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

S. Bolognesi$^{(a)}$, Y. Gao$^{(c)}$, A. Gritsan$^{(a)}$, K. Melnikov$^{(a)}$, M. Schulze$^{(b)}$, N. Tran$^{(c)}$, A. Whitbeck$^{(a)}$

(a) Johns Hopkins University,
(b) Argonne National Laboratory,
(c) Fermi National Laboratory
Properties measurement

- The signal observation is just the beginning ... long road ahead of us: **properties measurement**
  - observation of an excess -> **mass and width**
  - measure amplitude in different channels -> **xsec, branching ratios and couplings to V and f**
- differential distributions -> study tensor structure of the amplitudes: **spin/parity and couplings**
- All properties are correlated
"Higgs-like" most general amplitude

- Same amplitude for production (VV→X) and decay (X→VV):
  - Spin 0: $A(X \rightarrow V_1 V_2) = v^{-1} \epsilon_1^{* \mu} \epsilon_2^{* \nu} \left( a_1 g_{\mu \nu} M_X^2 + a_2 q_1 \mu q_2 \nu + a_3 \epsilon_{\mu \nu \alpha \beta} q_1^\alpha q_2^\beta \right)$
    - SM Higgs→ZZ,WW: $a_1 \neq 0$, $a_2 \sim O(10^{-2})$, $a_3 \sim O(10^{-11})$
    - SM Higgs→γγ: $a_1 = -a_2/2 \neq 0$
    - BSM pseudo-scalar Higgs $a_3 \neq 0$

- Spin 1: $A(X \rightarrow ZZ) = g_1^{(1)} [(\epsilon_1^* q) (\epsilon_2^* e_X) + (\epsilon_2^* q) (\epsilon_1^* e_X)] + g_2^{(1)} \epsilon_{\alpha \mu \nu \beta} \epsilon_X^{\alpha \beta} \epsilon_1^{* \mu} \epsilon_2^{* \nu} \tilde{q}^\beta$.

- Spin 2: $A(X \rightarrow ZZ) = \Lambda^{-1} e_1^{* \mu} e_2^{* \nu} \left[ c_1 (q_1 q_2) t_{\mu \nu} + c_2 g_{\mu \nu} t_{\alpha \beta} \tilde{q}^\alpha \tilde{q}^\beta + c_3 \frac{q_2 \mu q_1 \nu}{m_X^2} t_{\alpha \beta} \tilde{q}^\alpha q^\beta + 2c_4 (q_1 \nu q_2 \alpha t_{\mu \alpha} + q_2 \mu q_1 q_2 t_{\nu \alpha}) + c_5 t_{\alpha \beta} \tilde{q}^\beta \frac{m_X^2}{m_\chi^2} \epsilon_{\mu \nu \rho \sigma} q_1^\rho q_2^\sigma + c_6 t_{\alpha \beta} \tilde{q}^\beta \epsilon_{\mu \nu \alpha \rho} q^\rho + \frac{c_7 t_{\alpha \beta} \tilde{q}^\beta}{m_X^2} (\epsilon_{\mu \nu \rho \sigma} q^\rho q^\sigma + \epsilon_{\alpha \nu \rho \sigma} q^\rho \tilde{q}^\sigma) \right]$.

- Similarly for decay into fermions: $A(X_{J=0} \rightarrow q\bar{q}) = \frac{m_\bar{q}}{v} \bar{u}_{q_1} \left( \rho_1^{(0)} + \rho_2^{(0)} \gamma_5 \right) v_{q_2}$,
  - $A(X_{J=1} \rightarrow q\bar{q}) = \epsilon^{\mu} \bar{u}_{q_1} \left( \gamma_\mu \left( \rho_1^{(1)} + \rho_2^{(1)} \gamma_5 \right) + \frac{m_\bar{q}}{\Lambda^2} \left( \rho_3^{(1)} + \rho_4^{(1)} \gamma_5 \right) \right) v_{q_2}$,
  - $A(X_{J=2} \rightarrow q\bar{q}) = \frac{1}{\Lambda} \epsilon^{\mu \nu} \bar{u}_{q_1} \left( \gamma_\mu \bar{q}_\nu \left( \rho_1^{(2)} + \rho_2^{(2)} \gamma_5 \right) + \frac{m_\bar{q}}{\Lambda^2} \left( \rho_3^{(2)} + \rho_4^{(2)} \gamma_5 \right) \right) v_{q_2}$.
From couplings to angular analysis

