Exotic-spin and anomalous coupling study of the H boson with the H→ZZ→4l channel

Can You (Johns Hopkins University), for CMS collaboration

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Introduction

The observation of a new boson with a mass around 125 GeV and properties consistent with the standard model (SM) Higgs boson was reported by the ATLAS and CMS Collaborations in 2012. The discovery was followed by a comprehensive set of measurements of its properties to determine if the new boson follows the SM predictions or if there are indications for physics beyond the SM (BSM).

Tested Models

❖ Decay of spin-zero resonance

$$A(HVV) \sim \left[a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{\left(\Lambda_1^{VV}\right)^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

- The **tree-level SM-like** contribution corresponds to **a_1≠0**. Small values of other couplings can be generated through loop effects in the SM, and can be ascribed to **anomalous couplings**.
- **Λ_1** is the **scale of BSM physics** and is a free parameter of the model.
- The parity-conserving interaction of a **pseudoscalar** (CP-odd state) corresponds to the **a_3** terms, while the other terms describe the parity-conserving interaction of a scalar (CP-even state).
- The anomalous couplings are parameterized in terms of **effective fractional cross sections** $f_{\Lambda 1}$,f_{a2} and f_{a3} ,and their **phases** $\phi_{\Lambda 1}$, ϕ_{a2} and ϕ_{a3} .

❖ Decay of spin-one resonance

$$A(X_{J=1}VV) \sim b_1^{VV}\left[(\epsilon_{V1}^* q)(\epsilon_{V2}^* \epsilon_X) + (\epsilon_{V2}^* q)(\epsilon_{V1}^* \epsilon_X)\right] + b_2^{VV} \epsilon_{\alpha\mu\nu\beta} \epsilon_X^\alpha \epsilon_{V1}^{*\mu} \epsilon_{V2}^{*\nu} \tilde{q}^\beta$$

- In the case of a spin-one resonance, the amplitude of its interaction with a pair of massive gauge bosons consists of two independent terms. Here the ***b_1*≠0** coupling corresponds to a **vector particle**, while the ***b_2*≠0** coupling corresponds to a **pseudovector**.
- An **effective fractional cross section f_{b2}** is defined to test some particular **mixture** of the vector and pseudovector states.

$$f_{b2}^{VV} = \frac{\left|b_2^{VV}\right|^2 \sigma_{b2}}{\left|b_1^{VV}\right|^2 \sigma_{b1} + \left|b_2^{VV}\right|^2 \sigma_{b2}}$$

❖ Decay of spin-two resonance

$$\begin{aligned} A(X_{J=2}VV) \sim \Lambda^{-1}\Big[& 2c_1^{VV} t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2c_2^{VV} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta} + c_3^{VV} t_{\beta\nu} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} (f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}) \\ & + c_4^{VV} t_{\mu\nu} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} f^{*1,\alpha\beta} f^{*2}_{\alpha\beta} + m_V^2 \Big(2c_5^{VV} t_{\mu\nu} \epsilon_{V1}^{*\mu} \epsilon_{V2}^{*\nu} + 2c_6^{VV} t_{\mu\nu} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} (\epsilon_{V1}^{*\nu} \epsilon_{V2}^{*\alpha} - \epsilon_{V1}^{*\alpha} \epsilon_{V2}^{*\nu}) + c_7^{VV} t_{\mu\nu} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} \epsilon_{V1}^* \epsilon_{V2}^* \Big) \\ & + c_8^{VV} t_{\mu\nu} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} f^{*1,\alpha\beta} \tilde{f}^{*2}_{\alpha\beta} + m_V^2 \Big(c_9^{VV} t^{\mu\alpha} \frac{\tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon_{V1}^{*\nu} \epsilon_{V2}^{*\rho} q^\sigma}{\Lambda^2} + c_{10}^{VV} t^{\mu\alpha} \frac{\tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma (\epsilon_{V1}^{*\nu}(q\epsilon_{V2}^*) + \epsilon_{V2}^{*\nu}(q\epsilon_{V1}^*))}{\Lambda^4} \Big)\Big] \end{aligned}$$

