Measuring Higgs properties in proton-proton collisions with the CMS experiment

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6th of January 2016

Combination methodology

Our aim is to

- combine the data selected by individual analyses, and
- perform a fit to the combined data.

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

$\Rightarrow$ Include systematic uncertainties and correlations in the fit by using **the profile likelihood ratio** as the test statistic.

The standard model Higgs boson or something else?

- 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 $i \to H \to f$:

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

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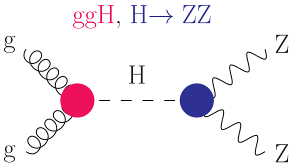
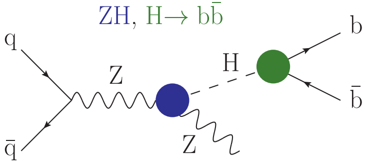
- New physics could produce a SM-like signal strength
  → *measure couplings from both production and decay!*





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

$$\kappa_\mathrm{g}^2 \sim 1.11 \cdot \kappa_\mathrm{t}^2 - 0.12 \cdot \kappa_\mathrm{b}^2 + 0.01 \cdot \kappa_\mathrm{t}\kappa_\mathrm{b}$$
$$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_\mathrm{W}^2 + 0.07 \cdot \kappa_\mathrm{t}^2 - 0.66 \cdot \kappa_\mathrm{W}\kappa_\mathrm{t}$$

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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

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

- 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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- If only SM physics is allowed → SM width rescaled by κ_{H}^2.
- If we allow also BSM contributions, $\mathrm{BR}_{\mathrm{BSM}}$ is not bounded
  → 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:

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

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

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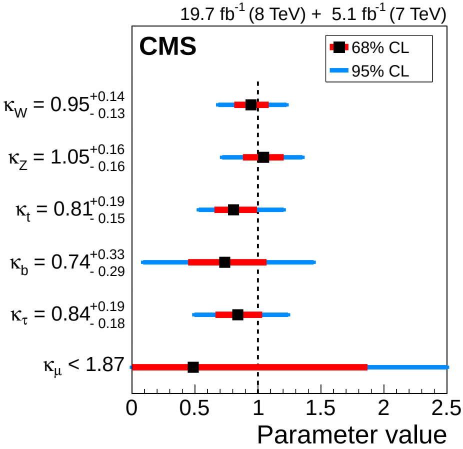

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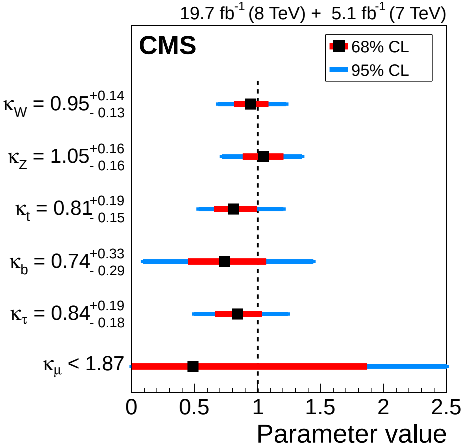
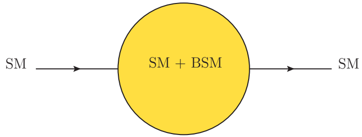
No significant deviations from the SM expectation!



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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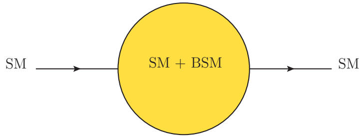
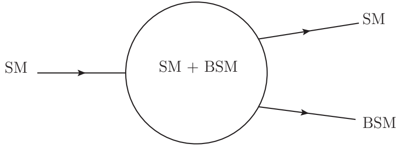


  2. **in loops and in decays**, thus $\mathrm{BR}_\mathrm{BSM} \geq 0$ and $\kappa_\mathrm{V} \leq 1$
     (natural bound in wide range of BSM physics models!)



