A combined ATLAS and CMS analysis: searches for mass-degenerate Higgs bosons

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The standard model Higgs boson or something else?

- LHC Run 1 data allows to probe for
  - production modes ggF, VBF, WH, ZH, and ttH and
  - decay channels $\gamma\gamma$, $\mathrm{ZZ} \rightarrow 4\ell$, $\mathrm{WW} \rightarrow 2\ell 2\nu$, $\tau\tau$, bb, and $\mu\mu$.

- The analysis of Run 2 data is ongoing and not yet completed.

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

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

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- Two main reasons for deviations from the SM expectation $\mu_i^f = 1$:

1. couplings are not SM-like, or
2. we are measuring the sum of the signals from multiple particles!

Why do we want to study if the signal is due to mass-degenerate states?

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No, if they are closer than $\mathcal{O}(1)$ GeV from each other...

We can use the measured values of signal strengths instead!

Connection between the rank and the number of resonances

- Grossman et al.: arrange the signal strengths in a matrix and determine its rank. [2]
- The rank implies a lower bound on the number of resonances
  $\Rightarrow$ **If there is a single Higgs boson, the rank is 1.**

	$H \to \gamma\gamma$	$H \to ZZ$	$H \to WW$	$H \to \tau\tau$	$H \to bb$
ggF	$\mu_{ggF}^{\gamma\gamma}$	μ_{ggF}^{ZZ}	μ_{ggF}^{WW}	$\mu_{ggF}^{\tau\tau}$	μ_{ggF}^{bb}
VBF	$\mu_{VBF}^{\gamma\gamma}$	μ_{VBF}^{ZZ}	μ_{VBF}^{WW}	$\mu_{VBF}^{\tau\tau}$	μ_{VBF}^{bb}
WH	$\mu_{WH}^{\gamma\gamma}$	μ_{WH}^{ZZ}	μ_{WH}^{WW}	$\mu_{WH}^{\tau\tau}$	μ_{WH}^{bb}
ZH	$\mu_{ZH}^{\gamma\gamma}$	μ_{ZH}^{ZZ}	μ_{ZH}^{WW}	$\mu_{ZH}^{\tau\tau}$	μ_{ZH}^{bb}
ttH	$\mu_{ttH}^{\gamma\gamma}$	μ_{ttH}^{ZZ}	μ_{ttH}^{WW}	$\mu_{ttH}^{\tau\tau}$	μ_{ttH}^{bb}

- Rank can be computed only if the matrix is known exactly
  $\Rightarrow$ In reality the situation is much more complicated...

