$ channels
- [Phys.Lett.B726(2013),120-144](ATLAS), [CMS-PAS-HIG-14-014](CMS)

ATLAS



combined excl. ZZ+WW 1^+ $CL_s = 99.97\%$
combined excl. ZZ+WW 1^- $CL_s = 99.70\%$

CMS

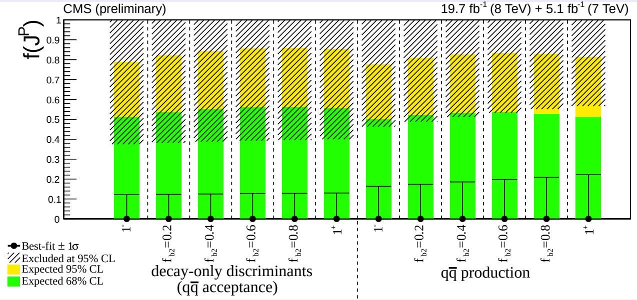


for various 1^+ and 1^- mixes $CL_s > 99.99\%$

Non-interfering spin 1 states

- Composite particles can have multiple narrow states with different J^P and nearly degenerate masses
  - ortho/para-positronium, χ_b,χ_c
- CMS analyzed for presence of second resonance with non-SM J^P close to dominant 0^+_{m}
  - Γ_{J^P} and $\Gamma_{0^+_{\mathrm{m}}} << |m_{J^P} - m_{0^+_{\mathrm{m}}}| << 1$ GeV
  - fractional cross-section $\mathbf{f(J^P) = \frac{\sigma_{J^P}}{\sigma_{0^+_m} + \sigma_{J^P}}}$

Limits for various (pseudo)vector mixtures and production:



Spin 2 hypotheses

Interaction of general spin-2 resonance with a ZZ or WW pair:

$$
\begin{aligned}
A(X_{J=2} \to V_1 V_2) \sim \Lambda^{-1} \Big[& 2c_1 t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2c_2 t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta} \\
& + c_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha} \right) + c_4 \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta} \\
& + m_V^2 \left(2c_5 t_{\mu\nu} \epsilon^{*\mu}_{V_1} \epsilon^{*\nu}_{V_2} + 2c_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} (\epsilon^{*\nu}_{V_1} \epsilon^{*\alpha}_{V_2} - \epsilon^{*\alpha}_{V_1} \epsilon^{*\nu}_{V_2}) + c_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon^*_{V_1} \epsilon^*_{V_2} \right) \\
& + c_8 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + c_9 t^{\mu\alpha} \tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon^{*\nu}_{V_1} \epsilon^{*\rho}_{V_2} q^\sigma \\
& + \frac{c_{10} t^{\mu\alpha} \tilde{q}_\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon^{*\nu}_{V_1} (q \epsilon^*_{V_2}) + \epsilon^{*\nu}_{V_2} (q \epsilon^*_{V_1}) \right) \Big]
\end{aligned}
$$

Spin 2 hypotheses

Interaction of general spin-2 resonance with a ZZ or WW pair:

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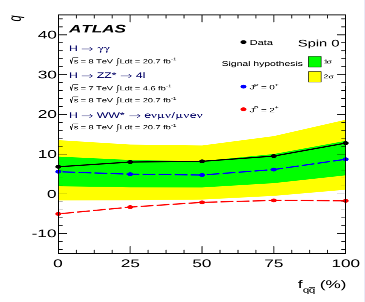
- $V_1 V_2 \in \{ZZ, WW\}$
- $t_{\mu\nu}$: wave function of X
- $c_1 = c_5 \neq 0$: graviton with minimal couplings (2^+_m)
- $c_1 << c_5$: graviton + SM fields can propagate to extra dimensions (2^+_b)
- $c_i \neq 0$: models with higher-dimension operators

Spin 2 results: 2^+_m model

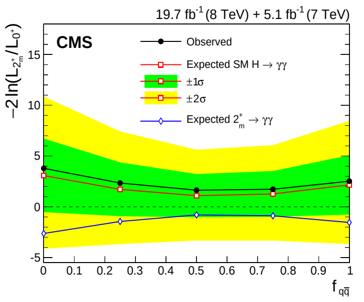
- CMS: only in $\gamma\gamma$ channel [CERN-PH-EP/2014-117]
- ATLAS: combination of $\gamma\gamma$, ZZ and WW [Phys.Lett.B726(2013),120-144]
- Angular distribution in diphoton rest frame ($|\cos\theta^*|$) sensitive to spin:
  - ATLAS: simultaneous fit to $m_{\gamma\gamma}$ and $m_{\gamma\gamma} \times |\cos\theta^*|$ distributions
  - CMS: divide events in bins of $|cos\theta^*|$ and fit $m_{\gamma\gamma}$ in each of them

ATLAS



combined excl. 2^+ $CL_s > 99.9\%$

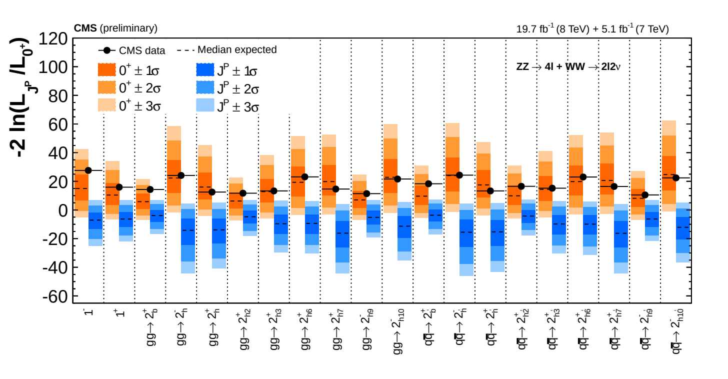
CMS



exclusion CL_s 1-2σ

Other spin-2 results and combinations

- CMS tested also the spin 2 model with ED and with higher-dimension operators
- results combined from ZZ and WW channels