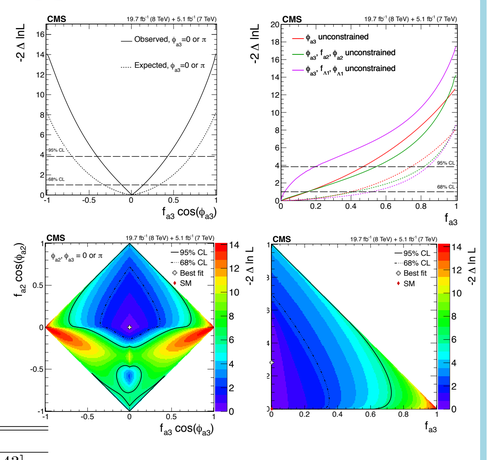
- The couplings **c_1** and **c_5** correspond to parity-conserving interaction of a spin-two tensor with **minimal gravity-like couplings**.
- List of spin-two models considered. The subscript m (minimal couplings), h (couplings with higher-dimension operators) and b (bulk) distinguish different scenarios.

J^P Model	gg→ X Couplings	$q\bar{q} \to X$ Couplings	$X \to VV$ Couplings
2^+_m	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_1^{VV} = c_5^{VV} \neq 0$
2^+_{h2}	$c_2^{gg} \neq 0$	$\rho_1 \neq 0$	$c_2^{VV} \neq 0$
2^+_{h3}	$c_3^{gg} \neq 0$	$\rho_1 \neq 0$	$c_3^{VV} \neq 0$
2^+_h	$c_4^{gg} \neq 0$	$\rho_1 \neq 0$	$c_4^{VV} \neq 0$
2^+_b	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_1^{VV} \ll c_5^{VV} \neq 0$
2^+_{h6}	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_6^{VV} \neq 0$
2^+_{h7}	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_7^{VV} \neq 0$
2^-_h	$c_8^{gg} \neq 0$	$\rho_2 \neq 0$	$c_8^{VV} \neq 0$
2^-_{h9}	$c_8^{gg} \neq 0$	$\rho_2 \neq 0$	$c_9^{VV} \neq 0$
2^-_{h10}	$c_8^{gg} \neq 0$	$\rho_2 \neq 0$	$c_{10}^{VV} \neq 0$

Spin-zero Results

❖ One parameter measurement

- Test 1 : All other couplings are fixed to SM predictions. Only real couplings are considered.
- Test 2 : Phase and additional HZZ couplings are unconstrained



❖ Two parameter measurement

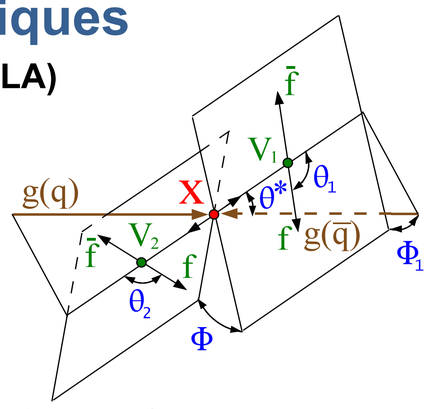
- Consider two anomalous couplings at the same time
- With and without the constraints on the couplings

