Search for a new spin-zero resonance in diboson channels at 13 TeV

Alessio Magitteri
(Université Catholique de Louvain, CP3, Belgium)
Higgs Discovery is the last tipping point in HEP

....but now a general bewilderment flutters in the air...

Which direction should we choose to have a real deeper comprehension of the nature?

we need a bolt from the blue…
…an unexpected discovery…
**CMS Preliminary**

\[ \sqrt{s} = 13 \text{ TeV} \]

**L = 12.9 fb⁻¹ L = 35.9 fb⁻¹**

For decays with intermediate mass, \( M_{\text{top}} \approx 0 \text{ GeV} \) unless stated otherwise

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**CMS long-lived particle searches, lifetime exclusions at 95% CL**

- RPV SUSY: \( \tilde{g}, m_{\tilde{g}} = 430 \text{ GeV} \)
  - 8 TeV, 19.7 fb⁻¹ (displaced leptons)
- H → XX (Y, \( \ell \)), \( X \rightarrow \ell \ell, m_{\tilde{\ell}} = 125 \text{ GeV}, m_{\tilde{\nu}} = 20 \text{ GeV} \)
  - 8 TeV, 19.6 fb⁻¹ (displaced leptons)
- H → XX (Y, \( \ell \)), \( X \rightarrow \mu \mu, m_{\tilde{\ell}} = 125 \text{ GeV}, m_{\tilde{\nu}} = 30 \text{ GeV} \)
  - 8 TeV, 20.5 fb⁻¹ (displaced leptons)
- GMSSS SPbS: \( \tilde{b} \rightarrow \tilde{G}, m_{\tilde{b}} = 250 \text{ GeV} \)
  - 8 TeV, 19.7 fb⁻¹ (disap. phot. bos.
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  - 8 TeV, 19.7 fb⁻¹ (disap. phot. bos.
- RPV SUSY: \( m_{\tilde{L}} = 1000 \text{ GeV}, m_{\tilde{\ell}} = 150 \text{ GeV} \)
  - 8 TeV, 18.5 fb⁻¹ (displaced dijets)
- RPV SUSY: \( m_{\tilde{L}} = 1000 \text{ GeV}, m_{\tilde{\nu}} = 500 \text{ GeV} \)
  - 8 TeV, 18.5 fb⁻¹ (displaced dijets)
- AMSB \( \tilde{t}_1 \rightarrow \tilde{t}_1^0, \tilde{e}_1 \rightarrow \tilde{e}_1^0, m_{\tilde{t}_1} = 230 \text{ GeV} \)
  - 8 TeV, 18.5 fb⁻¹ (disappearing tracks)
- AMSB: \( \tilde{t}_1 \rightarrow \tilde{t}_1^0, \tilde{t}_1 \rightarrow \tilde{e}_1 \), \( m_{\tilde{t}_1} = 1000 \text{ GeV} \)
  - 8 TeV, 18.6 fb⁻¹ (stoppped particle)
- AMSB: \( \tilde{t}_1 \rightarrow \tilde{t}_1^0, \tilde{t}_1 \rightarrow \tilde{e}_1 \), \( m_{\tilde{t}_1} = 800 \text{ GeV} \)
  - 8 TeV, 18.6 fb⁻¹ (stopper + TCF)
- AMSB: \( \tilde{t}_1 \rightarrow \tilde{t}_1^0, \tilde{t}_1 \rightarrow \tilde{e}_1 \), \( m_{\tilde{t}_1} = 200 \text{ GeV} \)
  - 8 TeV, 18.6 fb⁻¹ (stopper + TCF)

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**CMS Preliminary**

\[ \leq 5.1 \text{ fb}^{-1} (7 \text{ TeV}) + \leq 19.7 \text{ fb}^{-1} (8 \text{ TeV}) \]

**Model not strictly applicable**

- Observed exclusion 95% CL
- Expected exclusion 95% CL
- Model not strictly applicable
- H → \( Z(25) \) (Higgs-15-002)
- A/H → bb (arXiv:1506.08326)
- \( A/H \rightarrow W^+W^- \) (arXiv:1508.01437)
- A/H → \( \mu \mu \) (arXiv:1501.01181)
- H → \( \tilde{b} \tilde{b} \) (Higgs-15-003)
- H → WWZZ (arXiv:1504.00038)

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**A. Magitteri**

EPS2017, 06-07-2017
$X \rightarrow ZZ$
- CMS PAS HIG-16-001
- CMS PAS HIG-16-033
- CMS PAS HIG-16-034