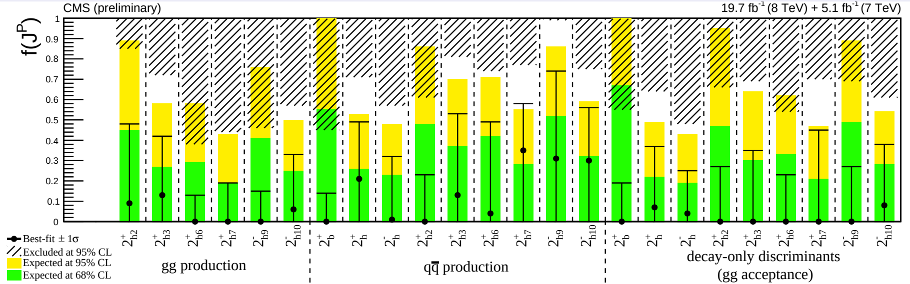


- Combination includes also $1^{\pm}$
- **All models excluded with $CL_s \geq 99.9\%$**

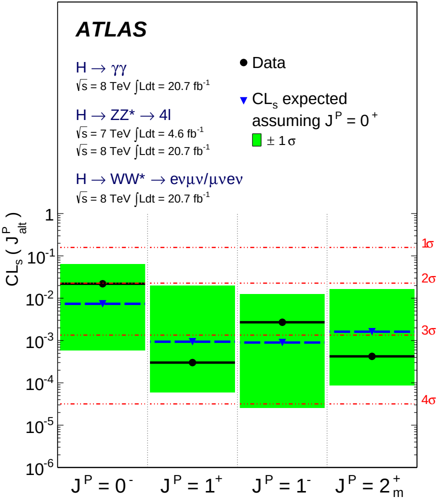
Non-interfering spin 2 states

- As for spin 1, CMS studied the presence of narrow spin-2 states close to main resonance
  - fractional cross-section $\mathbf{f(J^P)} = \frac{\sigma_{J^P}}{\sigma_{0_m^+} + \sigma_{J^P}}$

Limits for various spin 2 models and production:



Conclusion from J^P measurements



- Spin and parity tested in $\gamma\gamma$, ZZ and WW channels
- Scalar hypothesis favoured by data
  - All alternatives rejected by $> 99.9\%$
- CMS was studying also mixtures:
  - scalar-pseudoscalar
  - non-interfering spin 1 or 2 states
- Some limits on mixed states set but still large space for BSM physics

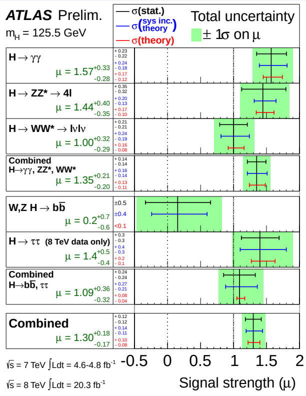
Combination of all channels

- Combination of many channels is used to check Higgs properties (signal strength, couplings)
- Most analyses use full Run I statistics (5+20 fb^{-1})
  - CMS uses only 8 TeV data from $t\bar{t}H \rightarrow$leptons
  - ATLAS uses only 8 TeV data from $H \rightarrow \tau\tau$
  - final ATLAS results for most channels coming out this autumn
- [ATLAS-CONF-2014-009](ATLAS), [CMS-PAS-HIG-14-009](CMS)

Decay/ production tag	untagged	VBF	VH	$t\bar{t}$H
H$\rightarrow \gamma\gamma$	both	both	both	CMS
H$\rightarrow b\bar{b}$			both	CMS
H$\rightarrow \tau^+\tau^-$	both	both	both	CMS
H$\rightarrow W^+W^-$	both	both	CMS	CMS
H$\rightarrow ZZ$	both	both	both	CMS

SM compatibility: signal strength

ATLAS



$\hat{\mu} = 1.3^{+0.18}_{-0.17}$ for $m_H = 125.5$ GeV (old mass comb.)

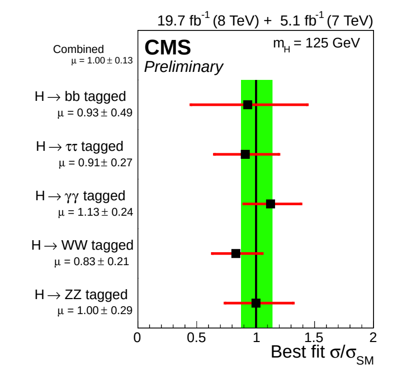
NEW RESULTS:

- $\hat{\mu}_{\gamma\gamma} = 1.17 \pm 0.27$ [CERN-PH-EP-2014-198]
- $\hat{\mu}_{ZZ} = 1.44^{+0.40}_{-0.33}$ [CERN-PH-EP-2014-170]

Method

- Use all channels
- Test statistics q_μ, $\hat{\mu} = \sigma/\sigma_{\rm SM}$

CMS

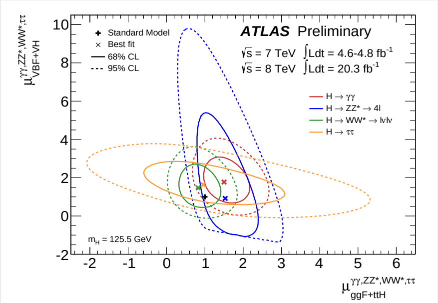


$\hat{\mu} = 1.00 \pm 0.13$ for $m_H = 125.0$ GeV

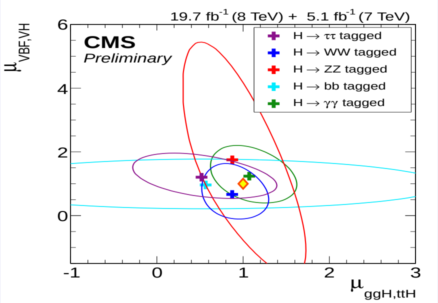
SM compatibility: 2D signal strength

- Test statistics $q(\mu_{\mathrm{ggH+ttH}}, \mu_{\mathrm{qqH+VH}})$, 2 + 2 production modes grouped together
- Decays as in SM, cross-channel contamination evaluated from MC