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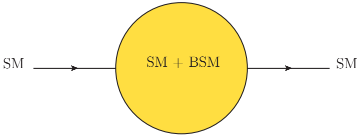

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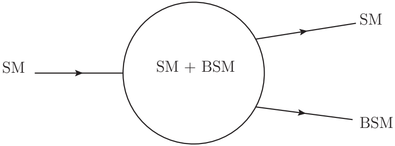
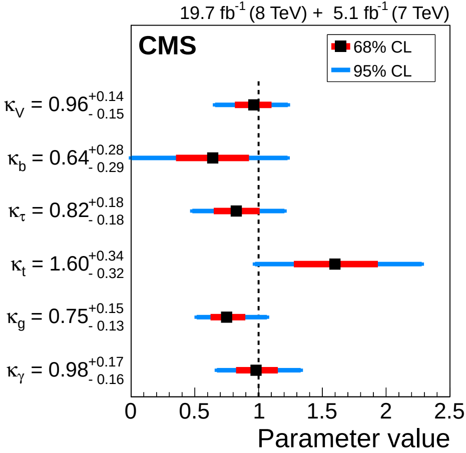


$\rightarrow$ Study κ_{g}, κ_{γ}, κ_{V}, κ_{b}, κ_{t}, and κ_{τ}, and in **scenario 2** also **BR**$_{\mathrm{BSM}}$.

Fit results when allowing BSM physics **only in loops**

- Fix $\mathrm{BR}_{\mathrm{BSM}} = 0$
  $\rightarrow$ study κ_{g}, κ_{γ}, κ_{V}, κ_{b}, κ_{t}, and κ_{τ}.

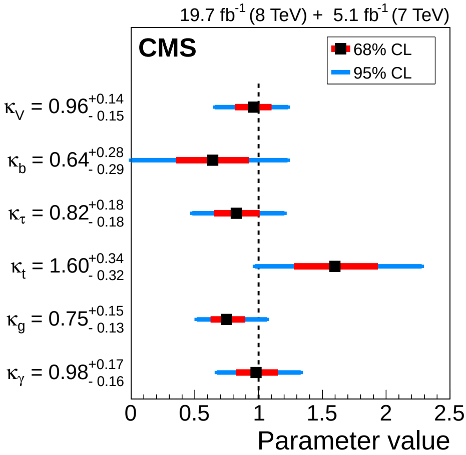


Fit results when allowing BSM physics **only in loops**

- Fix $\mathrm{BR}_{\mathrm{BSM}} = 0$
  $\rightarrow$ study κ_{g}, κ_{γ}, κ_{V}, κ_{b}, κ_{t}, and κ_{τ}.

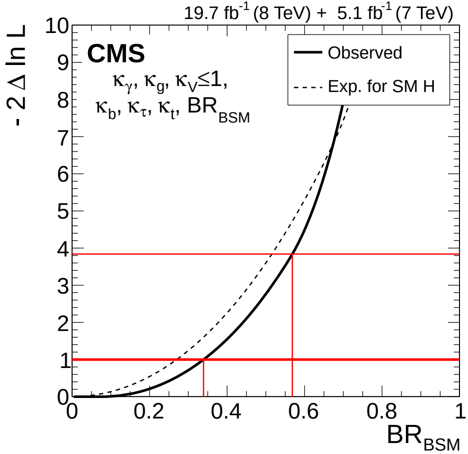
The p-value of the compatibility between the data and the SM predictions is 28%.

Couplings are compatible with the SM within uncertainties of $\sim$ 15% for bosons and $\sim$ 20% – 40% for t, b and τ.



