Higgs properties from the combined measurement

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30th of October 2015

What is a combined measurement?

- **NOT** a combination of separate measurements...
- Combine the data samples of ATLAS and CMS + perform a fit
  ⇒ A combined measurement

With great data comes...
great responsibility to treat uncertainties in the right way!

⇒ We include systematic uncertainties and correlations in the fit...

The standard model Higgs boson or something else?

- We found a Higgs boson, but *what kind of Higgs boson is it?*
- LHC Run 1 data allows to probe for
  - production modes ggH, VBF, WH, ZH, and ttH and
  - decay channels $\gamma\gamma$, $\mathrm{ZZ} \to 4\ell$, $\mathrm{WW} \to 2\ell 2\nu$, $\tau\tau$, bb, and $\mu\mu$.

- Signal strength μ_i^f = Higgs boson yields for a process $i \to H \to f$:

$$\mu_i^f \equiv \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \frac{\mathrm{BR}^f}{\mathrm{BR}^f_{\mathrm{SM}}} = \mu_i \times \mu^f .$$

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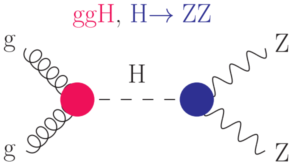
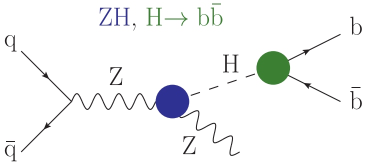
- New physics could produce a SM-like signal strength
  $\to$ *measure couplings from both production and decay!*





Deviations from the SM expectation: the κ-framework

- Parameterise the signal yield in terms of Higgs boson widths:

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_{\mathrm{H}}}.$$

- The coupling modifiers $\vec{\kappa}$ - potential deviation from the SM:

$$\sigma_j = \kappa_j^2 \cdot \sigma_j^{\mathrm{SM}} \text{ or } \quad \Gamma^j = \kappa_j^2 \cdot \Gamma^j_{\mathrm{SM}}.$$

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- Individual κ_j correspond to LO degrees of freedom
  $\rightarrow$ In SM, define effective coupling modifiers for ggH and $\mathrm{H} \rightarrow \gamma\gamma$ as

$$\kappa_{\mathrm{g}}^2 \sim 1.06 \cdot \kappa_{\mathrm{t}}^2 + 0.01 \cdot \kappa_{\mathrm{b}}^2 - 0.07 \cdot \kappa_{\mathrm{t}}\kappa_{\mathrm{b}}$$
$$\kappa_{\gamma}^2 \sim 1.59 \cdot \kappa_{\mathrm{W}}^2 + 0.07 \cdot \kappa_{\mathrm{t}}^2 - 0.66 \cdot \kappa_{\mathrm{W}}\kappa_{\mathrm{t}}$$

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Necessary to make an assumption on Γ_{H}: a theory dependence
$\rightarrow$ test for different hypotheses (SM, BSM)

The κ-framework and the total width of the Higgs boson

- General form for the Higgs boson width is

$$\Gamma_{\mathrm{H}} = \Gamma_{\mathrm{H}}^{\mathrm{SM}}(\vec{\kappa}) + \Gamma_{\mathrm{H}}^{\mathrm{BSM}}$$

- The total width depends on the allowed couplings
  $\rightarrow$ characterise the dependence with another modifier $\kappa_{\mathrm{H}}^2(\vec{\kappa})$:

$$\Gamma_{\mathrm{H}} = \frac{\kappa_{\mathrm{H}}^2 \cdot \Gamma_{\mathrm{H}}^{\mathrm{SM}}}{(1 - \mathrm{BR}_{\mathrm{BSM}})}, \text{ where}$$