- General amplitudes implemented in JHU MC - able to generate any spin hypothesis !!!
  QCD LO production but NLO correction to decay can be included in effective couplings $a_i$

$$A(X \rightarrow V_1 V_2) = v^{-1} \varepsilon_1^{*\mu} \varepsilon_2^{*\nu} \left( a_1 g_{\mu\nu} M_X^2 + a_2 q_{1\mu} q_{2\nu} + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta \right)$$

- Analytical computation of helicity amplitudes

$$A_{00} = -\frac{M_X^4}{v} \left( a_1 x + a_2 \frac{M_{Z1} M_{Z2}}{M_X^2} \left( x^2 - 1 \right) \right)$$

$$A_{\pm\pm} = \frac{M_X^2}{v} \left( a_1 \pm ia_3 \frac{M_{Z1} M_{Z2}}{M_X^2} \sqrt{x^2 - 1} \right)$$

- Amplitudes parameterize angular distributions -> they can be extracted from data
  eg, 0+ angular distribution:  
  \begin{align*}
  4(1 - f_{++} - f_{-+}) \sin^2 \theta_1 \sin^2 \theta_2 \\
  + (f_{++} + f_{-+})(1 + \cos^2 \theta_1)(1 + \cos^2 \theta_2) + 4R_1 R_2 \cos \theta_1 \cos \theta_2 \\
  -2(f_{++} - f_{-+})(R_1 \cos \theta_1(1 + \cos^2 \theta_2) + R_2(1 + \cos \theta_1 \cos \theta_2) \\
  + 4 \sqrt{f_{++}(1 - f_{++} - f_{--})(R_1 - \cos \theta_1) \sin \theta_1 (R_2 - \cos \theta_2) \sin \theta_2 \cos(\Phi + \Phi_{++})} \\
  + 4 \sqrt{f_{--}(1 - f_{++} - f_{--})(R_1 + \cos \theta_1) \sin \theta_1 (R_2 + \cos \theta_2) \sin \theta_2 \cos(\Phi - \Phi_{--})} \\
  + 2 \sqrt{f_{++} f_{--} \sin^2 \theta_1 \sin^2 \theta_2 \cos(2\Phi + \Phi_{++} - \Phi_{--})}
  \end{align*}

$$f_{ij} = |A_{ij}|^2, \phi_{ij} = \arg(A_{ij}/A_{00}), R_{1,2} = \frac{2c_A/c_V}{1+c_A^2/c_V^2} (=.15 \text{ for leptons})$$
Angular distributions for X->ZZ (250 GeV)

- "production" angles: $\theta^*, \phi_1$
- decay angles: $\theta_1, \theta_2, \phi$

1D projections for Vector, Pseudo-Vector
(generator from arxiv.org:1001.3396)

1D projections for $J^P = 2^+_M, 2^+_L, 2^-$
(generator from arxiv.org:1001.3396)

(much info also from correlations!)
Angular analysis for Higgs-$\rightarrow$ZZ search
Angular information can be used to separate Higgs signal from ZZ background

5 angles + mZ1, mZ2 + mZZ

- plots with toy MC: CMS-like resolution and acceptance (shape comparison, normalized to 1)
- angles correlated with mZZ
- offshell (mH<2*mZ) mZ2 and mZ1-mZ2 correlations very powerful to separate S/B

(Signal vs background -> Higgs search)

Matrix Element Likelihood Approach: analytical likelihood built from angular distributions

- acceptance effects cancel in the ratio to first order
- unaccounted effects make likelihood suboptimal