$X \rightarrow Z\gamma$
- CMS PAS EXO-16-021

$X \rightarrow WW$
- CMS PAS HIG-16-023

$X \rightarrow \gamma\gamma$
- CMS PAS EXO-16-018

$X \rightarrow VV$
Figure 7: Upper limits at the 95% CL for each of the contributing final states and their combination. The theoretical cross section, $\sigma_{SM}$, is computed in Ref. [66]. The observed and expected limits of the six individual channels are compared with each other and with the combined results (right), for $H \to WW$ channels (top right panel) and $H \to ZZ$ channels (bottom right panel) separately.
...and Now...
Analyzed 2015 (2.3 fb$^{-1}$) and 2016 (12.9 fb$^{-1}$) data collected by CMS at 13 TeV

- Categorization
- Shape analysis

Targeting up to 2.5 TeV Heavy Scalar Boson

- Mass region extended compared to Run I analysis
- Different benchmarks
  - Electroweak Singlet Model (EWS)
  - 2HDM Model
  - Narrow Resonance
  - Generic Scalar Boson, $\Gamma \in [0, 40]$ GeV
- Interference taken into account

<table>
<thead>
<tr>
<th>Process</th>
<th>Lumi (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW \rightarrow l\nu l\nu$</td>
<td>2.3</td>
</tr>
<tr>
<td>$ZZ \rightarrow 2l2\nu$</td>
<td>2.3</td>
</tr>
<tr>
<td>$ZZ \rightarrow 2l2q$</td>
<td>12.9</td>
</tr>
<tr>
<td>$ZZ \rightarrow 4l$</td>
<td>12.9</td>
</tr>
</tbody>
</table>
$ZZ \rightarrow 2l2\nu$
Features

✦ Wide spectrum of searches
  • \( M_H \in [200,1500] \text{ GeV} \), \( \Gamma \in [1\%,100\%] \Gamma_{\text{Heavy SM like}} \)

✦ Search model independent
  • Limits only as function of \( M_H \) and \( \Gamma \)
  • No interference terms

✦ Search based on
  • \( ee \) and \( \mu\mu \) final state
  • 0 jet, 1 jet, and VBF cat.

✦ \( M_T \) shape used as discriminant

\[
M_T^2 = \left( \sqrt{p_T(\ell\ell)}^2 + M(\ell\ell)^2 + \sqrt{E_{\text{miss}}^2 + M_Z^2} \right)^2 - (\vec{p}_T(\ell\ell) + \vec{E}_{\text{miss}})^2
\]
- SM ratio between ggH and VBF production rates assumed
- Phase Space excluded bigger than Run I for EWS
- No excess measured
$ZZ \rightarrow 4l$

CMS PAS HIG-16-033
- Signal modeled as convolution between gen-shape, efficiency, and resolution
  \[ \mathcal{P}_{\text{sig}}^{\text{reco}}(m_{4\ell}) = \mathcal{E}(m_{4\ell}) \times \left( \mathcal{R}(m_{4\ell}|m_{4\ell}^{\text{ideal}}) \otimes \mathcal{P}_{\text{sig}}(m_{4\ell}^{\text{ideal}}|m_X, \Gamma_X, m_H, \Gamma_H) \right) \]
- Interference fully considered (ggH, VBF)
- Event categorization exploiting
  - jets multiplicity
  - b-tagged jets
  - additional lep
  - kinematical discriminants

arXiv: 1610/07922
LHCHXSWG

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✧ Ratio between ggH and VBF floated
✧ $M_{4\ell}$ as discriminant $P(M_{4\ell} | M_X, \Gamma_X, \sigma_X)$
✧ No significant excess observed
$ZZ \rightarrow 2l2q$

CMS PAS HIG-16-034
- Tested boosted kinematical region
  - High mass, $P_T(Z) > 100/170$ GeV
- Event categorization
  - Jet topology (merged and resolved cat [Backup])
  - Jet flavor (b-tag, not b-tag)
  - VBF topology

- Kinematical Discriminants
  - Matrix Element
    - VBF Vs $ggH$ ($D_{2jet}$)
  - Signal Vs Bckg ($D_{Zjj}$)
  - Jet Structure
  - N-Subjettiness ($\tau_i$)
Ratio between ggH and VBF floated

$M_{ZZ}$ and $D_{Zjj}$ used as discriminant

No excess observed

$\sigma(pp \rightarrow X \rightarrow ZZ)$ [pb] vs $m_X$ [TeV]
$WW \rightarrow l\nu l\nu$

CMS PAS HIG-16-023
✦ Wide spectrum of searches
  • $M_H \in [200,1000] \text{ GeV}$, $\Gamma \in [10\%,100\%] \Gamma_{\text{Heavy_SM_like}}$
✦ Events categorized in 0 jets, 1 jets, and VBF
  • Only $e\mu$ channel selected
✦ Interference terms taken into account
✦ $M_{T,i}$ shape used as discriminant

$$m_{T,i} = \sqrt{(p_{ll} + E_{T}^{\text{miss}})^2 - (p_{ll} + \not{p}_T^{\text{miss}})^2}$$

