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Determination of properties of a Higgs-like resonance at LHC: separation of spin hypotheses

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A resonance has been recently discovered with mass around 126 GeV by CMS and ATLAS experiments in the search for the Higgs boson. Little is actually known about this new resonance and the measurement of its properties, in order to establish if it is the long-awaited Standard Model Higgs, is the most interesting topic in High Energy Physics nowadays. In this document, the prospects for the spin/parity measurement of the new resonance will be shown.

36th International Conference on High Energy Physics,
July 4-11, 2012
Melbourne, Australia

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[†] The work presented here has been done in collaboration with Y. Gao, A. V. Gritsan, K. Melnikov, M. Schulze, N. V. Tran, and A. Whitbeck

PoS(ICHEP2012)040

1. Amplitudes and angular distributions for $gg \to X \to VV$

The most general amplitude for production and decay of a spin 0 resonance into a couple of vector bosons can be written as

$$A(X \to VV) = v^{-1} \varepsilon_1^{*\mu} \varepsilon_2^{*\nu} (a_1 g_{\mu\nu} M_X^2 + a_2 q_{1\mu} q_{2\nu} + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta) \tag{1.1}$$

The non-zero values of the couplings a_i determine the spin/parity of the resonance: e.g., the decay of the scalar (0^+) Standard Model (SM) Higgs into ZZ or WW has non-zero a_1, very small contribution ($\sim$ 1%) from NLO for a_2 and completely negligible value of a_3. The decay into $\gamma\gamma$ has instead non zero value for $a_1 = -a_2/2$. Specific helicity amplitudes can be computed for particular configurations of helicity of the V bosons:

$$A_{00} = -\frac{M_X^4}{v}\left(a_1 x + a_2 \frac{M_{V1} M_{V2}}{M_X^2}(x^2-1)\right) \qquad A_{\pm\pm} = \frac{M_X^2}{v}\left(a_1 \pm i a_3 \frac{M_{V1} M_{V2}}{M_X^2}\sqrt{x^2-1}\right) \tag{1.2}$$

Where $x = (M_X^2 - M_{V1}^2 - M_{V2}^2)/(2M_{V1}M_{V2})$. These helicity amplitudes depend on the kinematics of the bosons and on the a_i couplings and they can be used to parametrize the distribution of the V masses and teh angular distributions of the final decay products. Comparing these distributions to data, the value of the a_i couplings can be measured, the needed ingredients being

- a complete analytical computation of the angular and mass distributions in terms of helicity amplitudes for any spin/parity hypothesis, as reported in [1, 2]

- a Monte Carlo (MC) implementing the most general tensorial structure for amplitude of any spin/parity hypothesis, also documented in [1, 2]

The analytical description of the ideal model is needed to build the most optimal likelihood discriminant for separation of different signal hypothesis. The MC is needed to include full simulation of detector effects. Moreover the analytical description and the MC are powerful tool to cross-check each other, as can be seen in Fig. 1.

2. Application to Higgs search in the $ZZ \to 4l$ channel

The complete information about angular and mass shapes is exploited in the CMS $H \to ZZ \to 4l$ analysis to enhance the separation between the SM signal and the ZZ EWK-continuum background. In Fig. 2 the $H \to ZZ \to 4l$ distributions, after including a simplified description of CMS-like detector effects (lepton smearing and acceptance cuts), are shown. Comparing the distributions with the ideal case in Fig. 1, the distortion of the shapes due to acceptance can be appreciated: the different sculpting for $cos\theta_1$ and $cos\theta_2$ is due to different p_T cuts on the leptons coming from the off-shell and on-shell Z, a large acceptance effect is also visible in ϕ_1. Despite of the mentioned acceptance effects, some angles keep sizable discrimination power between signal and background (eg, $cos\theta_1$, $cos\theta^*$, ϕ) but the most discriminating variable is the mass of the off-shell Z. It is also interesting to notice the enhancement in signal of the low mass tail for the on-shell Z.

