Off-shell Higgs Couplings in $H^* \rightarrow ZZ \rightarrow \ell \ell vv$

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• Higgs Couplings in Off-shell Regime
  • Higgs Width
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  • Higgs-Top Form Factor

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Motivation

So far, the Higgs measurements at the LHC agree with the SM predictions. However, these measurements mostly focus on the on-shell Higgs boson production, exploring the Higgs properties at low energy scales of the order $v$. If we explore the Higgs physics at far off-shell scale $Q$, the sensitivity can be enhanced as $Q^2/\Lambda^2$.

*ATLAS Preliminary*

$\sqrt{s} = 13$ TeV, 24.5 - 139 fb$^{-1}$

$m_H = 125.09$ GeV

$\bar{m}_q(m_H)$ used for quarks

**Preliminary ATLAS**

$\mu t b \ WZ \ t$ used for quarks

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Motivation

Naturalness Problem

Higgs mass is not protected in SM. To solve the naturalness problem, either new symmetry is needed, or the Higgs could be composite in nature.

Probing off-shell Higgs coupling is a good way to test.
**Signal Channel**

\[ g\ g \rightarrow H^* \rightarrow Z(l^+ l^-) \ Z(\nu \ \bar{\nu}) \ \ l = e, \mu \]

**Advantages**

- It has larger event rate by a factor of six than the four charged lepton channel

- The transverse mass of the ZZ system sets the physical scale \( Q^2 \) and results in a precise probe to underlying physics
Higgs Width

Additional unobserved Higgs decay channels will lead to an increase in the Higgs boson width $\Gamma_H/\Gamma_H^{SM} > 1$

$$
\sigma_{i\rightarrow H\rightarrow f}^{\text{on-shell}} \propto \frac{g_i^2(m_H) g_f^2(m_H)}{\Gamma_H}
$$

$$
\sigma_{i\rightarrow H^*\rightarrow f}^{\text{off-shell}} \propto g_i^2(\sqrt{s}) g_f^2(\sqrt{s})
$$

The relative measurement of on-shell and off-shell signal strengths can uncover the Higgs boson width$^{[1]}$

$$
\mu_{\text{off-shell}} / \mu_{\text{on-shell}} = \Gamma_H/\Gamma_H^{SM}
$$

Analysis Setup

- $\sqrt{s} = 14$ TeV at High-Luminosity LHC

- MC events of gluon-gluon fusion processes are generated with MG5 at LO, $q\bar{q}$ backgrounds are generated with MG5 at NLO

- All parton-level events are hadronized by Pythia8 then passed to Delphes3 to take account of detector effects.

- Higher order QCD effects to the loop-induced gluon fusion component are included via a global K-factor.

- Interference between signal($gg \rightarrow H^* \rightarrow ZZ$) and GGF continuum background ($gg \rightarrow ZZ$) is obtained by $\sigma_{int} = \sigma_{gg \rightarrow (H^* \rightarrow ZZ} - \sigma_{gg \rightarrow H^* \rightarrow ZZ} - \sigma_{gg \rightarrow ZZ}$
Selection Cuts

$|\eta| < 2.5$ and $p_{T\ell} > 10 \text{ GeV}$

$76 \text{ GeV} < m_{\ell\ell} < 106 \text{ GeV}$

$E_T^{\text{miss}} > 175 \text{ GeV}$

$\Delta \phi(\vec{p}_{T\ell}, \vec{E}_T^{\text{miss}}) > 2.7$

$\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 1.8$

$|p_{T,j}^{\text{miss}} - p_{T\ell}^{\ell\ell}| / p_{T\ell}^{\ell\ell} < 0.2$, where $p_{T,j}^{\text{miss}} = |\vec{E}_T^{\text{miss}} + \sum_j \vec{p}_{T,j}|$

$E_T^{\text{miss}} / H_T > 0.33$

$m_{T ZZ} > 250 \text{ GeV}$

$m_{T ZZ} = \sqrt{\left(\sqrt{m_Z^2 + p_{TZ}^2} + \sqrt{m_Z^2 + (E_T^{\text{miss}})^2}\right)^2 - |\vec{p}_{TZ} + \vec{E}_T^{\text{miss}}|^2}$

Same-flavor opposite-sign lepton pair
Event with third lepton will be rejected
To further distinguish signal and background, we built a boosted decision tree (BDT). Two of the observables we used are $\cos \theta \cos \phi$, where $\theta$ and $\phi$ are the polar and azimuthal angles of the charged lepton in Z boson rest frame (Collins-Soper frame).

$$
\cos \theta = \frac{2|q^0 p_\ell^3 - q^3 p_\ell^0|}{Q \sqrt{Q^2 + |q_T|^2}} \quad cos\phi = \frac{2}{sin\theta} \frac{|Q^2 \vec{p}_T \ell \cdot \vec{q}_T - |\vec{q}_T|^2 p_\ell \cdot q|}{Q^2 |\vec{q}_T| \sqrt{Q^2 + |\vec{q}_T|^2}}
$$
The difference arises from the different $Z$ boson polarizations for the signal and background components at large diboson invariant mass. The s-channel Higgs tends to have $Z_L$ dominance, while the background is mostly $Z_T$ dominated.
To maximize $\frac{S}{\sqrt{S+B}}$ at $3 \text{ ab}^{-1}$, we choose a BDT cut at -0.26 with signal efficiency 88% and background rejection of 34%.