Measurement	$f_{\Lambda 1}$	f_{a2}	f_{a3}
$\phi_{ai} = 0$	$0.22^{+0.10}_{-0.16}$ [0.00, 0.37] ($0.00^{+0.16}_{-0.00}$ [0.00, 0.27] ∪[0.92, 1.00])	$0.00^{+0.42}_{-0.00}$ [0.00, 1.00] ($0.00^{+0.35}_{-0.00}$ [0.00, 1.00])	$0.00^{+0.14}_{-0.00}$ [0.00, 0.43] ($0.00^{+0.33}_{-0.00}$ [0.00, 0.70])
$\phi_{ai} = \pi$	$0.00^{+0.08}_{-0.00}$ [0.00, 0.82] ($0.00^{+0.87}_{-0.00}$ [0.00, 1.00])	$0.00^{+0.06}_{-0.00}$ [0.00, 0.15] ∪[0.56, 0.68] ($0.00^{+0.08}_{-0.00}$ [0.00, 0.18] ∪ [0.62, 0.73])	$0.00^{+0.11}_{-0.00}$ [0.00, 0.40] ($0.00^{+0.32}_{-0.00}$ [0.00, 0.70])
any ϕ_{ai}	$0.39^{+0.16}_{-0.31}$ [0.00, 0.57] ($0.00^{+0.85}_{-0.00}$ [0.00, 1.00])	$0.32^{+0.28}_{-0.32}$ [0.00, 1.00] ($0.00^{+0.59}_{-0.00}$ [0.00, 1.00])	$0.00^{+0.17}_{-0.00}$ [0.00, 0.47] ($0.00^{+0.40}_{-0.00}$ [0.00, 0.74])
any $\phi_{ai}, f_{\Lambda 1}, \phi_{\Lambda 1}$		$0.11^{+0.16}_{-0.11}$ [0.00, 0.65] ($0.00^{+0.72}_{-0.00}$ [0.00, 1.00])	$0.00^{+0.02}_{-0.00}$ [0.00, 0.19] ($0.00^{+0.52}_{-0.00}$ [0.00, 0.84])
any $\phi_{ai}, f_{a2}, \phi_{a2}$	$0.28^{+0.21}_{-0.15}$ [0.00, 0.63] ($0.00^{+0.85}_{-0.00}$ [0.00, 1.00])		$0.00^{+0.15}_{-0.00}$ [0.00, 0.54] ($0.00^{+0.42}_{-0.00}$ [0.00, 0.81])
any $\phi_{ai}, f_{a3}, \phi_{a3}$	$0.42^{+0.09}_{-0.33}$ [0.00, 0.57] ($0.00^{+0.86}_{-0.00}$ [0.00, 1.00])	$0.28^{+0.29}_{-0.28}$ [0.00, 0.97] ($0.00^{+0.59}_{-0.00}$ [0.00, 1.00])	

Overall, all anomalous HVV couplings are found to be consistent with zero, which is also consistent with the expectation from the SM.

Analysis Techniques

Matrix Element Likelihood Approach (MELA)

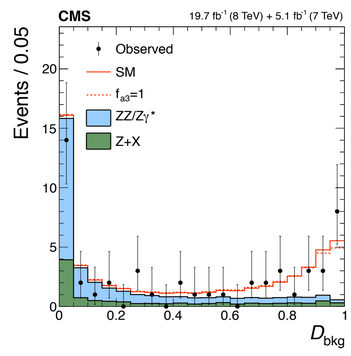


Observables :

- five production and decay angles
- invariant masses of dilepton pairs
- invariant mass of the four-lepton system

Kinematic Discriminants :

- Probabilities are calculated using the LO matrix elements as a function of angular and mass observables.

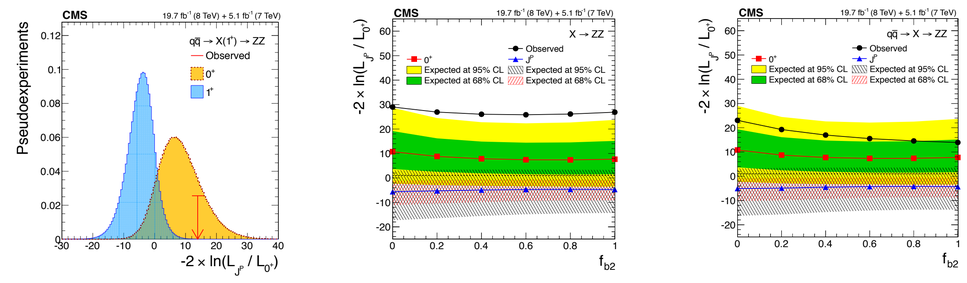


- $\mathcal{D}_{\rm bkg}$: separate signal from backgrounds
$$\mathcal{D}_{\rm bkg} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + c \times \mathcal{P}_{q\bar{q}ZZ}}$$
- $\mathcal{D}_{JP}$: separate SM signal from alternative J^P state.
$$\mathcal{D}_{JP} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + \mathcal{P}_{JP}}$$
- $\mathcal{D}_{\rm int}$: isolate interference between SM and anomalous coupling contributions.
$$\mathcal{D}_{\rm int} = \frac{\mathcal{P}_{JP}^{\rm int}(m_1, m_2, \vec{\Omega} | m_{4\ell})}{\mathcal{P}_{\rm SM}^{\rm kin} + \mathcal{P}_{JP}^{\rm kin}}$$