Fit results when allowing BSM physics **in loops and in decays**

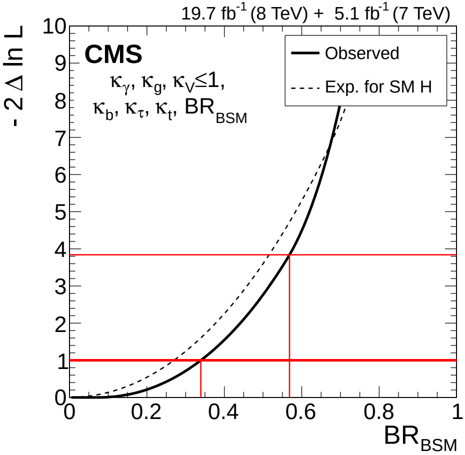
- Constrain $\kappa_V \leq 1$.
- Study $\mathrm{BR}_{\mathrm{BSM}} \geq 0$ while profiling κ_g, κ_γ, κ_V, κ_b, κ_t, and κ_τ.



Fit results when allowing BSM physics **in loops and in decays**

- Constrain $\kappa_{\rm V} \leq 1$.
- Study $\rm BR_{BSM} \geq 0$ while profiling $\kappa_{\rm g}$, κ_{γ}, $\kappa_{\rm V}$, $\kappa_{\rm b}$, $\kappa_{\rm t}$, and κ_{τ}.

We find $\rm BR_{BSM} < 0.57$ *at 95% CL.*



Conclusion

- 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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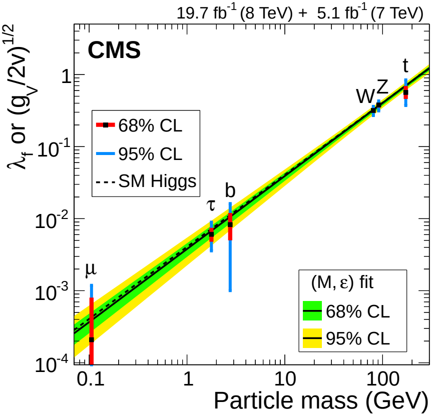


- We find couplings compatible with the SM within uncertainties of $\sim 15\%$ for bosons and $\sim 20\% - 40\%$ for the heavier fermions.

Further reading

- The CMS Collaboration:
  Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV
  http://dx.doi.org/10.1140/epjc/s10052-015-3351-7

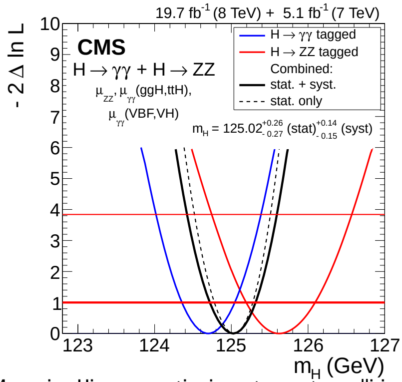
Backup

The profile likelihood ratio $\Lambda(\vec{\alpha})$

- Treat systematic uncertainties as nuisance parameters $\vec{\theta}$, study parameter(s) of interest $\vec{\alpha}$.
- 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 $-2 \ln \Lambda(\vec{\alpha}) \leq 1$.



BSM **in loops and in decays**: $\mathrm{BR}_{\mathrm{inv}}$ and $\mathrm{BR}_{\mathrm{undet}}$

- Recall $\mathrm{BR}_{\mathrm{BSM}} = \mathrm{BR}_{\mathrm{inv}} + \mathrm{BR}_{\mathrm{undet}}$.
- Combine the H(inv) search data and visible decay channels $\rightarrow$ study $\mathrm{BR}_{\mathrm{inv}}$ and $\mathrm{BR}_{\mathrm{undet}}$.
- Study $\mathrm{BR}_{\mathrm{inv}}$, assume $\mathrm{BR}_{\mathrm{undet}} = 0 \rightarrow \mathrm{BR}_{\mathrm{inv}} < 0.49$ at 95% CL.
- Study $\mathrm{BR}_{\mathrm{undet}}$, profile also $\mathrm{BR}_{\mathrm{inv}} \rightarrow \mathrm{BR}_{\mathrm{undet}} < 0.52$ at 95% CL.