$$\begin{aligned}\kappa_{\mathrm{H}}^2(\vec{\kappa}) \sim\ & 0.57 \cdot \kappa_{\mathrm{b}}^2 + 0.22 \cdot \kappa_{\mathrm{W}}^2 + 0.09 \cdot \kappa_{\mathrm{g}}^2 + 0.06 \cdot \kappa_{\tau}^2 \\ & + 0.03 \cdot \kappa_{\mathrm{Z}}^2 + 0.03 \cdot \kappa_{\mathrm{c}}^2 + 0.0023 \cdot \kappa_{\gamma}^2 + 0.0016 \cdot \kappa_{\mathrm{Z}\gamma}^2 \\ & + 0.0001 \cdot \kappa_{\mathrm{s}}^2 + 0.00022 \cdot \kappa_{\mu}^2\end{aligned}$$

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  → SM width rescaled by κ_{H}^2.

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- If only SM physics is allowed: $\mathrm{BR}_{\mathrm{BSM}} = 0$
  $\rightarrow$ SM width rescaled by κ_{H}^2.
- If we allow also BSM contributions, $\mathrm{BR}_{\mathrm{BSM}}$ is not bounded
  $\rightarrow$ introduce another assumption to bound $\kappa_{\mathrm{H}}^2(\vec{\kappa})$.

Assuming only SM physics

- No BSM decays: $\mathrm{BR}_{\mathrm{BSM}} = 0$.
- No BSM in the loops:

$\rightarrow$ $\kappa_{\mathrm{g}}^{\mathbf{2}}(\kappa_{\mathrm{t}}, \kappa_{\mathrm{b}})$ and $\kappa_{\gamma}^{\mathbf{2}}(\kappa_{\mathrm{W}}, \kappa_{\mathrm{t}})$

$\rightarrow$ measure κ_{W}, κ_{Z}, κ_{b}, κ_{t}, κ_{τ}, and κ_{μ}.

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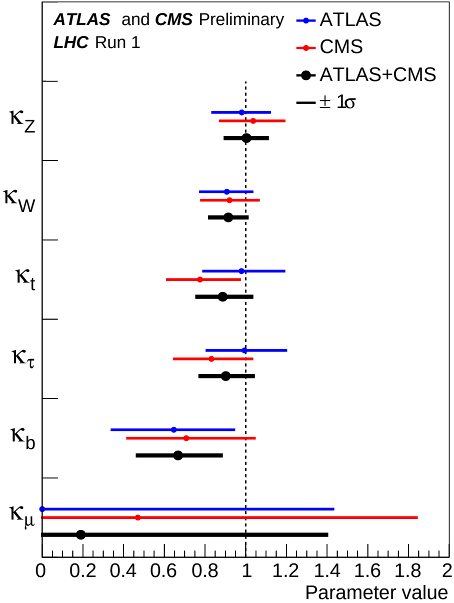

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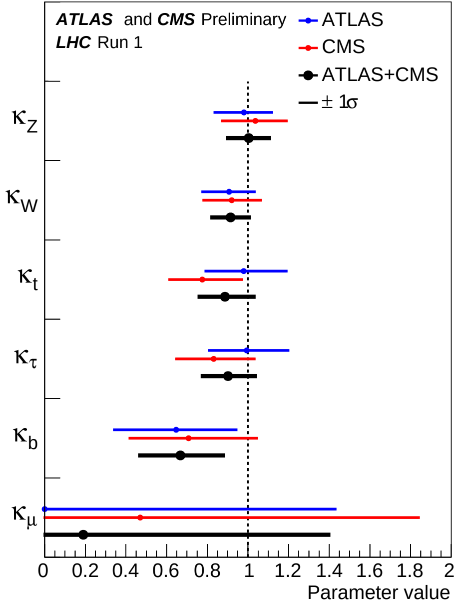
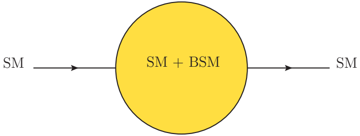
The p-value of the compatibility between the data and the SM predictions is 65%.