Best fit values of signal strength for each channel $i \to H \to f$

Production process		$H \to \gamma\gamma$ [fb] Best fit value	Uncertainty Stat	Syst	$H \to ZZ$ [fb] Best fit value	Uncertainty Stat	Syst	$H \to WW$ [pb] Best fit value	Uncertainty Stat	Syst	$H \to \tau\tau$ [fb] Best fit value	Uncertainty Stat	Syst	$H \to bb$ [pb] Best fit value	Uncertainty Stat	Syst
ggF	Measured	$48.0^{+10.0}_{-9.7}$	$^{+9.4}_{-9.4}$	$^{+3.2}_{-2.3}$	580^{+170}_{-160}	$^{+170}_{-160}$	$^{+40}_{-40}$	$3.5^{+0.7}_{-0.7}$	$^{+0.5}_{-0.5}$	$^{+0.5}_{-0.5}$	1300^{+700}_{-700}	$^{+400}_{-400}$	$^{+500}_{-500}$	–		
		$\left(^{+9.7}_{-9.5}\right)$	$\left(^{+9.4}_{-9.4}\right)$	$\left(^{+2.5}_{-1.6}\right)$	$\left(^{+150}_{-130}\right)$	$\left(^{+140}_{-130}\right)$	$\left(^{+30}_{-20}\right)$	$\left(^{+0.7}_{-0.7}\right)$	$\left(^{+0.5}_{-0.5}\right)$	$\left(^{+0.5}_{-0.5}\right)$	$\left(^{+700}_{-700}\right)$	$\left(^{+400}_{-400}\right)$	$\left(^{+500}_{-500}\right)$	–		
	Predicted	44 ± 5			510 ± 60			4.1 ± 0.5			1210 ± 140			11.0 ± 1.2		
	Ratio	$1.10^{+0.23}_{-0.22}$	$^{+0.22}_{-0.21}$	$^{+0.07}_{-0.05}$	$1.13^{+0.34}_{-0.31}$	$^{+0.33}_{-0.30}$	$^{+0.09}_{-0.07}$	$0.84^{+0.17}_{-0.17}$	$^{+0.12}_{-0.12}$	$^{+0.12}_{-0.11}$	$1.0^{+0.6}_{-0.6}$	$^{+0.4}_{-0.4}$	$^{+0.4}_{-0.4}$	–		
VBF	Measured	$4.6^{+1.9}_{-1.8}$	$^{+1.8}_{-1.7}$	$^{+0.6}_{-0.5}$	3^{+46}_{-26}	$^{+46}_{-25}$	$^{+7}_{-7}$	$0.39^{+0.14}_{-0.13}$	$^{+0.13}_{-0.12}$	$^{+0.07}_{-0.05}$	125^{+39}_{-37}	$^{+34}_{-32}$	$^{+19}_{-18}$	–		
		$\left(^{+1.8}_{-1.6}\right)$	$\left(^{+1.7}_{-1.6}\right)$	$\left(^{+0.5}_{-0.4}\right)$	$\left(^{+60}_{-39}\right)$	$\left(^{+60}_{-39}\right)$	$\left(^{+8}_{-5}\right)$	$\left(^{+0.15}_{-0.13}\right)$	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.07}_{-0.06}\right)$	$\left(^{+39}_{-37}\right)$	$\left(^{+34}_{-32}\right)$	$\left(^{+19}_{-18}\right)$	–		
	Predicted	3.60 ± 0.20			42.2 ± 2.0			0.341 ± 0.017			100 ± 6			0.91 ± 0.04		
	Ratio	$1.3^{+0.5}_{-0.5}$	$^{+0.5}_{-0.5}$	$^{+0.2}_{-0.1}$	$0.1^{+1.1}_{-0.6}$	$^{+1.1}_{-0.6}$	$^{+0.2}_{-0.2}$	$1.2^{+0.4}_{-0.4}$	$^{+0.4}_{-0.3}$	$^{+0.2}_{-0.2}$	$1.3^{+0.4}_{-0.4}$	$^{+0.3}_{-0.3}$	$^{+0.2}_{-0.2}$	–		
WH	Measured	$0.7^{+2.1}_{-1.9}$	$^{+2.1}_{-1.8}$	$^{+0.3}_{-0.3}$	–			$0.24^{+0.18}_{-0.16}$	$^{+0.15}_{-0.14}$	$^{+0.10}_{-0.08}$	-64^{+64}_{-61}	$^{+55}_{-50}$	$^{+32}_{-34}$	$0.42^{+0.21}_{-0.20}$	$^{+0.17}_{-0.16}$	$^{+0.12}_{-0.11}$