ATLAS



CMS



Compatibility of couplings

Scaling factors

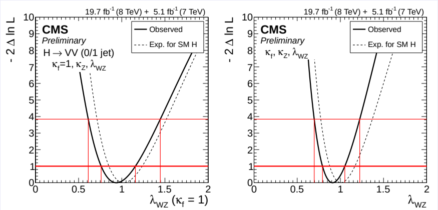
$$N(xx \to H \to yy) \sim \sigma(xx \to H) \cdot \mathcal{B}(H \to yy) \sim \frac{\Gamma_{xx}\Gamma_{yy}}{\Gamma_{\mathrm{tot}}}$$

- 8 **independent** parameters relevant for current searches
- Γ_{ZZ}, Γ_{WW}, $\Gamma_{\tau\tau}$, Γ_{bb}, $\Gamma_{\gamma\gamma}$, Γ_{gg}, Γ_{tt}, Γ_{tot}
- Not possible to extract those parameters at the moment
- **Scaling factors for couplings:** $\mathbf{g_i} = \kappa_{\mathbf{i}} \cdot \mathbf{g_i}^{\mathrm{SM}}$
- Introducing Γ_{BSM}

- Following slides are **compatibility tests**, not measurements
- Significant deviation of κ's from 1 would mean BSM physics
  - Re-fit of event yields in particular BSM framework would be also needed

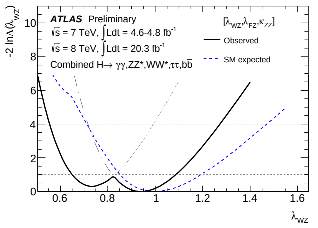
Custodial symmetry

Testing $\lambda_{WZ} = \kappa_W/\kappa_Z$, κ_Z and κ_f



CMS

1. use $gg \to H \to WW/ZZ$
   - nearly model independent
   - fit for λ_{WZ} and κ_Z, $\kappa_f = 1$
   - $\lambda_{WZ} = 0.94^{+0.22}_{-0.18}$
2. use all channels
   - model dependent (uniform κ_f)
   - fit for λ_{WZ}, κ_Z and κ_f, $\Gamma_{\mathrm{BSM}} = 0$
   - $\lambda_{WZ} = 0.91^{+0.14}_{-0.12}$

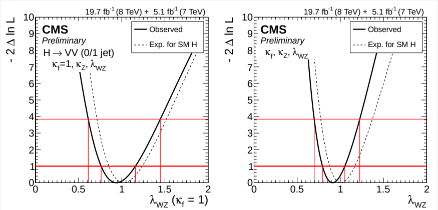


ATLAS

- fitting λ_{WZ}, κ_Z and $\kappa_F Z$
- $\lambda_{WZ} = 0.94^{+0.14}_{-0.29}$
- $\kappa_{ZZ} = \kappa_Z^2/\kappa_H = 1.41^{+0.49}_{-0.34}$
- $\lambda_{FZ} = \kappa_F/\kappa_Z \in [-0.91, -0.63] \cup [0.65, 1.00]$

Custodial symmetry

Testing $\lambda_{WZ} = \kappa_W / \kappa_Z$, κ_Z and κ_f



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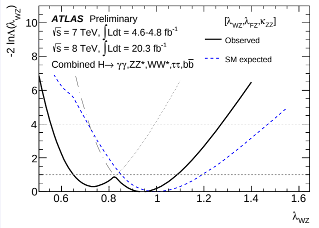

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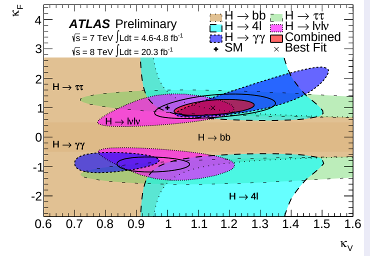
- $\lambda_{FZ} = \kappa_F / \kappa_Z \in [-0.91, -0.63] \cup [0.65, 1.00]$

- Data are consistent with custodial symmetry
- Further tests assume $\kappa_W = \kappa_Z = \kappa_V$

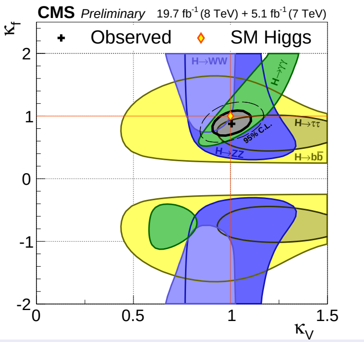
Couplings to fermions and W/Z: 2D contours

- Assume common scaling factors for fermion and W/Z couplings: κ_f, κ_V
- $\Gamma_{\mathrm{BSM}} = 0$
- $\Gamma_{gg} \sim \kappa_f^2$
- $\Gamma_{\gamma\gamma} \sim |\alpha\kappa_V + \beta\kappa_f|^2$ (W and t loop)$\Rightarrow$ $\gamma\gamma$ sensitive to relative sign of κ_V and κ_f

ATLAS



CMS



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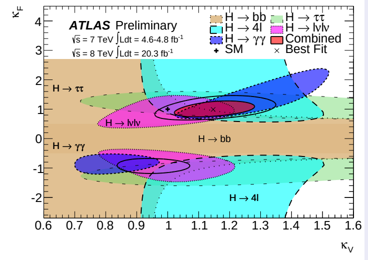
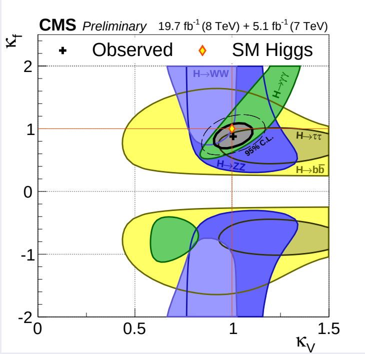
ATLAS