PoS(ICHEP2012)040

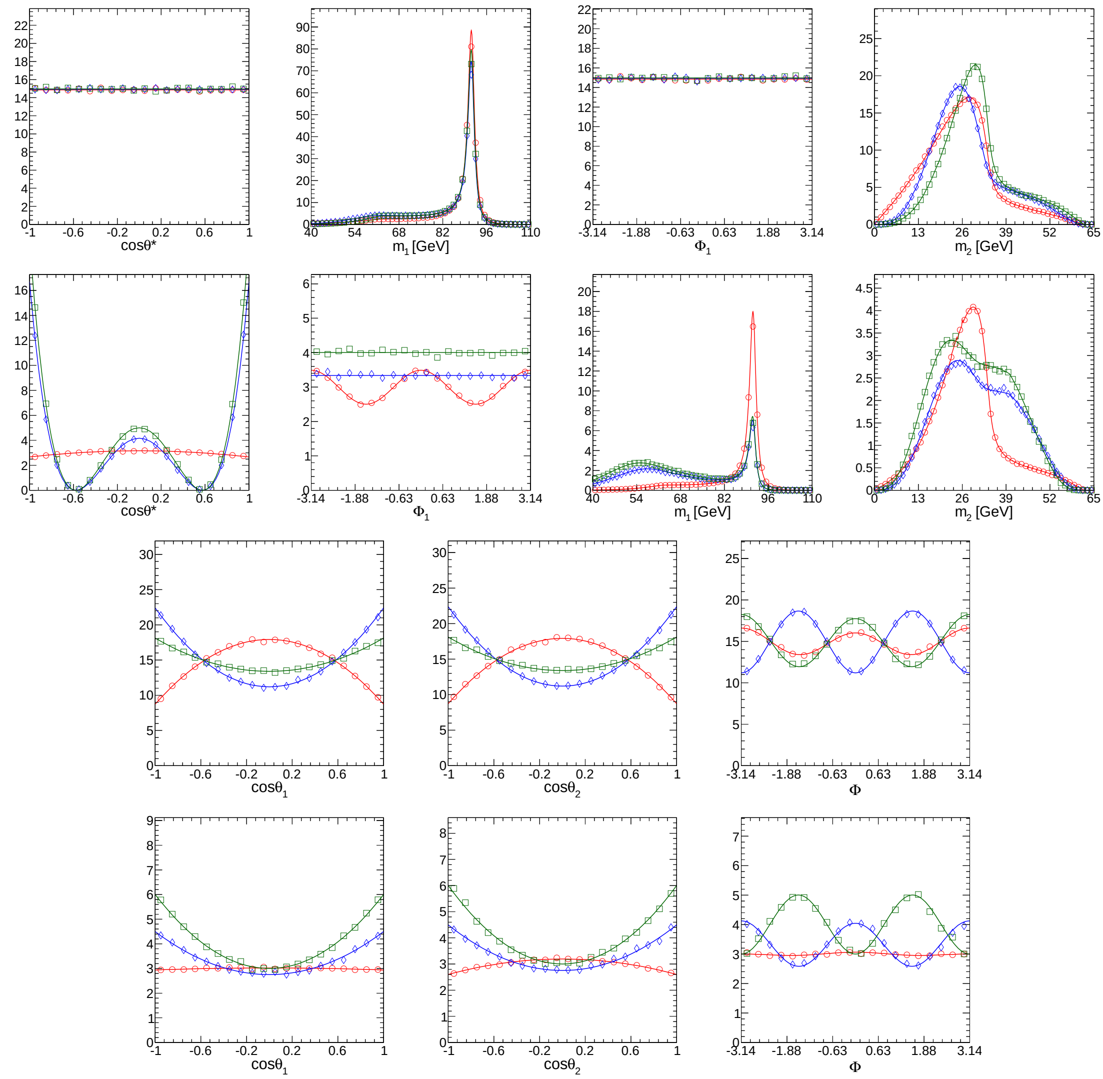

Figure 1: Distributions of the observables in the $H \to ZZ \to 4l$ analysis, as defined in [1]. First and third row: spin-zero signal; second and fourth row: spin-two signal. The signal hypotheses shown are J+m (red circles), J+h (green squares), J-h (blue diamonds), as defined in [1]. Points show simulated events and lines show projections of analytical distributions.