Allowing BSM physics

- To bound $\kappa_{\mathrm{H}}^2(\vec{\kappa})$, introduce two scenarios allowing BSM particles:
  1. **only in loops**, thus $\mathrm{BR}_{\mathrm{BSM}} = 0$



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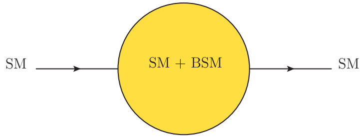
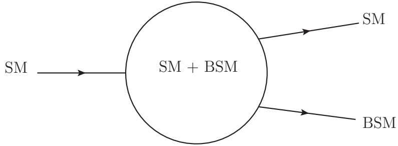


  2. **in loops and in decays**, thus $\mathrm{BR}_{\mathrm{BSM}} \geq 0$ and $\kappa_W, \kappa_Z \leq 1$
     (natural bound in wide range of BSM physics models!)



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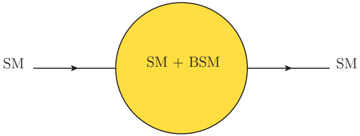

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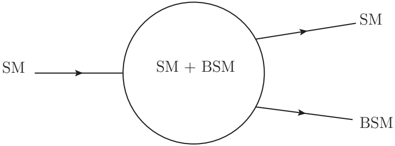
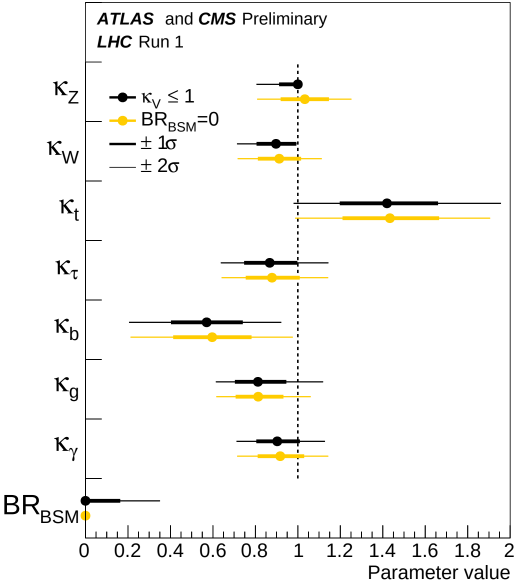


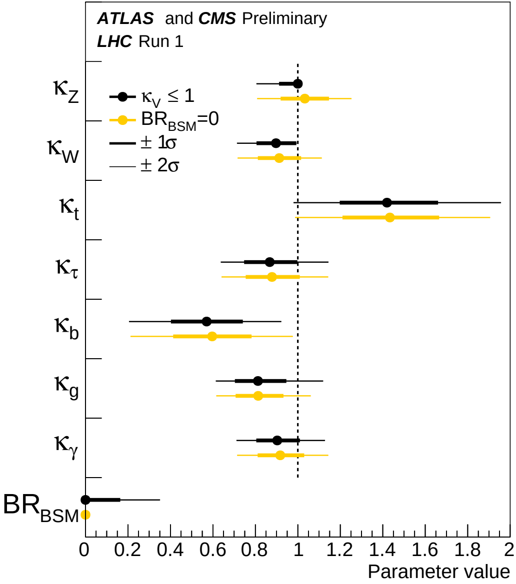
→ Measure κ_{g} and κ_γ, κ_{W}, κ_{Z}, κ_{b}, κ_{t}, κ_τ, and in **scenario 2** also **BR**$_{\mathrm{BSM}}$.

Fit results when allowing BSM physics



Fit results when allowing BSM physics

- From **scenario 1**:
  The p-value of the compatibility between the data and the SM predictions is 11%.