$(\kappa_V, \kappa_f) = (1, 1)$ within 1-2σ from the best fit

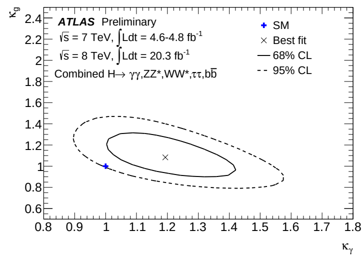
CMS



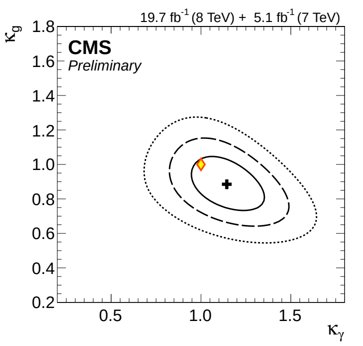
New physics in the loops: κ_g and κ_γ

- Loop diagrams sensitive to new particles, κ_g and κ_γ allow contributions from new particles
- $\Gamma_{\mathrm{BSM}} = 0$, all other $\kappa_i = 1$

ATLAS



CMS



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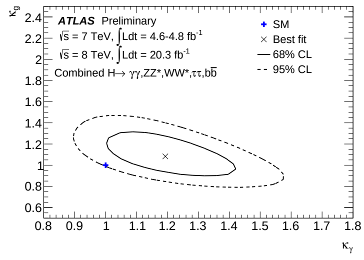
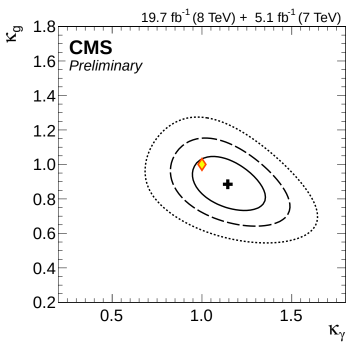
ATLAS



CMS



ATLAS @68% CL

$\kappa_g = 1.08^{+0.15}_{-0.13}$

$\kappa_\gamma = 1.19^{+0.15}_{-0.12}$

CMS @95% CL

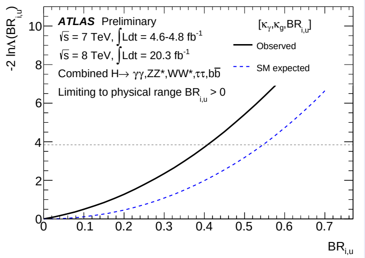
$\kappa_g \in [0.69, 1.1]$

$\kappa_\gamma \in [0.89, 1.42]$

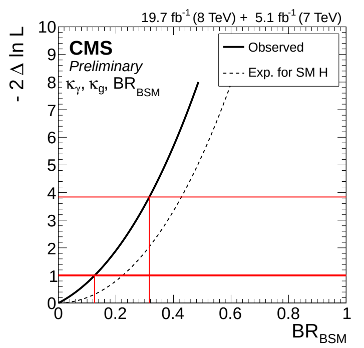
Non SM Higgs decays

- Assume tree-level couplings are SM
- fit for Γ_{BSM}, κ_γ and κ_g

ATLAS



CMS



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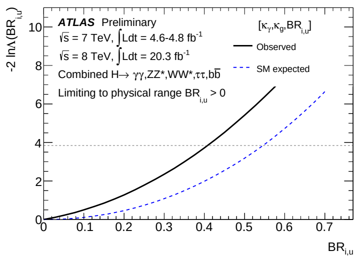
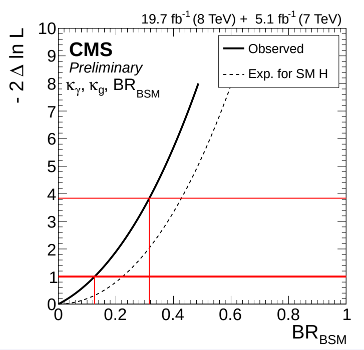
- fit for Γ_{BSM}, κ_γ and κ_g

ATLAS



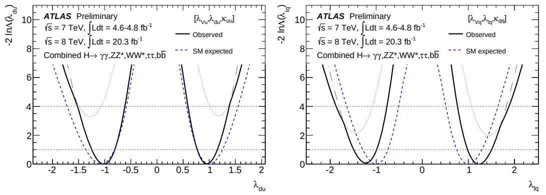
CMS



ATLAS @95% CL	CMS @95% CL
$\Gamma_{\mathrm{BSM}}/\Gamma_{\mathrm{tot}} < 0.41$	$\Gamma_{\mathrm{BSM}}/\Gamma_{\mathrm{tot}} < 0.32$

Fermion coupling asymmetries

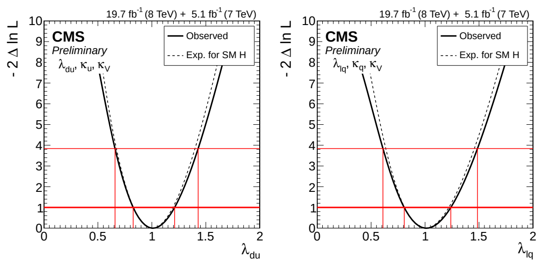
ATLAS



Input from $H \to \tau\tau$ and $H \to bb$
κ_u, κ_q: from gg production

- $\lambda_{du} = \kappa_d/\kappa_u \in [-1.24, -0.81] \cup [0.78, 1.15]$ @ 95% CL
- $\lambda_{lq} = \kappa_l/\kappa_q \in [-1.48, -0.99] \cup [0.99, 1.50]$ @ 95% CL