The most optimal way to combine these discriminating variables in a single likelihood is by defining

$$MELA = \frac{P_{sig}}{P_{sig}+P_{bkg}} = \left[1+\frac{P_{bkg}(\theta^*,\phi_1,m_1,m_2,\theta_1,\theta_2,\phi)}{P_{sig}(\theta^*,\phi_1,m_1,m_2,\theta_1,\theta_2,\phi)}\right]^{-1} \tag{2.1}$$

also known as MELA (Matrix Element Likelihood Approach), where P_{sig} and P_{bkg} are the analytical PDF for signal and background. The distribution of the MELA discriminant in SM signal and ZZ background is shown in Fig. 2. Adding this variable to the $H \to ZZ \to 4l$ search, on top of the 4-leptons mass distribution, is expected to increase the signal/background significance by ∼15%. Indeed, the $H \to ZZ \to 4l$ discovery analysis from the CMS experiment [3] includes MELA: the resulting observed significance is 3.2 σ with $5+5fb^{-1}$ at 7 and 8 TeV, compared to 2.2 σ which is obtained with a simple 1D analysis exploiting only the 4-leptons mass distribution.

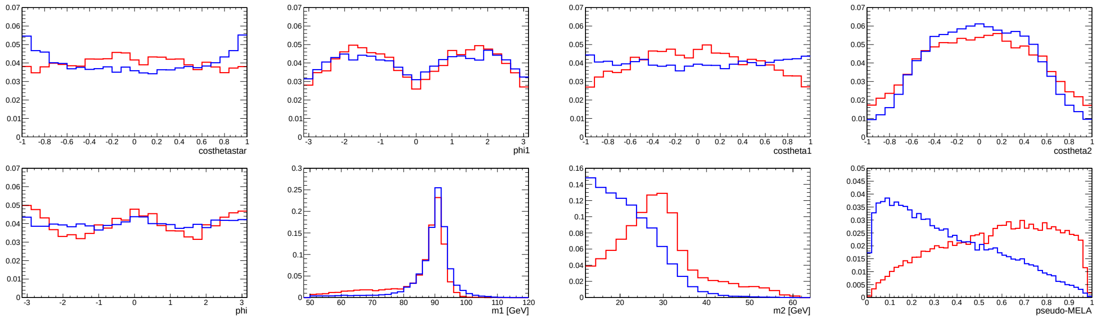

Figure 2: Distributions of the observables in the $H \to ZZ \to 4l$ analysis, as defined in [1], with lepton smearing and acceptance cuts: SM Higgs signal (red) and $qq \to ZZ$ background (blue). The last plot (bottom, right) is distribution of signal-over-background likelihood discriminant (MELA).

3. Application to Higgs spin/parity measurement

As previously mentioned, angular and mass shapes can also be exploited to measure the spin and parity of the new discovered resonance. The expected distributions in the $H \to ZZ \to 4l$ channel after CMS-like lepton smearing and acceptance cuts are shown in Fig. 3. Some angles (eg, ϕ, $cos\theta_1$) have large discrimination between odd and even parity. The case of spin 2 with minimal couplings tends to lie in between the 0^+ and 0^- case.