		$\left(^{+1.9}_{-1.8}\right)$	$\left(^{+1.9}_{-1.8}\right)$	$\left(^{+0.1}_{-0.1}\right)$	–			$\left(^{+0.16}_{-0.14}\right)$	$\left(^{+0.14}_{-0.13}\right)$	$\left(^{+0.08}_{-0.07}\right)$	$\left(^{+67}_{-64}\right)$	$\left(^{+60}_{-54}\right)$	$\left(^{+30}_{-32}\right)$	$\left(^{+0.22}_{-0.21}\right)$	$\left(^{+0.18}_{-0.17}\right)$	$\left(^{+0.12}_{-0.11}\right)$
	Predicted	1.60 ± 0.09			18.8 ± 0.9			0.152 ± 0.007			44.3 ± 2.8			0.404 ± 0.017		
	Ratio	$0.5^{+1.3}_{-1.2}$	$^{+1.3}_{-1.1}$	$^{+0.2}_{-0.2}$	–			$1.6^{+1.2}_{-1.0}$	$^{+1.0}_{-0.9}$	$^{+0.6}_{-0.5}$	$-1.4^{+1.4}_{-1.4}$	$^{+1.2}_{-1.1}$	$^{+0.7}_{-0.8}$	$1.0^{+0.5}_{-0.5}$	$^{+0.4}_{-0.4}$	$^{+0.3}_{-0.3}$
ZH	Measured	$0.5^{+2.9}_{-2.4}$	$^{+2.8}_{-2.3}$	$^{+0.5}_{-0.2}$	–			$0.53^{+0.23}_{-0.20}$	$^{+0.21}_{-0.19}$	$^{+0.10}_{-0.07}$	58^{+56}_{-47}	$^{+52}_{-44}$	$^{+20}_{-16}$	$0.08^{+0.09}_{-0.09}$	$^{+0.08}_{-0.08}$	$^{+0.04}_{-0.04}$
		$\left(^{+2.3}_{-1.9}\right)$	$\left(^{+2.3}_{-1.9}\right)$	$\left(^{+0.1}_{-0.1}\right)$	–			$\left(^{+0.17}_{-0.14}\right)$	$\left(^{+0.16}_{-0.14}\right)$	$\left(^{+0.05}_{-0.04}\right)$	$\left(^{+49}_{-40}\right)$	$\left(^{+46}_{-38}\right)$	$\left(^{+16}_{-12}\right)$	$\left(^{+0.10}_{-0.09}\right)$	$\left(^{+0.09}_{-0.08}\right)$	$\left(^{+0.05}_{-0.04}\right)$
	Predicted	0.94 ± 0.06			11.1 ± 0.6			0.089 ± 0.005			26.1 ± 1.8			0.238 ± 0.012		
	Ratio	$0.5^{+3.0}_{-2.5}$	$^{+3.0}_{-2.5}$	$^{+0.5}_{-0.2}$	–			$5.9^{+2.6}_{-2.2}$	$^{+2.3}_{-2.1}$	$^{+1.1}_{-0.8}$	$2.2^{+2.2}_{-1.8}$	$^{+2.0}_{-1.7}$	$^{+0.8}_{-0.6}$	$0.4^{+0.4}_{-0.4}$	$^{+0.3}_{-0.3}$	$^{+0.2}_{-0.2}$
ttH	Measured	$0.64^{+0.48}_{-0.38}$	$^{+0.48}_{-0.38}$	$^{+0.07}_{-0.04}$	–			$0.14^{+0.05}_{-0.05}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	-15^{+30}_{-26}	$^{+26}_{-22}$	$^{+15}_{-15}$	$0.08^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.06}_{-0.06}$
		$\left(^{+0.45}_{-0.34}\right)$	$\left(^{+0.44}_{-0.33}\right)$	$\left(^{+0.10}_{-0.05}\right)$	–			$\left(^{+0.04}_{-0.04}\right)$	$\left(^{+0.04}_{-0.04}\right)$	$\left(^{+0.02}_{-0.02}\right)$	$\left(^{+31}_{-26}\right)$	$\left(^{+26}_{-22}\right)$	$\left(^{+16}_{-13}\right)$	$\left(^{+0.07}_{-0.06}\right)$	$\left(^{+0.04}_{-0.04}\right)$	$\left(^{+0.06}_{-0.05}\right)$
	Predicted	0.294 ± 0.035			3.4 ± 0.4			0.0279 ± 0.0032			8.1 ± 1.0			0.074 ± 0.008		
	Ratio	$2.2^{+1.6}_{-1.3}$	$^{+1.6}_{-1.3}$	$^{+0.2}_{-0.1}$	–			$5.0^{+1.8}_{-1.7}$	$^{+1.5}_{-1.5}$	$^{+1.0}_{-0.9}$	$-1.9^{+3.7}_{-3.3}$	$^{+3.2}_{-2.7}$	$^{+1.9}_{-1.8}$	$1.1^{+1.0}_{-1.0}$	$^{+0.5}_{-0.5}$	$^{+0.8}_{-0.8}$