CMS

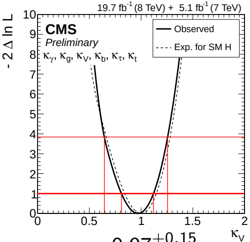


Using also ttH production for κ_u
Results for $\lambda_{du} > 0$ and $\lambda_{lq} > 0$

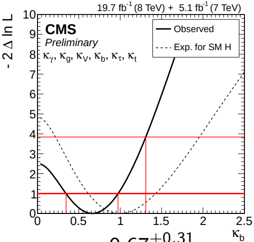
- $\lambda_{du} = \kappa_d/\kappa_u \in [0.66, 1.43]$ @ 95% CL
- $\lambda_{lq} = \kappa_l/\kappa_q \in [0.61, 1.49]$ @ 95% CL

C6 model @ CMS

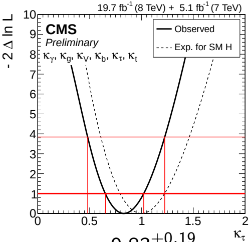
- Assume 6 independent parameters: κ_V, κ_t, κ_b, κ_τ, κ_γ, κ_g; $\Gamma_{\mathrm{BSM}} = 0$



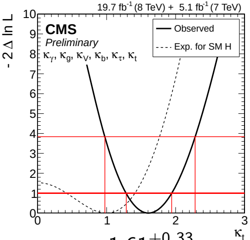
$\kappa_V = 0.97^{+0.15}_{-0.16}$



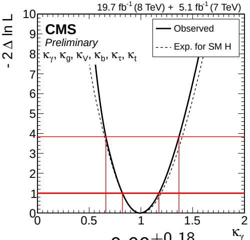
$\kappa_b = 0.67^{+0.31}_{-0.32}$



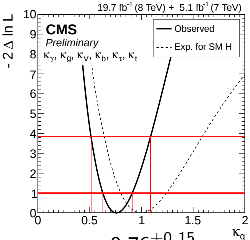
$\kappa_\tau = 0.83^{+0.19}_{-0.18}$



$\kappa_t = 1.61^{+0.33}_{-0.32}$



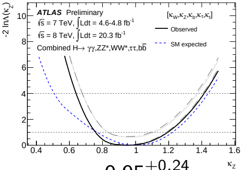
$\kappa_\gamma = 0.99^{+0.18}_{-0.17}$



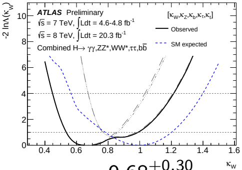
$\kappa_g = 0.76^{+0.15}_{-0.13}$

5 parameter model @ ATLAS

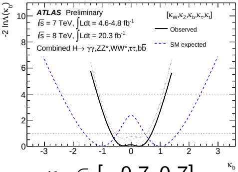
- Assume 5 independent parameters: κ_Z, κ_W, κ_t, κ_b, κ_τ; Only SM particles in the loops
- Results on κ_t from gg production



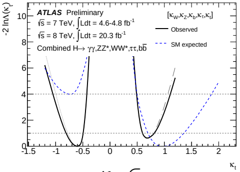
$\kappa_Z = 0.95^{+0.24}_{-0.19}$



$\kappa_W = 0.68^{+0.30}_{-0.14}$

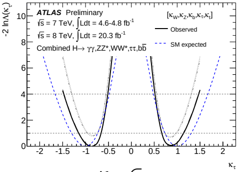


$\kappa_b \in [-0.7, 0.7]$



$\kappa_t \in$

$[-0.80, -0.50] \cup [0.61, 0.8]$



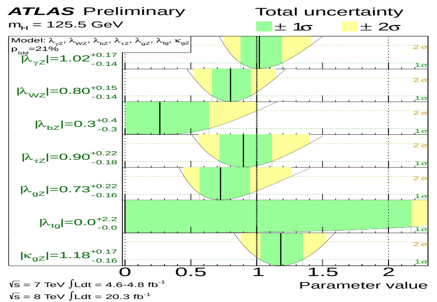
$\kappa_\tau \in$

$[-1.15, -0.67] \cup [0.67, 1.14]$

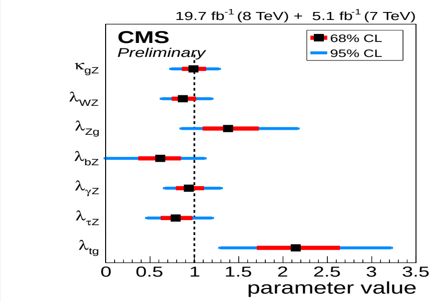
Coupling compatibility: summary

- Tested also generic 7 parameter model (free total width)

ATLAS



CMS



Coupling compatibility: summary

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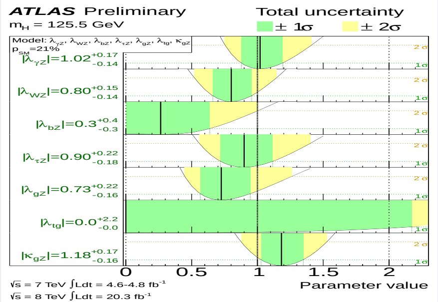
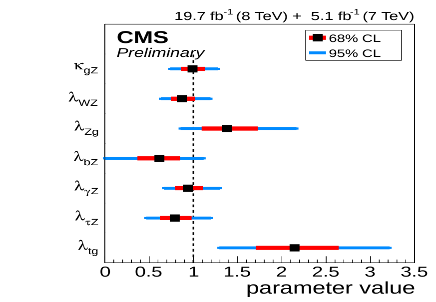
ATLAS



CMS



- Coupling to W,Z and 3rd generation fermions tested with 10-15% precision
- **In all tests no statistically significant deviation from the SM observed**

Summary

- Final Run 1 mass measurements available
  - measured with precision 2-3 ‰
  - uncertainty dominated by statistics
  - $\gamma\gamma$ and $ZZ \to 4l$ results compatible within 2σ
- **No statistically significant deviations from the SM couplings observed in any decay channels at both experiments**
  - Constraints on 10-50% level
  - room for BSM
- Pure non-scalar hypotheses excluded
- Mixtures of states still allowed