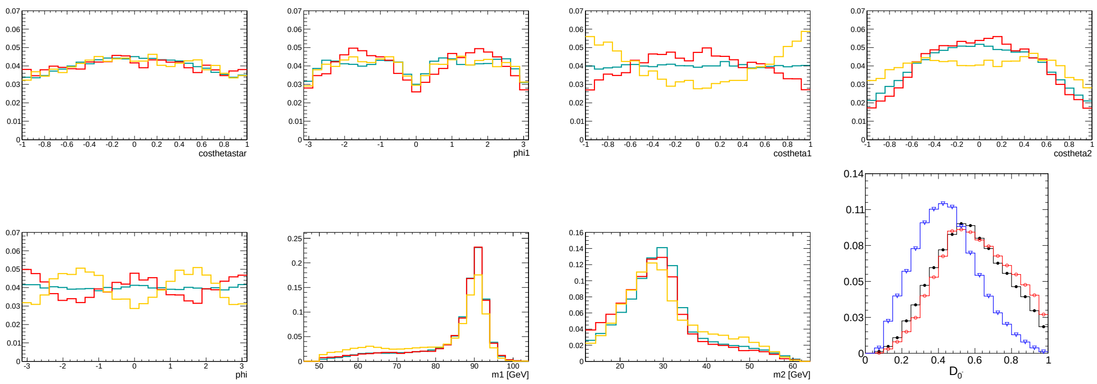

Figure 3: Distributions of the observables in the $H \to ZZ \to 4l$ analysis, as defined in [1], with lepton smearing and acceptance cuts: SM Higgs signal (red), pure pseudo-scalar hypothesis (yellow), spin 2 with minimal couplings (green). The last plot (bottom, right) is the distribution of 0^+ vs 0^- likelihood discriminant (pseudo-MELA): SM Higgs signal is shown with red open circles, pure pseudo-scalar hypothesis with blue open triangles, and $qq \to ZZ$ background with black solid circles

Similarly to what discussed in Sec. 2 for S/B, the most optimal likelihood to discriminate between different spin/parity models can be built as

$$spin-MELA = \frac{P_1}{P_1+P_2} = \left[1+\frac{P_2(\theta^*,\phi_1,m_1,m_2,\theta_1,\theta_2,\phi)}{P_1(\theta^*,\phi_1,m_1,m_2,\theta_1,\theta_2,\phi)}\right]^{-1} \tag{3.1}$$

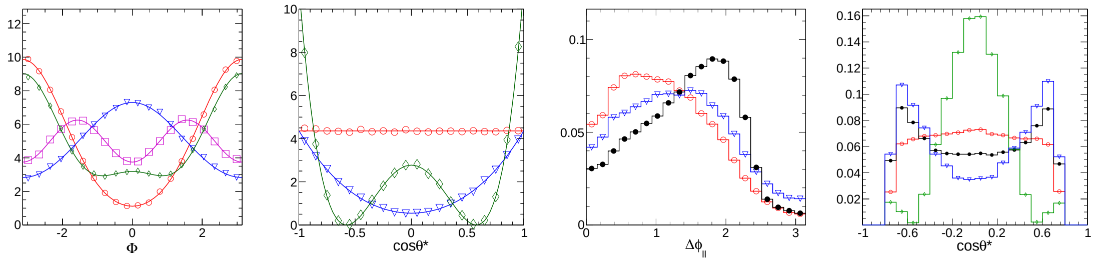

Figure 4: Left: distribution of the angle Φ in $H \to WW$ and $\cos\theta^*$ in $H \to \gamma\gamma$, as defined in [1]. Points show simulated events and lines show projections of analytical distributions. Right: distribution of the $\Delta\phi$ angle between the two charged leptons in $WW \to l\nu l\nu$ and of $\cos\theta^*$ in $H \to \gamma\gamma$, after lepton/photon smearing and acceptance cuts. Four signal hypotheses are shown and background: SM Higgs boson (red circles), 0^-(magenta squares), 2^+_m (blue triangles), 2^+_h (green diamonds), as defined in [1], and $qq \to ZZ$ background (black solid circles).

where P_1 refers to the SM Higgs PDF and P_2 is the PDF for the alternative spin/parity hypothesis. A different likelihood may be built for each model to be tested, e.g. “pseudo-MELA” for 0^+ vs 0^-, “gravi-MELA” for 0^+ vs spin 2 minimal coupling. The distribution of pseudo-MELA is shown in Fig. 3. In general many different models can be considered depending on the particular tensorial structures which are allowed in the amplitude (up to 10 different terms can be considered for spin 2). In [1] complete and general formulas for all spin hypotheses are reported and a few benchmarks models have been tested, in Tab. 1 a subset of these results are listed.