http://arxiv.org/abs/1606.02266

Missing elements, uncertainties, and correlations!

A solution: the profile likelihood ratio test

Evaluate the statistical compatibility of the measured matrix with a rank 1 matrix, i.e.

1. **construct parametrizations** for null and alternative hypotheses: rank 1 vs. rank N
2. **define the test statistic** as a profile likelihood ratio to discriminate between the two hypotheses
3. generate the expected distribution of the test statistic and **determine the p-value** for the null hypothesis.

$\Rightarrow$ Discriminate between a single Higgs boson, with arbitrary scalar couplings, and the sum of any number of nearly-degenerate Higgs bosons!

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Check how consistent the data is with the assumption of a single particle!

Two hypotheses, two parametrizations

General matrix parameterisation: rank($\mathcal{M}$) =5

Signal model	$H \to \gamma\gamma$	$H \to ZZ$	$H \to WW$	$H \to \tau\tau$	$H \to bb$
ggF	$\mu_{ggF}^{\gamma\gamma}$	μ_{ggF}^{ZZ}	μ_{ggF}^{WW}	$\mu_{ggF}^{\tau\tau}$	μ_{ggF}^{bb}
VBF	$\lambda_{VBF}^{\gamma\gamma}\,\mu_{ggF}^{\gamma\gamma}$	$\lambda_{VBF}^{ZZ}\,\mu_{ggF}^{ZZ}$	$\lambda_{VBF}^{WW}\,\mu_{ggF}^{WW}$	$\lambda_{VBF}^{\tau\tau}\,\mu_{ggF}^{\tau\tau}$	$\lambda_{VBF}^{bb}\,\mu_{ggF}^{bb}$
WH	$\lambda_{WH}^{\gamma\gamma}\,\mu_{ggF}^{\gamma\gamma}$	$\lambda_{WH}^{ZZ}\,\mu_{ggF}^{ZZ}$	$\lambda_{WH}^{WW}\,\mu_{ggF}^{WW}$	$\lambda_{WH}^{\tau\tau}\,\mu_{ggF}^{\tau\tau}$	$\lambda_{WH}^{bb}\,\mu_{ggF}^{bb}$
ZH	$\lambda_{ZH}^{\gamma\gamma}\,\mu_{ggF}^{\gamma\gamma}$	$\lambda_{ZH}^{ZZ}\,\mu_{ggF}^{ZZ}$	$\lambda_{ZH}^{WW}\,\mu_{ggF}^{WW}$	$\lambda_{ZH}^{\tau\tau}\,\mu_{ggF}^{\tau\tau}$	$\lambda_{ZH}^{bb}\,\mu_{ggF}^{bb}$
ttH	$\lambda_{ttH}^{\gamma\gamma}\,\mu_{ggF}^{\gamma\gamma}$	$\lambda_{ttH}^{ZZ}\,\mu_{ggF}^{ZZ}$	$\lambda_{ttH}^{WW}\,\mu_{ggF}^{WW}$	$\lambda_{ttH}^{\tau\tau}\,\mu_{ggF}^{\tau\tau}$	$\lambda_{ttH}^{bb}\,\mu_{ggF}^{bb}$

Single-state matrix parameterisation: rank($\mathcal{M}$) =1

Signal model	$H \to \gamma\gamma$	$H \to ZZ$	$H \to WW$	$H \to \tau\tau$	$H \to bb$
ggF	$\mu_{ggF}^{\gamma\gamma}$	μ_{ggF}^{ZZ}	μ_{ggF}^{WW}	$\mu_{ggF}^{\tau\tau}$	μ_{ggF}^{bb}
VBF	$\lambda_{VBF}\,\mu_{ggF}^{\gamma\gamma}$	$\lambda_{VBF}\,\mu_{ggF}^{ZZ}$	$\lambda_{VBF}\,\mu_{ggF}^{WW}$	$\lambda_{VBF}\,\mu_{ggF}^{\tau\tau}$	$\lambda_{VBF}\,\mu_{ggF}^{bb}$
WH	$\lambda_{WH}\,\mu_{ggF}^{\gamma\gamma}$	$\lambda_{WH}\,\mu_{ggF}^{ZZ}$	$\lambda_{WH}\,\mu_{ggF}^{WW}$	$\lambda_{WH}\,\mu_{ggF}^{\tau\tau}$	$\lambda_{WH}\,\mu_{ggF}^{bb}$
ZH	$\lambda_{ZH}\,\mu_{ggF}^{\gamma\gamma}$	$\lambda_{ZH}\,\mu_{ggF}^{ZZ}$	$\lambda_{ZH}\,\mu_{ggF}^{WW}$	$\lambda_{ZH}\,\mu_{ggF}^{\tau\tau}$	$\lambda_{ZH}\,\mu_{ggF}^{bb}$
ttH	$\lambda_{ttH}\,\mu_{ggF}^{\gamma\gamma}$	$\lambda_{ttH}\,\mu_{ggF}^{ZZ}$	$\lambda_{ttH}\,\mu_{ggF}^{WW}$	$\lambda_{ttH}\,\mu_{ggF}^{\tau\tau}$	$\lambda_{ttH}\,\mu_{ggF}^{bb}$