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  - room for BSM
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Tightening the constraints on Higgs boson couplings and J^P mixtures will be main goal of Run II, LHC upgrades and future machines

Additional material

References and further reading

- ATLAS preliminary combination: ATLAS-CONF-2014-009
- ATLAS mass measurement: CERN-PH-EP-2014-122
- ATLAS spin testing: Phys.Lett.B726(2013),120-144
- ATLAS results in H$\rightarrow \gamma\gamma$ channel: CERN-PH-EP-2014-198
- ATLAS results in H$\rightarrow ZZ \rightarrow 4l$ channel: CERN-PH-EP-2014-170
- CMS preliminary combinations: CMS PAS HIG-14-009
- CMS anomalous spin 0 in HZZ: CMS PAS HIG-14-014
- CMS anomalous spin 0 in HWW: CMS PAS HIG-14-012
- CMS results in H$\rightarrow ZZ \rightarrow 4l$ channel: Phys.Rev.D89(2014)092007
- CMS results in H$\rightarrow \gamma\gamma$ channel: CERN-PH-EP/2014-117
- Procedure for the LHC Higgs boson search combination: ATL-PHYS-PUB 2011-11, CMS NOTE 2011/005
- Higgs cross-sections and BR's: CERN Yellow Report

Statistical combination methodology

Based on the approach agreed by ATLAS and CMS in http://cdsweb.cern.ch/record/1379837

Likelihood

$$\mathcal{L}(\mathrm{data}|\mu \cdot s + b, \theta) = \mathcal{P}(\mathrm{data}|\mu \cdot s + b, \theta) \cdot p(\tilde{\theta}|\theta)$$

- $\mathcal{P}$ ... Product of probabilities over all channels and all bins (or all events)
- $p(\tilde{\theta}|\theta)$ ... Probability of observing measured value $\tilde{\theta}$ of nuisance parameter θ

Excess

Test statistics: $q_0 = -2 \ln \frac{\mathcal{L}(\mathrm{obs}|b, \hat{\theta}_0)}{\mathcal{L}(\mathrm{obs}|\hat{\mu} \cdot s + b, \hat{\theta})}$, $\hat{\mu} > 0$

- $\mathcal{L}(\mathrm{obs}|b, \hat{\theta}_0)$ ... maximal likelihood for background only hypothesis
- $\mathcal{L}(\mathrm{obs}|\hat{\mu} \cdot s + b, \hat{\theta})$ ... global maximal likelihood
- local p-value: $p_0 = \mathrm{P}(q_0 \geq q_0^{\mathrm{obs}}|b)$
- significance Z: $p_0 = \int_Z^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} \mathrm{d}x$

Statistical combination methodology

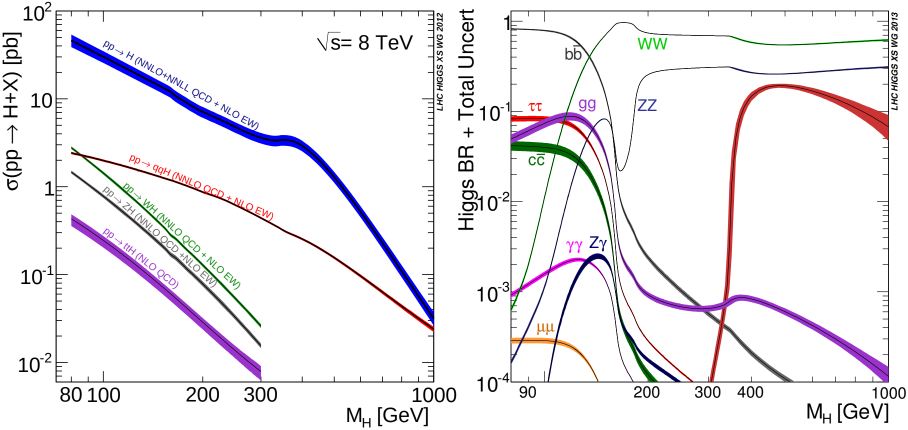
Based on the approach agreed by ATLAS and CMS in
http://cdsweb.cern.ch/record/1379837

Signal model parameters limits

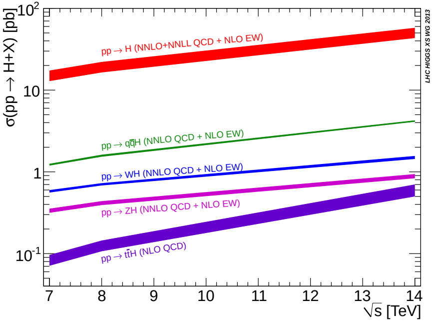
$$\textbf{Test statistics: } q(a) = -2\ln\frac{\mathcal{L}(\mathrm{obs}|s(a)+b,\hat{\theta}_a)}{\mathcal{L}(\mathrm{obs}|s(\hat{a})+b,\hat{\theta})}$$

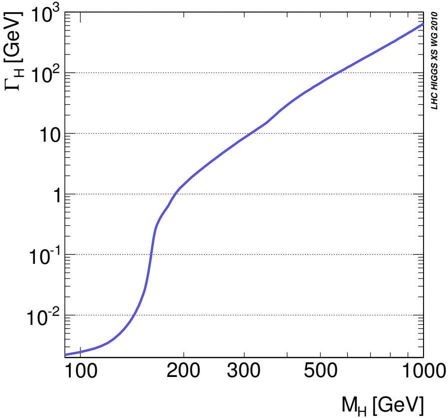
- The 68% (95%) CL on a given parameter of interest a_i: $q(a_i) = 1$ (3.84)
- For 2D contours, The 68% (95%) CL on a given parameter of interest a_i: $q(a_i, a_j) = 2.3$ (6.99)