4. Considering different channels: ZZ, WW, $\gamma\gamma$

In the previous sections the $H \to ZZ \to 4l$ channel is shown, which is the more reach on kinematic information. Other final states can also be considered, e.g., $H \to WW \to l\nu l\nu$ and $H \to \gamma\gamma$.

In the fully leptonic WW channel, due to the presence of neutrinos, only one angle can be reconstructed: the $\Delta\phi$ angle between the two charged leptons. This angle is typically used in the SM Higgs search to separate the signal from the WW EWK-continuum background. As can be seen in Fig. 4, the distribution of this angle is very sensitive to the spin of the resonance: eg, the distribution for spin 2 minimal coupling is in between the SM signal case and the background.

In the $H \to \gamma\gamma$ decay only the angle between the two photons can be exploited. This angle is completely symmetric for different parity hypotheses but has large discrimination power between spin 0 and spin 2 case, as shown in Fig. 4.

In [1] a full phenomenological study of the $H \to ZZ \to 4l$, $H \to WW \to l\nu l\nu$ and $H \to \gamma\gamma$ channels is performed including a simplified description of CMS-like detector effects. The diboson background is simulated while the reducible background yields is included with same shapes as for the EWK-continuum diboson background. The background is left free to float and no systematics are included. The results are summarized in Tab. 1 and Fig. 5.

scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$	combined
0^+_m vs background	7.1 σ	4.5 σ	5.2 σ	9.9 σ
0^+_m vs 0^-	4.1 σ	1.1 σ	0.0 σ	4.2 σ
0^+_m vs 2^+_m	2.2 σ	2.5 σ	2.5 σ	4.2 σ

Table 1: Expected separation significance (Gaussian σ) between the SM Higgs boson scenario (0^+_m) and pseudo-scalar (0^-) or spin 2 minimal coupling (2^+_m) hypotheses in the analyzed channels and combined, for the scenario corresponding approximately to 35 fb^{-1} of integrated luminosity at one LHC experiment.

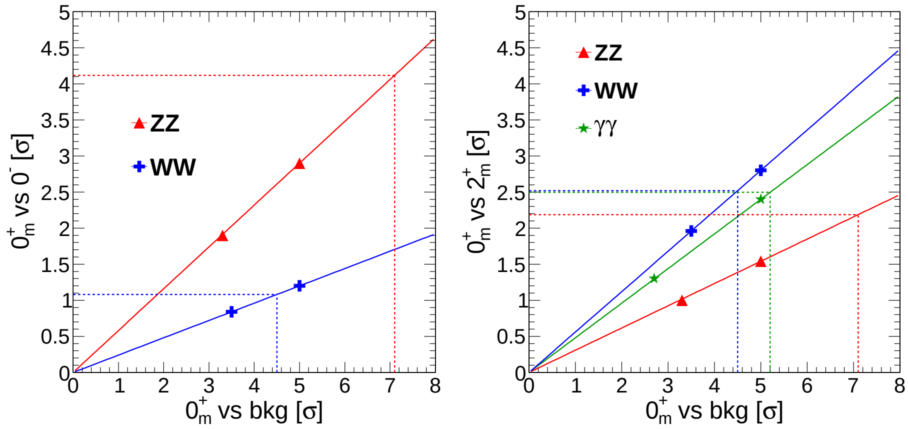

Figure 5: Expected hypotheses separation significance vs signal observation significance for the SM Higgs boson vs 0^- (left) and spin 2 minimal coupling (right) hypotheses. Points show two luminosity scenarios tested with generated experiments and expectations are extrapolated linearly to other significance scenarios. Dashed lines indicate what might be expected with 35 fb^{-1} of data in one LHC experiment.

References

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[2] Y. Gao, A. V. Gritsan, Z. Guo, K. Melnikov, M. Schulze and N. V. Tran *Spin determination of single-produced resonances at hadron colliders*, *Phys. Rev. D* **81** 075022 (2010) [arXiv:1001.3396 [hep-ph]].

[3] CMS Collaboration *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys. Rev. B* **176** (2012) 30-61 [arXiv:1207.7235 [hep-ex]].