1 Jet Cat.
✦ Ratio between ggH and VBF as in SM
✦ EWS as benchmark
✦ No excess observed
Conclusions
The 13 TeV data corresponding to 2.3 fb$^{-1}$ and 12.9 fb$^{-1}$ were analyzed in di-boson channels

• underlined common aspects and features of each of them

• No Significant excess measure

• …a bolt from the blue…still lacking both in ZZ and WW channels…

• A warm suggestion: keep calm and stay tuned. New results will come very soon!
Thanks!
Backup
$ZZ \rightarrow 2l2\nu$

CMS PAS HIG-16-001
1. Trigger selection
   1. Double e/µ ($P_T$ thrs: 23-17 $e_1$ - 12 $e_2$ GeV, 17 $\mu_1$ - 8 $\mu_2$ GeV)
2. Events categorization
   1. 0-jet
   2. $\geq$ 1-jet
   3. Vbf ($P_T > 30$ GeV, $\Delta\eta_{jj} > 4.0$, $M_{jj} > 500$ GeV, 0 central jets, central leptons)
3. Selection
   1. Exactly two leptons (e/µ), Tight Id and Iso
   2. $P_T^{lep} > 25$ GeV, $|\eta| < 2.5$ (e)/ 2.4 (µ)
   3. Z mass window constrain, $P_T^Z > 55$ GeV
   4. Veto cuts (third lepton, b-jet)
   5. $\Delta\phi$(jet,MET) > 0.5
   6. MET > 125 GeV
4. Performed statistical analysis using Transverse Mass ($M_T$) shape distribution
✦ SM ratio between ggH and VBF production rates assumed
✦ Phase Space excluded bigger than Run I for EWS
✦ No excess measured
Results

2HDM Type-1

- \cos(\beta - \alpha) = 0.10

2HDM Type-2

- \cos(\beta - \alpha) = 0.10

### 2HDM Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_h )</td>
<td>125.09 GeV</td>
</tr>
<tr>
<td>( m_A )</td>
<td>( m_H + 100 \text{ GeV} )</td>
</tr>
<tr>
<td>( m_{H^+} )</td>
<td>( m_H + 100 \text{ GeV} )</td>
</tr>
<tr>
<td>( \cos(\beta - \alpha) )</td>
<td>0.1</td>
</tr>
<tr>
<td>( m_{h_2} )</td>
<td>( \max(1 - \tan^2 \beta, 0) ) ( \frac{1}{2} \sin(2\beta)(m_A^2 + \lambda_3 v^2) )</td>
</tr>
<tr>
<td>( m_H )</td>
<td>scanned</td>
</tr>
<tr>
<td>( \tan \beta )</td>
<td>scanned</td>
</tr>
</tbody>
</table>
$ZZ \rightarrow 4l$

CMS PAS HIG-16-033
After kinematical cuts the events are selected according to the matrix element discriminant value $D_{\text{KinBkg}}^{\text{Kin}}$

Two categories defined in the high mass search

- VBF-2jet-tagged category
  - exactly 4 leptons
  - high $D_{\text{2jet}}$ value
  - either 2 or 3 jets of which at most 1 is b-tagged, or at least 4 jets and no b-tagged jets
- Not VBF
  - all the events that not pass the previous category are grouped together in the following category

$$D_{\text{bkg}}^{\text{kin}} = \left[ 1 + \frac{P_{\text{bbg}}^{\text{qg}}(\tilde{\Omega}^H\rightarrow 4\ell|m_{4\ell})}{P_{\text{sig}}^{\text{gg}}(\tilde{\Omega}^H\rightarrow 4\ell|m_{4\ell})} \right]^{-1}$$

$$D_{\text{2jet}} = \left[ 1 + \frac{P_{\text{HJJ}}^{\text{H+JJ}}(\tilde{\Omega}^H+\text{JJ}|m_{4\ell})}{P_{\text{VBF}}^{\text{H+JJ}}(\tilde{\Omega}^H+\text{JJ}|m_{4\ell})} \right]^{-1}$$
ZZ → 2l2q

CMS PAS HIG-16-034
**Features**

\[
D_{Zjj} = \left[ 1 + \frac{\mathcal{P}_{Zjj}(\bar{\Omega}^{X\rightarrow 2\ell q}|M_{ZZ})}{\mathcal{P}_{X\rightarrow 2\ell q}^{\bar{\Omega}^{X\rightarrow 2\ell q}|M_{ZZ})} \right]^{-1}
\]

\[
D_{2\text{jet}} = \left[ 1 + \frac{\mathcal{P}_{XJJ}(\bar{\Omega}^{X\rightarrow JJJ}|M_{ZZ})}{\mathcal{P}_{VBF}^{\bar{\Omega}^{X\rightarrow JJJ}|M_{ZZ})} \right]^{-1}
\]

\[
\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k})
\]

\[
d_0 = \sum_k p_{T,k} R_0
\]