Higgs cross-section and BR

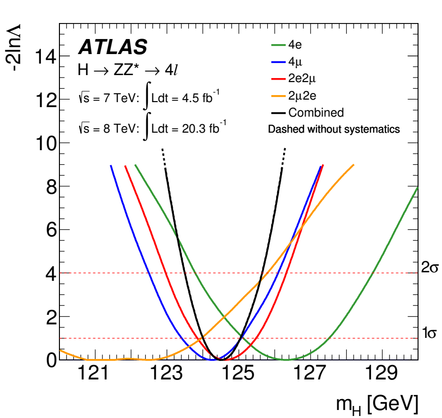


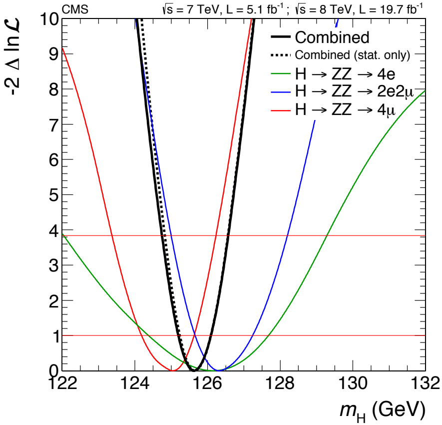
Higgs cross-section and width



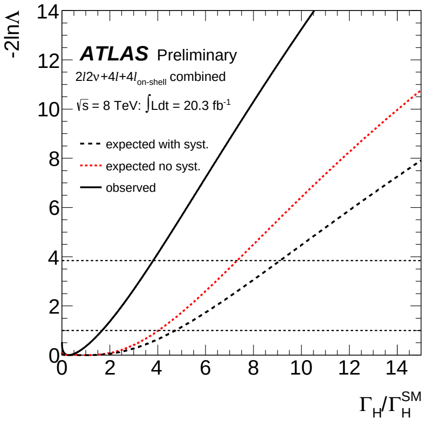


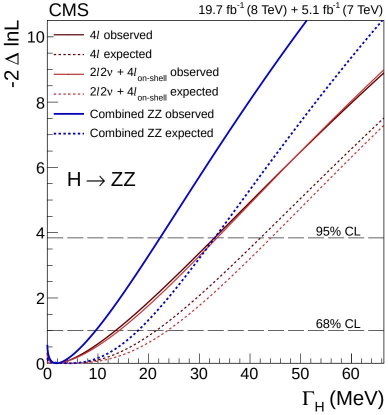
Mass in the ZZ subchannels





Limits on width



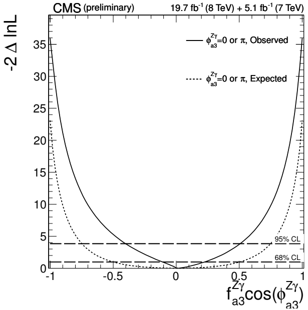


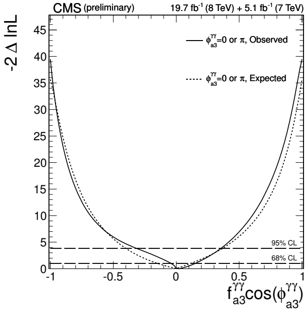
$\Gamma_H/\Gamma_H^{SM} < 5.7(8.5)$ @95%

$\Gamma_H/\Gamma_H^{SM} < 5.4(8.0)$ @95%

Constraints on $H \to Z\gamma^*/\gamma^*\gamma^*$

- Constraints on the fractional presence of $Z\gamma^*$ and $\gamma^*\gamma^*$
- Similar approach as before (assuming real phases)



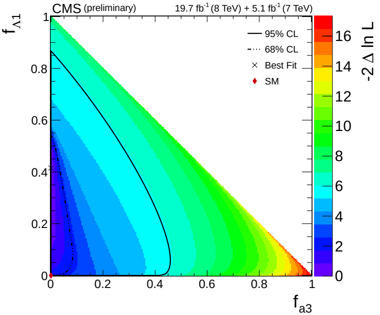


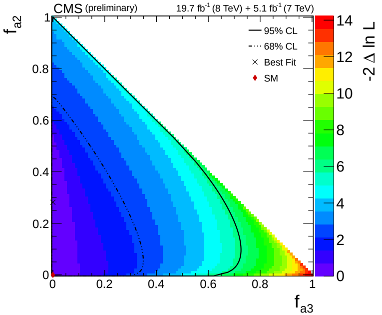
$$\mathbf{f}_{\mathbf{a_3}}^{\mathbf{Z}\gamma}\cos(\phi_{\mathbf{a_3}}^{\mathbf{Z}\gamma}) = 0.02^{+0.21}_{-0.13}$$
$$\mathbf{f}_{\mathbf{a_2}}^{\mathbf{Z}\gamma}\cos(\phi_{\mathbf{a_2}}^{\mathbf{Z}\gamma}) = 0.00^{+0.14}_{-0.20}$$

$$\mathbf{f}_{\mathbf{a_3}}^{\gamma\gamma}\cos(\phi_{\mathbf{a_3}}^{\gamma\gamma}) = 0.02^{+0.13}_{-0.06}$$
$$\mathbf{f}_{\mathbf{a_2}}^{\gamma\gamma}\cos(\phi_{\mathbf{a_2}}^{\gamma\gamma}) = -0.12^{+0.11}_{-0.20}$$

Pair of spin-0 couplings

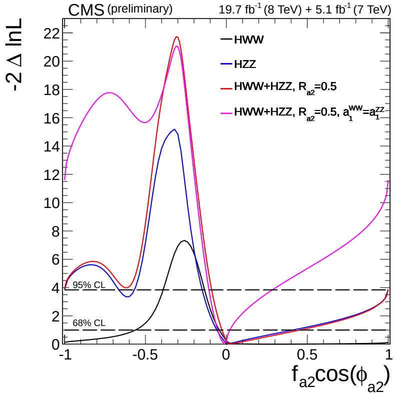
- Simultaneous presence of 2 anomalous ZZ couplings
- Profiling the phases of studied pair
- Other parameters have SM values