$L = 273 \text{ fb}^{-1}$ to reach $\frac{S}{\sqrt{B}} = 5$, about 10% improvement compared to cut-based analysis.
Higgs Width Limit

After BDT cut, we performed a binned log-likelihood fit to transverse mass $M_T$

$$-2 \Delta \ln L = \sum_{\text{all bins}} -2 \ln \frac{L \left( \Gamma_H / \Gamma_H^{\text{SM}} \right)}{L_{\text{max}}}$$

For HL-LHC, at 95% CL, the Higgs width can be constrained to

$$\Gamma_H / \Gamma_H^{\text{SM}} < 1.31$$

or

$$\Gamma_H < 5.33 \text{ MeV}$$
**EFT Framework**

\[ \mathcal{L} \supset c_g \frac{\alpha_s}{12\pi v^2} |\mathcal{H}|^2 G_{\mu\nu} G^{\mu\nu} + c_t \frac{y_t}{v^2} |\mathcal{H}|^2 \tilde{Q}_L \tilde{H} t_R + \text{h.c.} \]

\[ \mathcal{L} \supset \kappa_g \frac{\alpha_s}{12\pi v} H G_{\mu\nu} G^{\mu\nu} - \kappa_t \frac{m_t}{v} H (t_R t_L + \text{h.c.}) \]

\[ M_{t++00}^+ \approx + \frac{m_t^2}{2m_Z^2} \log^2 \frac{m_Z^2}{m_t^2} \]

\[ M_{g++00}^+ \approx - \frac{m_Z^2}{2m_Z^2} \]

\[ M_{c++00}^+ \approx - \frac{m_t^2}{2m_Z^2} \log^2 \frac{m_Z^2}{m_t^2} \]
HL-LHC can bound the top Yukawa within $\kappa_t \approx [0.4, 1.1]$ at 95% CL using this single off-shell channel.
Top-Higgs Form Factor

Higgs boson could be a bound state of a strongly interacting sector with composite scale $\Lambda$. In addition, the top quark can also be composite.

The top Yukawa coupling will be modified by a momentum dependent form factor at scale $Q^2$ close or above the new physics scale $\Lambda^2$

$$\Gamma \left( \frac{Q^2}{\Lambda^2} \right) = \frac{1}{(1 + Q^2/\Lambda^2)^n}$$

Phenomenological ansatz motivated by the nucleon form factor.

For $n = 2$, it is a dipole-form factor, higher values of $n$ correspond to higher multipoles.
In high mass region, the interference between s-channel Higgs and continuum background is significant and negative. The difference between SM and form-factor cases become noticeable when the energy scales are comparable or above $\Lambda$ due to the suppression of the destructive interference.
We observe that the HL-LHC can bound this possible new physics effect, at 95% C.L. up to $\Lambda = 1.5$ TeV for $n = 2$ and $\Lambda = 2.1$ TeV for $n = 3$ with $2l2\nu$ final state.
Summary and Outlook

<table>
<thead>
<tr>
<th></th>
<th>$\Gamma_H/\Gamma_{H}^{SM}$</th>
<th>$\Lambda_{EFT}$</th>
<th>$\Lambda_{n=2}^{\text{Composite}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H^* \rightarrow ZZ \rightarrow ll\nu\nu$</td>
<td>1.31</td>
<td>0.8 TeV</td>
<td>1.5 TeV</td>
</tr>
<tr>
<td>$H^* \rightarrow ZZ \rightarrow 4\ell$</td>
<td>1.3 (68%CL)[36]</td>
<td>0.55 TeV[37]</td>
<td>0.8 TeV[18]</td>
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</tbody>
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- Off-shell Higgs is essential to probe new physics at ultraviolet regime

- Promising $H^* \rightarrow ZZ \rightarrow ll\nu\nu$ channel with large signal rate renders improved sensitivity for all considered BSM scenarios

- Off-shell Higgs processes probe Higgs coupling in time-like domain. Complementarily, $t\bar{t}H$ can probe both space-like and time-like domains at high scale. More details in Roshan’s Talk
Thank You!