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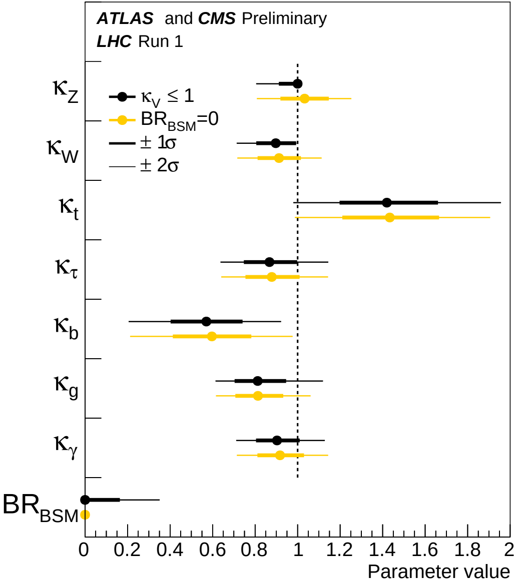
  $\mathrm{BR_{BSM}} < 0.34$ at 95% CL.



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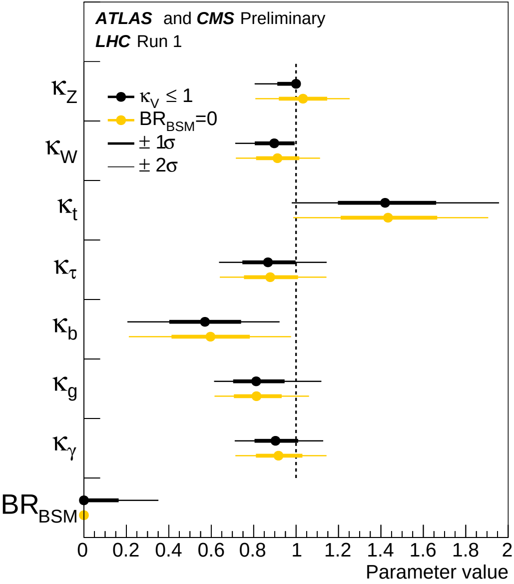
Couplings are compatible with the SM within uncertainties of
$\sim$ 10% *for bosons and*
$\sim$ 15% – 30% *for* t, b *and* τ.



Conclusion

- The combined measurement is obtained by fitting the combined data samples.
- The κ-framework is used to measure couplings of the Higgs boson to SM particles, and requires an explicit modelling of the Higgs boson width.
- The explicit modelling of the width allows us to test for both SM and BSM physics.

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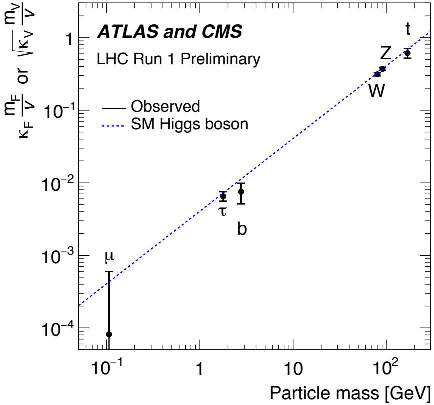

- We find couplings compatible with the SM within uncertainties of $\sim 10\%$ for bosons and $\sim 15\% - 30\%$ for the heavier fermions.

Further reading

- The ATLAS and CMS Collaborations:
  Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s}$=7 and 8 TeV with the ATLAS and CMS Experiments
  `http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.114.191803`
- The ATLAS and CMS Collaborations:
  Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s}$ = 7 and 8 TeV
  `https://cds.cern.ch/record/2053103`
- Nicholas Wardle's presentation at LHC seminar on March 2015
  `https://indico.cern.ch/event/360243/`
- Wouter Verkerke's presentation at LHC seminar on September 2015
  `https://indico.cern.ch/event/442438/`

Backup

Our weapon: the profile likelihood ratio $\Lambda(\vec{\alpha})$

- We estimate parameter of interest $\vec{\alpha}$, and treat systematic uncertainties as nuisance parameters $\vec{\theta}$.
- Construct the profile likelihood ratio to estimate $\vec{\alpha}$:

$$\Lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}, \text{ and}$$

derive the 68.3% confidence level interval from

$$-2 \ln \Lambda(\vec{\alpha}) \leq 1.$$