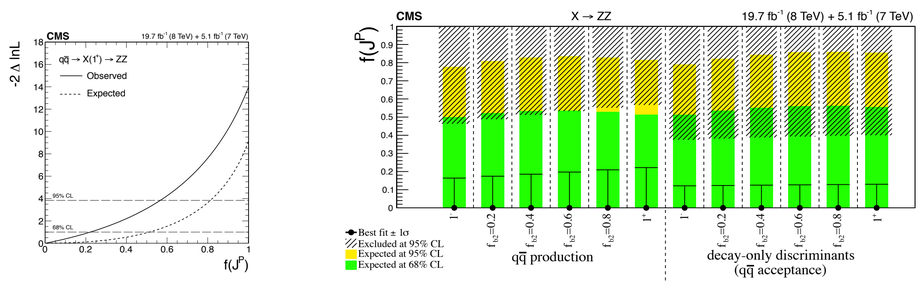
Spin-one Results

- Two scenarios are tested : $q\bar{q}$ production and using only decay information (production-independent)
- Hypothesis testing is performed for a discrete set of values of the parameter f_{b2}
- The input observables are $(\mathcal{D}_{\rm bkg}, \mathcal{D}_{1^-}, \mathcal{D}_{1^+})$

Distribution of the test statistic for $q\bar{q}$ produced 1^+ hypothesis and the summary as a function of f_{b2} in the $q\bar{q}$ production and decay-only analysis :



Likelihood scan as a function of the non-interfering fractions $f(J^P)$ for $q\bar{q}$ produced 1^+ and the summary of $f(J^P)$ as a function of f_{b2} :

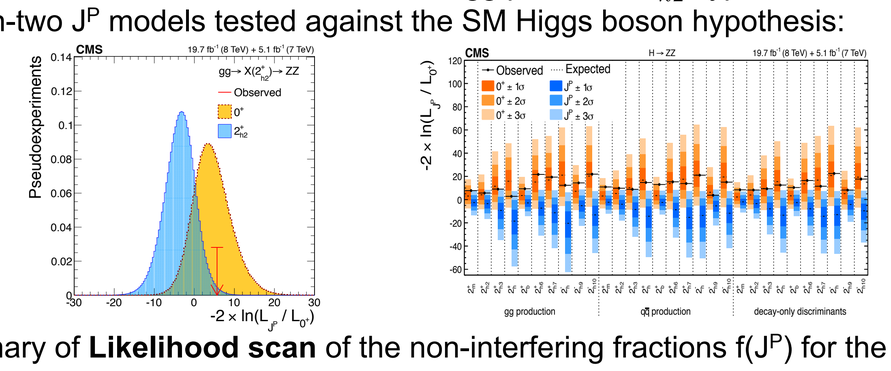


Any arbitrary spin-one model for the resonance observed in the X → ZZ → 4l decay mode with any mixture of parity-even and parity-odd interactions and any production mechanism is excluded at a CL of 99.97% or higher.

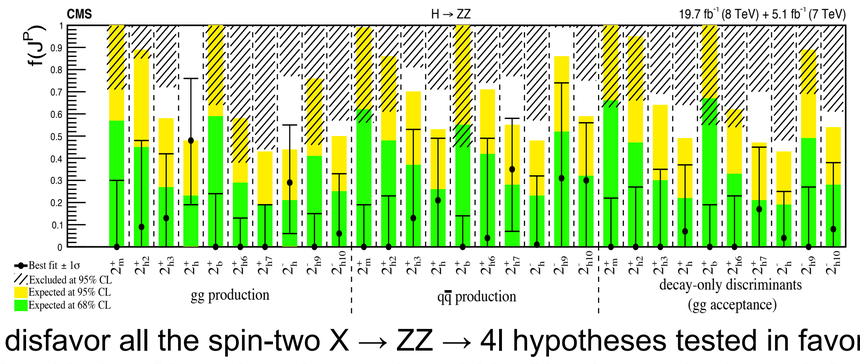
Spin-two Results

- Three scenarios are tested : gg, $q\bar{q}$ production and using only decay information (production-independent)
- The input observables are $(\mathcal{D}_{\rm bkg}, \mathcal{D}_{JP})$

Distribution of the test statistic for the gg produced 2^+_{h2} hypothesis and summary of spin-two J^P models tested against the SM Higgs boson hypothesis:



Summary of **Likelihood scan** of the non-interfering fractions $f(J^P)$ for the spin-two models:



The data disfavor all the spin-two X → ZZ → 4l hypotheses tested in favor of the SM hypothesis with 1 − *CLs* values larger than 99% CL when only decay information is used.

References

CMS Collaboration, "Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV", arXiv:1411.3441