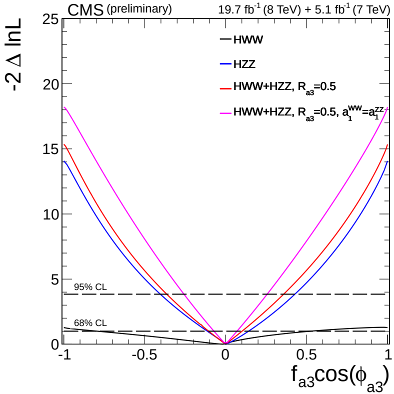




Combination with $WW \to l\nu l\nu$

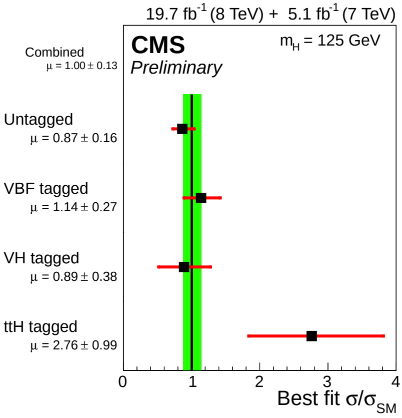
- Also in CMS-PAS-HIG-14-012
- Assume same ratio of couplings in ZZ and WW channels
- Improving constraints wrt ZZ alone

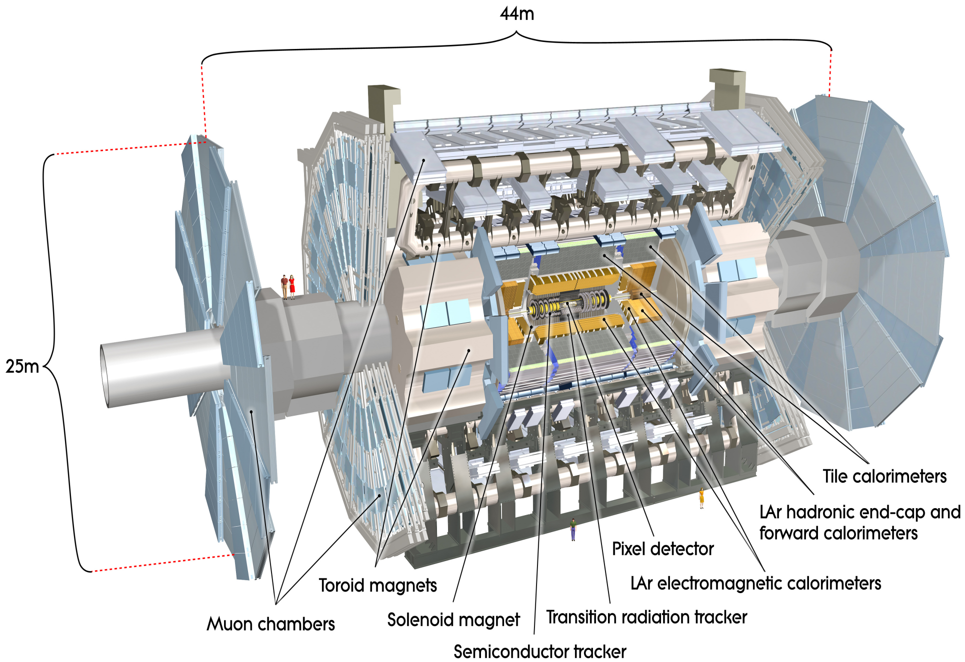


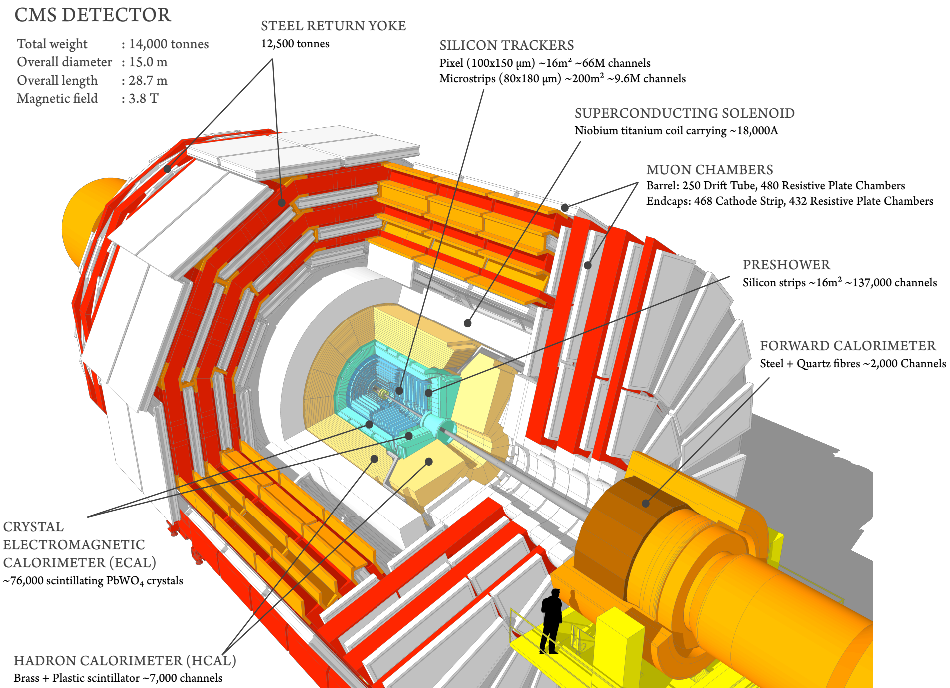


with and **without** assuming custodial symmetry

Signal strength by production tag




44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels