Electroweak Restoration at the LHC and Beyond: The $V h$ Channel

Li Huang, Samuel D. Lane, Ian M. Lewis, Zhen Liu

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Outline

• Introduction/Theory
• Parton Level
• Simulation (Detector Level)
• Results
• Statistics (if have time)
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Introduction/ Theory

\[ V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \]

\[ H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}} (v + h + i G^0) \end{pmatrix} \]

\[ \mathcal{L}_{\text{kin}} = |D_\mu H|^2 \]

\[ \text{W and Z mass terms} \]
Goldstone Boson Equivalence

\[ \mathcal{A}(q_+ \bar{q}_- \rightarrow Z_L h) = \pm i \frac{e^2 g_R^{qZ}}{2 c_W^2 s_W^2} \sin \theta + \mathcal{O}(\hat{s}^{-1}). \]

\[ \mathcal{A}(q_- \bar{q}_+ \rightarrow G^0 h) = \frac{e^2 g_L^{qZ}}{2 c_W^2 s_W^2} \sin \theta. \]
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Vh Helicity Dependence

Longitudinally Dominated
WV Helicity Dependence

Transverse Dominated
Parton Level Signal Strength

$$\mu_{Wh} = \frac{d\sigma(pp \rightarrow W^\pm h)/dp_T^h}{d\sigma(pp \rightarrow G^\pm h)/dp_T^h},$$

$$\mu_{Zh} = \frac{d\sigma(pp \rightarrow Zh)/dp_T^h}{d\sigma(pp \rightarrow G^0 h)/dp_T^h}.$$
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Event after DNN: 1 lepton

Use MG5/Pythia/Delphes Chain to generate data

Use DNN to separate signal and backgrounds

\[ L = -y_s \log p - (1 - y_s) \log(1 - p) + \lambda \| W \|_2^2, \]
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Signal Strength: 1 Lepton

\[ \mu_{W h} = \frac{d\sigma(pp \rightarrow W^\pm h)/dp_T^h}{d\sigma(pp \rightarrow G^\pm h)/dp_T^h}, \]

\[ \mu_{Z h} = \frac{d\sigma(pp \rightarrow Zh)/dp_T^h}{d\sigma(pp \rightarrow G^0 h)/dp_T^h}. \]

SM VH cross section
EW restored GH cross section
Signal Strength: Combined

\[ \mu_{Vh} = \begin{cases} 
1 \pm 0.4 & \text{at the HL-LHC} \\
1 \pm 0.06 & \text{at the HE-LHC}
\end{cases} \]
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Delta Chi Square
Chi Square

$$\Delta \chi^2_m = \frac{1}{m} \sum_{l=1}^{m} \log \left( \frac{\text{Pois}(n_{obs,l} | \sum_j \Delta \sigma_j^{Gh} \epsilon_{l,j} L + B_l)}{\text{Pois}(n_{obs,l} | S_l + B_l)} \right)$$

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To test how well EW restoration is being observed, one needs to measure how the convergence is improving by using higher and higher energy bins. At low $p_T$ bins, although the statistical error is small, the Goldstone and gauge boson distributions do not agree. As one moves towards higher $p_T$ bins, while the two distributions converge, the statistical errors also increase, as shown in Figs. 4 and 5. In this section we explore statistical measures of the restoration and discuss their implications, taking into account both the theory convergence as well as the experimental uncertainties. The goal is, assuming that the SM is a good description of the data, we want to test the agreement between the $q\bar{q}!Vh$ and $q\bar{q}!Gh$ product amplitudes.

As a first choice, using the language that the high energy physics community is more familiar with, we consider using "$\chi^2$ per degree of freedom" as a function of $p_T$ bins. One generically anticipates this quantity to decrease as an indicator of better convergence. After using the method in the previous sections in separating signal and background, we now have six-category samples, post-selection cuts, that have the significance of our analysis as a function of $p_T$. One can define "$\chi^2$ per degree of freedom":

$$2 \Delta \chi^2_m = \log \left( \frac{\text{Pois}(n_{obs,l} | \sum_j \Delta \sigma_j^{Gh} \epsilon_{l,j} L + B_l)}{\text{Pois}(n_{obs,l} | S_l + B_l)} \right)$$

where we sum over the $m$ ranked $p_T$ bins (from low to high). Using the methods of the previous section, we perform 10,000 pseudo-experiments. The results are shown in the left panel of Fig. 6. We show the median over all pseudo-experiments as well as the band where 68% and 95% of the pseudo-experiments lie. From the figure we can see, as anticipated, the $\Delta \chi^2_m$ decreases as one includes more high $p_T$ bins. However, we note here that $\chi^2$ has some disadvantages in measuring restoration. First, for the low $p_T$ bins, each bin contributes to a sizable $\Delta \chi^2$ since the $Gh$ and $Vh$ hypothesis are in poor agreement and statistical uncertainty is small. At high $p_T$, the statistical uncertainties increase. Hence, even if the $Gh$ and $Vh$ distributions do not converge, as more bins are averaged over $\Delta \chi^2_m$ will decrease. In other words, even if the higher bins contain no separation power, e.g. the background uncertainty being infinitely larger than the signal.
KL Divergence

\[
p^\leq m_i = \prod_{\text{6 signal categories}} \frac{\text{Pois}(n_{\text{obs},i} | S_i + B_i)}{\sum_{l=1}^{m} \text{Pois}(n_{\text{obs},l} | S_l + B_l)}
\]

\[
q^\leq m_i = \prod_{\text{6 signal categories}} \frac{\text{Pois}(n_{\text{obs},i} | \sum_j \Delta \sigma^G_{j} \epsilon_{ij} L + B_i)}{\sum_{l=1}^{m} \text{Pois}(n_{\text{obs},l} | \sum_j \Delta \sigma^G_{j} \epsilon_{lj} L + B_l)},
\]

\[
KL_m = \sum_{i=1}^{m} p^\leq m_i \log \left( \frac{p^\leq m_i}{q^\leq m_i} \right)
\]

- Small KL implies agreement with hypothesis
- Expect KL to decrease as we include more $P_T$ bins
KL Divergence

\[ KL_m \]

\[ p_T^H \text{ (GeV)} \]

27 TeV 15 ab\(^{-1}\)

14 TeV 3 ab\(^{-1}\)
Conclusions

• We have shown the capabilities of HL-LHC and HE-LHC in observing the GBET and Electroweak restoration.
• We find for $p_t^h > 400 \text{ GeV}$ the $G\ h$ and the $V\ h$ distributions agree at about 80%.
• The KL divergence shows that the two hypotheses agree at high energy.
• HL can confirm electroweak restoration to 40%.
• HE can confirm it to 6%.
Thank You!
Any Questions?
Signal Strength: 2 Lepton

2-lepton, $\sqrt{s} = 14$ TeV, 3 $ab^{-1}$

- 2-jet
- $\geq$ 3-jet

68% C.L.

$\mu_{\nu h}$ vs $p_T^h$ [GeV]

2-lepton, $\sqrt{s} = 27$ TeV, 15 $ab^{-1}$

- 2-jet
- $\geq$ 3-jet

68% C.L.

$\mu_{\nu h}$ vs $p_T^h$ [GeV]
Signal Strength: 1 Lepton

1-lepton, $\sqrt{s} = 14$ TeV, $3 \text{ ab}^{-1}$

2-jet
3-jet

68% C.L.

$\mu_{\ell h}$ $p_T^h$ [GeV]

1-lepton, $\sqrt{s} = 27$ TeV, $15 \text{ ab}^{-1}$

2-jet
3-jet

68% C.L.

$\mu_{\ell h}$ $p_T^h$ [GeV]
Signal Strength: 0 Lepton

0-lepton, $\sqrt{s} = 14$ TeV, 3 $ab^{-1}$

0-lepton, $\sqrt{s} = 27$ TeV, 15 $ab^{-1}$
Z \ h \ and \ W \ h \ Amplitudes

\[ A(q_+ \bar{q}_- \to Z_L h) = \pm i \frac{e^2 g_{qZ}^q}{2 c_W^2 s_W^2} \sin \theta + \mathcal{O}(\hat{s}^{-1}), \]

\[ A(q_- \bar{q}_+ \to Z_L h) = \pm i \frac{e^2 g_{qZ}^q}{2 c_W^2 s_W^2} \sin \theta + \mathcal{O}(\hat{s}^{-1}), \]

\[ A(q_- \bar{q}_+ \to W^+_L h) = -i \frac{e^2}{2 \sqrt{2} s_W^2} \sin \theta + \mathcal{O}(\hat{s}^{-1}), \]

\[ A(q_\pm \bar{q}_\mp \to Z_\pm h) \sim A(q_- \bar{q}_+ \to W^+_L h) \sim \mathcal{O}(\hat{s}^{-1/2}), \]

\[ A(q_+ \bar{q}'_- \to W^\pm_\mp h) = A(q_+ \bar{q}'_- \to W^\pm_\mp h) = 0. \]
WZ, WW, and ZZ Amplitudes

\[ A(q_\pm \bar{q}_+ \to W^\pm W_{\mp}) = \mp i \frac{e^2}{2 s^2_W} \frac{1 + 2 T^q_3 \cos \theta}{1 \pm \cos \theta} \sin \theta + O(\hat{s}^{-1}) , \]

\[ A(q_\pm \bar{q}_+ \to W^\pm Z_{\mp}) = \mp i \frac{e^2}{\sqrt{2} s^2_W c_W} \left( g^q_{\pm Z} (1 + \cos \theta) + g^q_{\pm Z} (1 - \cos \theta) \right) \frac{\sin \theta}{1 \pm \cos \theta} + O(\hat{s}^{-1}) , \]

\[ A(q_\pm \bar{q}_+ \to Z_+ Z_-) = 2 i \frac{e^2}{s^2_W c^2_W} g^q_{Z^2} \sqrt{\frac{1 - \cos \theta}{1 + \cos \theta}} + O(\hat{s}^{-1}) , \]

\[ A(q_+ \bar{q}_- \to Z_+ Z_-) = -2 i \frac{e^2}{s^2_W c^2_W} g^q_{Z^2} \sqrt{\frac{1 + \cos \theta}{1 - \cos \theta}} + O(\hat{s}^{-1}) , \]

\[ A(q_\pm \bar{q}_\mp \to W^\pm W_{\mp}) \sim A(q_\pm \bar{q}_+ \to W^\pm Z_L) \sim A(q_\pm \bar{q}_+ \to Z_\pm W^\pm_L) \sim A(q_\pm \bar{q}_\mp \to Z_\pm Z_L) \sim O(\hat{s}^{-1/2}) , \]

\[ A(q_\pm \bar{q}_\mp \to W^\pm W_{\mp}) \sim A(q_\pm \bar{q}_+ \to W^\pm Z_{\pm}) \sim A(q_\pm \bar{q}_\mp \to Z_\pm Z_{\pm}) \sim O(\hat{s}^{-1}) , \]

\[ A(q_+ \bar{q}_- \to W^\pm W_{\mp}) = A(q_+ \bar{q}_- \to W^\pm Z_{\pm} X_{\mp}) = 0. \]
Relevant Goldstone Amplitudes

\[ \mathcal{A}(q_+ \bar{q}_- \to G^0 h) = - \frac{e^2 g_R^{qZ}}{2 c_W^2 s_W^2} \sin \theta, \]

\[ \mathcal{A}(q_- \bar{q}_+ \to G^0 h) = \frac{e^2 g_L^{qZ}}{2 c_W^2 s_W^2} \sin \theta, \]

\[ \mathcal{A}(q_- \bar{q}_+ \to G^\pm h) = \mp i \frac{e^2}{2 \sqrt{2} s_W^2} \sin \theta, \]

\[ \mathcal{A}(q_- \bar{q}_+ \to G^\pm G^0) = \frac{e^2}{2 \sqrt{2} s_W^2} \sin \theta, \]

\[ \mathcal{A}(q_+ \bar{q}_- \to G^+ G^-) = -i \frac{e^2 Q_q}{2 c_W^2} \sin \theta, \]

\[ \mathcal{A}(q_- \bar{q}_+ \to G^+ G^-) = -i \frac{e^2 T_3^q}{6 c_W^2 s_W^2} (3 c_W^2 + 2 T_3^q s_W^2) \sin \theta. \]
**$Zh \rightarrow \ell^+ \ell^- b\bar{b}$**

|                      | 14 TeV       | 27 TeV       |
|----------------------|--------------|--------------|
|                      | $n_j = 2$    | $n_j = 3$    | $n_j = 2$    | $n_j = 3$    |
|                      | Pre-Cut      | DNN          | Pre-Cut      | DNN          |
| $h_{bb}Z_{\ell\ell}$ | 1.1 fb       | 0.22 fb      | 1.1 fb       | 0.23 fb      | 2.0 fb       | 0.87 fb      | 1.6 fb       | 1.2 fb       |
| $Z+HF$               | 300 fb       | 1.4 fb       | 530 fb       | 3.3 fb       | 580 fb       | 16 fb        | 780 fb       | 120 fb       |
| $tt$                 | 27 fb        | 0.14         | 69 fb        | 0.095 fb     | 92 fb        | 1.6 fb       | 180 fb       | 19 fb        |
| single top           | 0.85 fb      | 0.0036 fb    | 3.5 fb       | 0.0041 fb    | 2.9 fb       | 0.047 fb     | 11 fb        | 1.0 fb       |
| $Zcl$                | 0.18         | 0.0036 fb    | 2.1 fb       | 0.025 fb     | 0.75 fb      | 0.034 fb     | 6.4 fb       | 0.94 fb      |
| $Zll$                | 0.68         | 0.019 fb     | 13 fb        | 0.20 fb      | 2.0 fb       | 0.096 fb     | 27 fb        | 4.1 fb       |
| $VV'$                | 4.8 fb       | 0.026 fb     | 5.4 fb       | 0.051 fb     | 6.5 fb       | 0.22 fb      | 7.8 fb       | 1.5 fb       |
| Signal Significance  | 9.4          | 6.5          | 25           | 13           |
### IV. COLLIDER ANALYSIS

To determine the binned signal strengths, we consider signals, we consider.

Finally, we use the global likelihood across all bins to determine the number of observed events.

One lepton final states, we consider.

For the zero and one-lepton signals, we include backgrounds from missing.

### TABLE II: Cut flow table and signal significance after the DNN for the one lepton categories. The

| Signal | Pre-Cut | DNN |
|--------|---------|-----|
| $h_{bb}W_{\ell\nu}$ | 12 fb | 6.1 fb |
| $W+HF$ | 580 fb | 38 fb |
| $Z+HF$ | 310 fb | 8.5 fb |
| $tt$ | 150 fb | 15 fb |
| single top | 11 fb | 1.1 fb |
| $Wcl$ | 4.9 fb | 0.46 fb |
| $Wll$ | 10 fb | 1.2 fb |
| $Zcl$ | 0.15 fb | $4.2 \times 10^{-3}$ fb |
| $Zll$ | 0.49 fb | 0.014 fb |
| $VV'$ | 34 fb | 2.0 fb |

| Signal Significance | 40 | 28 | 120 | 98 |
**Zh → ννbb.**

|                          | 14 TeV       | 27 TeV       |
|--------------------------|--------------|--------------|
|                          | $n_j = 2$    | $n_j = 3$    | $n_j = 2$    | $n_j = 3$    |
|                          | Pre-Cut     | DNN          | Pre-Cut     | DNN          |
| $h_{bb}Z_{\nu\nu}$      | 9.8 fb       | 4.7 fb       | 18 fb       | 7.9 fb       |
| $W + \text{HF}$          | 310 fb       | 7.6 fb       | 420 fb      | 14 fb        |
| $Z + \text{HF}$          | 2900 fb      | 110 fb       | 5700 fb     | 260 fb       |
| $tt$                     | 7.6 fb       | 0.16 fb      | 42 fb       | 0.22 fb      |
| single top               | 1.3 fb       | 0.035 fb     | 1.5 fb      | 0.0057 fb    |
| $Wcl$                    | 1.1 fb       | 0.026 fb     | 2.4 fb      | 0.059 fb     |
| $Wll$                    | 3.7 fb       | 0.087 fb     | 13 fb       | 0.38 fb      |
| $Zcl$                    | 1.4 fb       | 0.15 fb      | 3.3 fb      | 0.23 fb      |
| $Zll$                    | 6.8 fb       | 0.78 fb      | 22 fb       | 1.6 fb       |
| $VV'$                    | 68 fb        | 3.9 fb       | 89 fb       | 4.7 fb       |
| Signal Significance      | 23           | 84           | 58          | 140          |