R₀ initial radius of the jet

<table>
<thead>
<tr>
<th>Observable</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau_2) (GeV)</td>
<td>&gt; 170 (merged)</td>
</tr>
<tr>
<td>(\tau_{21})</td>
<td>[0.6) (merged only)</td>
</tr>
<tr>
<td>VBF-tagged</td>
<td>(M_{ZZ})-dependent selection on (D_{2\text{jet}})</td>
</tr>
<tr>
<td>b-tagged</td>
<td>not VBF-tagged and two b-tagged components of (Z_{\text{had}})</td>
</tr>
<tr>
<td>untagged</td>
<td>not VBF-tagged and not b-tagged</td>
</tr>
</tbody>
</table>

\(\eta(\ell)\) | (e) < 2.5, (\(\mu\)) < 2.4 |
\(M(\ell^+\ell^-)\) (GeV) | \[60, 120\] |
\(p_T(\ell^+\ell^-)\) (GeV) | > 100 |
\(p_T(\text{jet})\) (GeV) | > 30 |
\(\Delta R(\ell, \ell)\) | > 0.02 |
\(\Delta R(\ell, \text{jet})\) | > 0.4 (AK4 jets) |
| | > 0.8 (AK8 jets) |

\(M(Z_{\text{had}})\) (GeV) | \[40, 70\) (lower sideband) |
| | \[70, 105\) (signal region) |
| | \[105, 135\) (Higgs boson region, not used in this analysis) |
| | \[135, 180\) (upper sideband) |
In HZZ212q the hadronic Z decay can be either reconstructed by two resolved jets (AK4) or one merged jet with larger cone size (AK8).

• In each event the hadronic Z is reconstructed as boosted or resolved BUT the boosted is chosen if $P_t(J) > 300$ GeV and $P_t(l^+l^-) > 200$ GeV; the resolved candidates have precedence otherwise.
$WW \rightarrow \ell\nu\ell\nu$

CMS PAS HIG-16-023
1. Events categorization

1. 0-jet
2. >= 1-jet
3. Vbf ($p_T > 50$ GeV, $\Delta \eta_{jj} > 3.5$, $M_{jj} > 500$ GeV, 0 central jets, central leptons)

2. Selection

1. Exactly two leptons $e+\mu$
2. $p_{T}^{lep} > 20$ GeV, $|\eta| < 2.5$ (e)/ 2.4 ($\mu$)
3. $M^{ll} > 50$ GeV, $p_{T}^{ll} > 30$ GeV
4. Veto cuts (third lepton, b-jet ($p_T > 20$ GeV if originating from a b-quark))
5. MET ($m_T$) > 60 GeV

$$m_T = \sqrt{2p_T^{\ell\ell}E_T^{miss}(1 - \cos \Delta \phi(\ell\ell, p_T^{miss}))}$$

3. Performed statistical analysis using Transverse Mass $M_{T,i}$ shape distribution

$$m_{T,i} = \sqrt{(p_{ll} + E_T^{miss})^2 - (\vec{p}_{ll} + \vec{p}_T^{miss})^2}$$
Features

0 Jet Cat.

1 Jet Cat.

VBF Cat.
Results

CMS Preliminary

$\sigma(X \rightarrow WW \rightarrow 2l2\nu)$ [pb]

$M_X$ [GeV]

2.3 fb$^{-1}$ (13 TeV)

- Observed
- Expected

$\Gamma = 0.09 \times \Gamma_{SM}$

$\pm 1 \sigma$ Expected

$\pm 2 \sigma$ Expected

$\sigma(X \rightarrow WW \rightarrow 2l2\nu)$ [pb]

$M_X$ [GeV]

2.3 fb$^{-1}$ (13 TeV)

- Observed
- Expected

$\Gamma = 0.25 \times \Gamma_{SM}$

$\pm 1 \sigma$ Expected

$\pm 2 \sigma$ Expected

$\sigma(X \rightarrow WW \rightarrow 2l2\nu)$ [pb]

$M_X$ [GeV]

2.3 fb$^{-1}$ (13 TeV)

- Observed
- Expected

$\Gamma = 0.49 \times \Gamma_{SM}$

$\pm 1 \sigma$ Expected

$\pm 2 \sigma$ Expected

$\sigma(X \rightarrow WW \rightarrow 2l2\nu)$ [pb]

$M_X$ [GeV]

2.3 fb$^{-1}$ (13 TeV)

- Observed
- Expected

$\Gamma_{SM}$

$\pm 1 \sigma$ Expected

$\pm 2 \sigma$ Expected

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