Toy analysis with MC applying CMS-like resolution and acceptance effects:
increase in significance 15%-30% from low to high Higgs mass
Example from CMS: $H\rightarrow ZZ\rightarrow 4\text{lep}$ angular analysis

- Signal extraction from 2D fit: $m(4l)$ vs MELA

- Significance with 10 fb$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>1D</th>
<th>2D</th>
</tr>
</thead>
</table>
  expected | 3.2 | 3.8 |
  observed  | 2.2 | 3.2 |

See: M. Klute talk, CMS HIG-12-016

Sara Bolognesi (Johns Hopkins University)
Analysis for $X \rightarrow ZZ$ spin / parity measurement
Different spin/parity for $X \rightarrow ZZ$ ($m_X$ 125 GeV)

- Plots with toy MC: CMS-like resolution and acceptance (shape comparison, normalized to 1)

Sara Bolognesi  (Johns Hopkins University)

ICHEP 2012, Melbourne
PseudoMELA: scalar vs pseudoscalar

- Similar approach for spin-hypothesis separation
  \[ \text{pseudoMELA} = \frac{P_{0+}}{P_{0+} + P_{0-}} \]

Toy results: hypothesis separation with 20 fb\(^{-1}\) (assume same signal strength as SM)

- Separation signif: 2.1 σ
  (number of signal events ~11)
Example from CMS

- Full CMS simulation, with complete H->ZZ analysis (as published)
  - status: 1.6 \( \sigma \) expected separation with 5+5 fb\(^{-1}\)
  - prospects: 3 \( \sigma \) separation before shutdown

<table>
<thead>
<tr>
<th>Integ. Lumi.</th>
<th>Expected Separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 (8) TeV</td>
<td></td>
</tr>
<tr>
<td>5/fb (5/fb)</td>
<td>1.6( \sigma )</td>
</tr>
<tr>
<td>5/fb (20/fb)</td>
<td>2.6( \sigma )</td>
</tr>
<tr>
<td>5/fb (30/fb)</td>
<td>3.1( \sigma )</td>
</tr>
</tbody>
</table>
Spin/parity analysis in X→WW channel
0+ vs 0- in WW channel (125 GeV)

Sara Bolognesi (Johns Hopkins University)
Δφ variable (used to discriminate Higgs from WW background) also very powerful to discriminate different spin hypothesis

see also Ellis et al. arXiv:1202.6660
2D fit: $\Delta\phi$, $m(ll)$ or $m_T$

- **Toy studies:** only partial info available (kinematic not fully reconstructable)
  - CMS-like acceptance cuts, only 0-jets opposite-flavor channel
  - loose cuts to avoid sculpting distribution
  - $\Rightarrow$ 25/250 signal/background events per $fb^{-1}$

- **2D fit:** $m(ll)$, $m_T$

- **10 fb$^{-1}$, NO SYSTEMATICS**
  - only WW background
  - **Signal significance:**
    - $\sim 4.5$ for spin 0, $\sim 3$ for spin 2+
  - **Spin separation significance:**

Sara Bolognesi (Johns Hopkins University)
Conclusions and prospects

- JHU MC available for any spin VV->X->VV

- Angular analysis based with analytical likelihood (MELA) successfully used
  - to boost signal search in X->ZZ: 3σ -> 4σ
  - to separate X spin hypothesis: 3σ separation 0+/0- before shutdown

- Combination of various channels (eg ZZ, WW):
  - increase signal sensitivity
  - complementary information

- All models can be tested, starting from most general couplings
BACKUP
Scenarios studied in **arXiv:1001.3396**

**TABLE I:** The list of scenarios chosen for the analysis of the production and decay of an exotic $X$ particle with quantum numbers $J^P$. For the two $2^+$ cases, the superscripts $m$ (minimal) and $L$ (longitudinal) distinguish two scenarios, as discussed in the last column. When relevant, the relative fraction of $gg$ and $qar{q}$ production is taken to be 1:0 at $m_X = 250$ GeV and 3:1 at $m_X = 1$ TeV. The spin-zero $X$ production mechanism does not affect the angular distributions and therefore is not specified.