In the case of a single resonance, i.e. rank 1 matrix,

the relative scaling factors $\lambda_i = \mu_i^f / \mu_{ggF}^f$ do not depend on the decay mode!

The profile likelihood ratio

- Define the test statistic using ratio between the profile likelihood of the two aforementioned models:

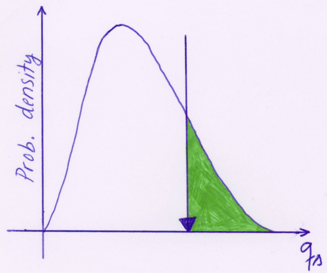
$$q_\lambda = -2 \ln \frac{\mathcal{L}(\text{data}|\lambda_i^j = \hat{\lambda}_i, \hat{\mu}^j_{ggF})}{\mathcal{L}(\text{data}|\hat{\lambda}_i^j, \hat{\mu}'^j_{ggF})}$$

- If the signal strength matrix has rank 1, both parametrizations fit the data equally well $\rightarrow q_\lambda$ is small.

- If the rank is not equal to unity, the most general 5×5 parametrization will fit the data better $\rightarrow q_\lambda$ is large.

P-values for the single Higgs boson hypothesis

- Generate pseudo-data samples randomly from the best fit values of rank 1 hypothesis to obtain the expected distribution
- Compare the observed value of q_λ in data with the expected distribution
  $\rightarrow$ the p-value for the single Higgs boson hypothesis.
- Apply the approach to the ATLAS, CMS, and LHC measurements!



	$p = P(q_\lambda > q_\lambda^{\mathrm{obs}} \mid \hat{\mu}_{\mathrm{i}}^{\mathrm{obs}}, \hat{\lambda}_{\mathrm{j}}^{\mathrm{obs}})$
ATLAS	58%
CMS	33%
LHC	$(29 \pm 2)\%$

http://arxiv.org/abs/1606.02266

Conclusion

- A method that can be used to test for the presence of multiple Higgs bosons has been developed.
- The method takes into account the uncertainties, correlations and missing elements of data.
- Applying the method to the ATLAS, CMS and LHC measurements results p-values of 58%, 33%, and 29% for the single Higgs boson hypothesis, respectively

  ⇒ **Compatible with the hypothesis of a single Higgs boson (as in the SM)!**

Thank you for your attention!

Any questions?

Call for contributions

At the moment we only study how compatible the data are with the single Higgs boson hypothesis...

but if *specific benchmark models* were provided, the method could also be adapted to *quote exclusions for alternative BSM hypotheses*!

⟹ **Inputs from the theory community are welcome!**

References for further reading

1. John F. Gunion, Yun Jiang, Sabine Kraml:
   Diagnosing Degenerate Higgs Bosons at 125 GeV
   (http://arxiv.org/abs/1208.1817)
2. Yuval Grossman, Ze'ev Surujon, Jure Zupan:
   How to test for mass degenerate Higgs resonances
   (http://arxiv.org/abs/1301.0328)
3. André David, Jaana Heikkilä, Giovanni Petrucciani:
   Searching for degenerate Higgs bosons
   (http://arxiv.org/abs/1409.6132).
3. 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
   (https://arxiv.org/abs/1412.8662).
4. 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://arxiv.org/abs/1606.02266).

- The Higgs boson cartoon by Jorge Cham, Picture of Einstein by unknown.