<table>
<thead>
<tr>
<th>scenario $(J^P)$</th>
<th>$X \rightarrow ZZ$ decay parameters</th>
<th>$X$ production parameters</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+$</td>
<td>$a_1 \neq 0$ in Eq. (2)</td>
<td>$gg \rightarrow X$</td>
<td>SM Higgs-like scalar</td>
</tr>
<tr>
<td>$0^-$</td>
<td>$a_3 \neq 0$ in Eq. (2)</td>
<td>$gg \rightarrow X$</td>
<td>pseudo-scalar</td>
</tr>
<tr>
<td>$1^+$</td>
<td>$g_{12} \neq 0$ in Eq. (4)</td>
<td>$qar{q} \rightarrow X$: $\rho_{11}$, $\rho_{12} \neq 0$ in Eq. (9)</td>
<td>exotic pseudo-vector</td>
</tr>
<tr>
<td>$1^-$</td>
<td>$g_{11} \neq 0$ in Eq. (4)</td>
<td>$qar{q} \rightarrow X$: $\rho_{11}$, $\rho_{12} \neq 0$ in Eq. (9)</td>
<td>exotic vector</td>
</tr>
<tr>
<td>$2^+_m$</td>
<td>$g_1^{(2)} = g_5^{(2)} \neq 0$ in Eq. (5)</td>
<td>$gg \rightarrow X$: $g_1^{(2)} \neq 0$ in Eq. (5)</td>
<td>Graviton-like tensor with minimal couplings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$qar{q} \rightarrow X$: $\rho_{21} \neq 0$ in Eq. (10)</td>
<td></td>
</tr>
<tr>
<td>$2^+_L$</td>
<td>$\alpha_2 \neq 0$ in Eq. (6)</td>
<td>$gg \rightarrow X$: $g_2^{(2)} = g_3^{(2)} \neq 0$ in Eq. (5)</td>
<td>Graviton-like tensor longitudinally polarized</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$qar{q} \rightarrow X$: $\rho_{21}$, $\rho_{22} \neq 0$ in Eq. (10)</td>
<td>and with $J_z = 0$ contribution</td>
</tr>
<tr>
<td>$2^-$</td>
<td>$g_8^{(2)} = g_9^{(2)} \neq 0$ in Eq. (5)</td>
<td>$gg \rightarrow X$: $g_1^{(2)} \neq 0$ in Eq. (5)</td>
<td>“pseudo-tensor”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$qar{q} \rightarrow X$: $\rho_{21}$, $\rho_{22} \neq 0$ in Eq. (10)</td>
<td></td>
</tr>
</tbody>
</table>
**WW: JHU generator validation (J=2)**

$MX = 250$ GeV (MC validation)
Define a minimal selections for the hypothesis separations

- Lepton acceptance (20, 10) selections
- Dilepton mass range [12-80] GeV
- Transverse higgs mass [0 - 125] GeV

With this selection the number of events per luminosity at 8 TeV

- Signal: 25
- Background: 250
Hypothesis separation in WW

![Graphs showing data for Black: WW, Red: 0+, Blue: 0-]

![Graphs showing data for Black: WW, Red: 0+, Blue: 2m+]
Hypothesis separation in WW

<table>
<thead>
<tr>
<th>signal significance</th>
<th>2D (mll/MT)</th>
<th>2D (ΔΦ/MT)</th>
<th>2D (mll/MT)</th>
<th>2D (ΔΦ/MT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0+</td>
<td>4.6 ± 1.0</td>
<td>3.2 ± 1.0</td>
<td>0+</td>
<td>4.6 ± 1.0</td>
</tr>
<tr>
<td>0-</td>
<td>4.4 ± 1.0</td>
<td>2.8 ± 1.0</td>
<td>0-</td>
<td>3.0 ± 1.0</td>
</tr>
<tr>
<td>2+</td>
<td>3.0 ± 1.1</td>
<td>2.5 ± 1.0</td>
<td>2+</td>
<td>3.0 ± 1.1</td>
</tr>
</tbody>
</table>

2D: mll/mT

2D: ΔΦ/mT