

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

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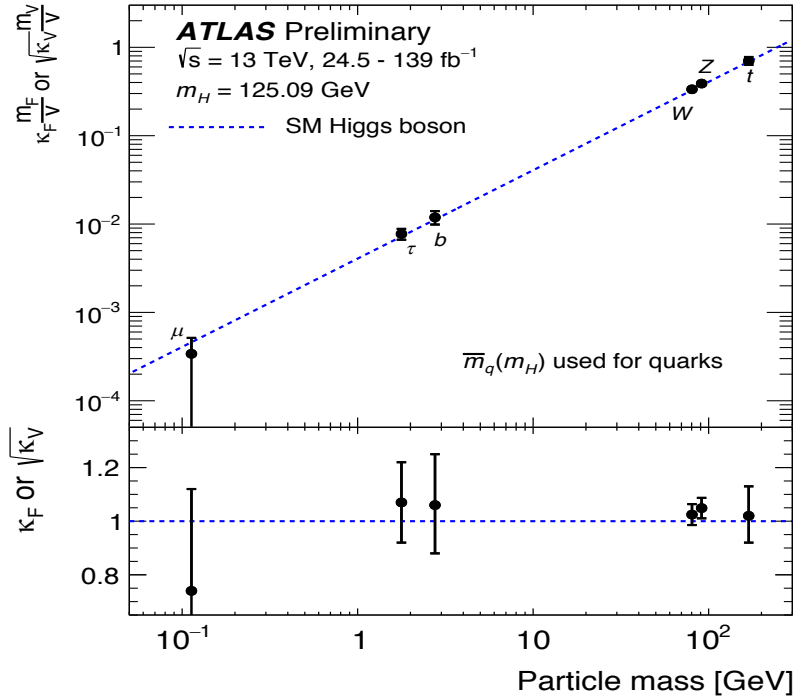
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In collaboration with: Dorival Goncalves, Tao Han and Sze Ching Iris Leung
Based on arXiv: [2012.05272](https://arxiv.org/abs/2012.05272) (Phys.Lett.B 2021)

Outline

- Motivation
- Higgs Couplings in Off-shell Regime
 - Higgs Width
 - EFT Couplings
 - Higgs-Top Form Factor
- Summary and Outlook

Motivation



with the SM

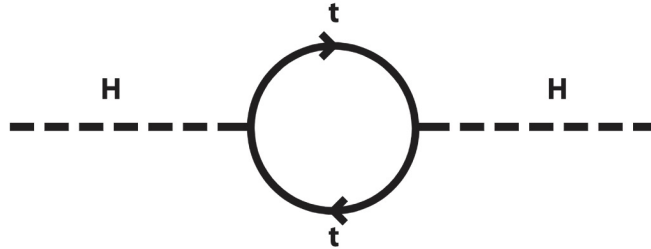
the on-shell
 properties at low

scale Q , the

Sensitivity can be enhanced as $Q \rightarrow \Lambda$
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Motivation

Naturalness Problem



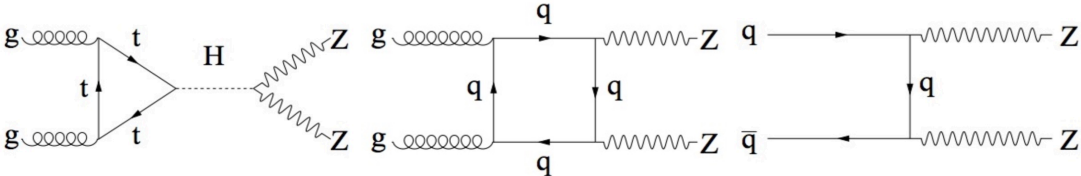
$$\delta m_h^2 \propto -\frac{3y_t^2}{4\pi^2} \Lambda^2$$

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

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



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 $\Gamma_H/\Gamma_H^{SM} > 1$

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

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

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

- $\sqrt{s} = 14 \text{ TeV}$ 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

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

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

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

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

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

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

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

$$m_T^{ZZ} > 250 \text{ GeV}$$

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

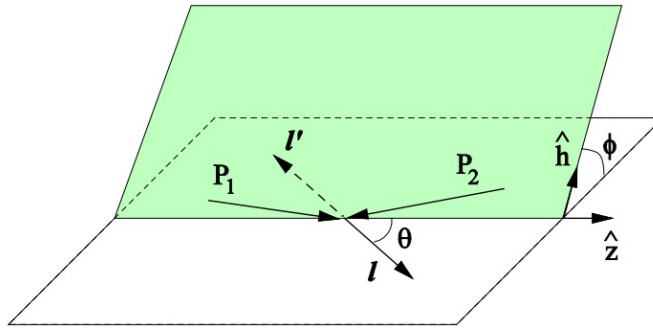
Same-flavor opposite-sign lepton pair
Event with third lepton will be rejected

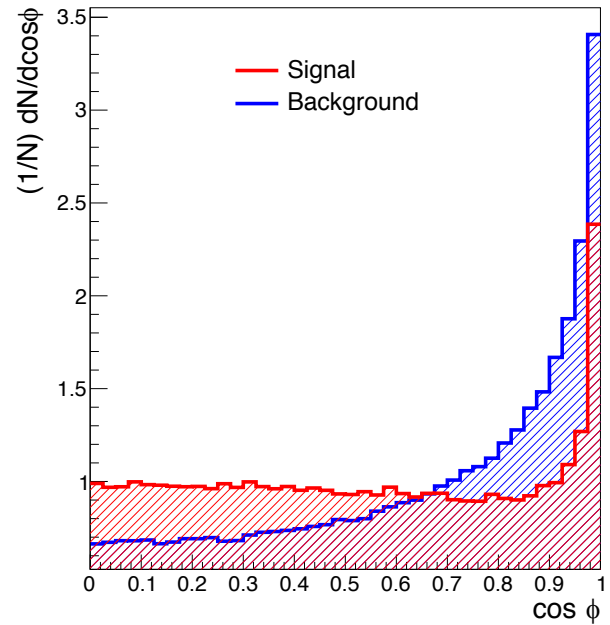
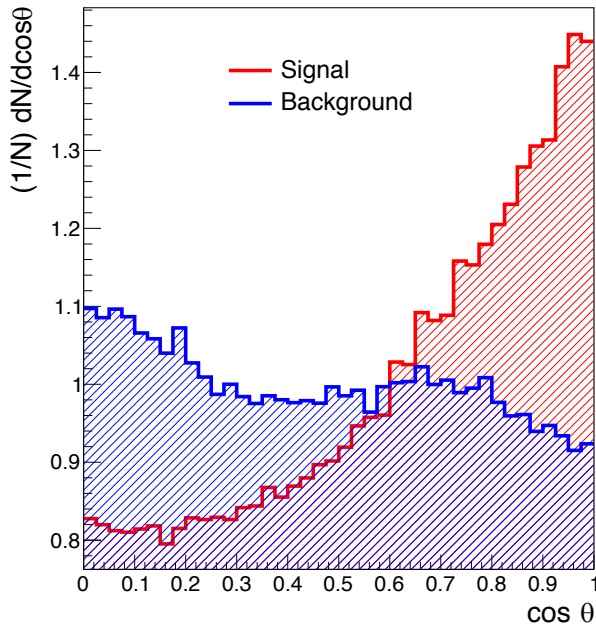
BDT

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 θ and ϕ are the polar and azimuthal angles of the charged lepton in Z boson rest frame (Collins-Soper frame).

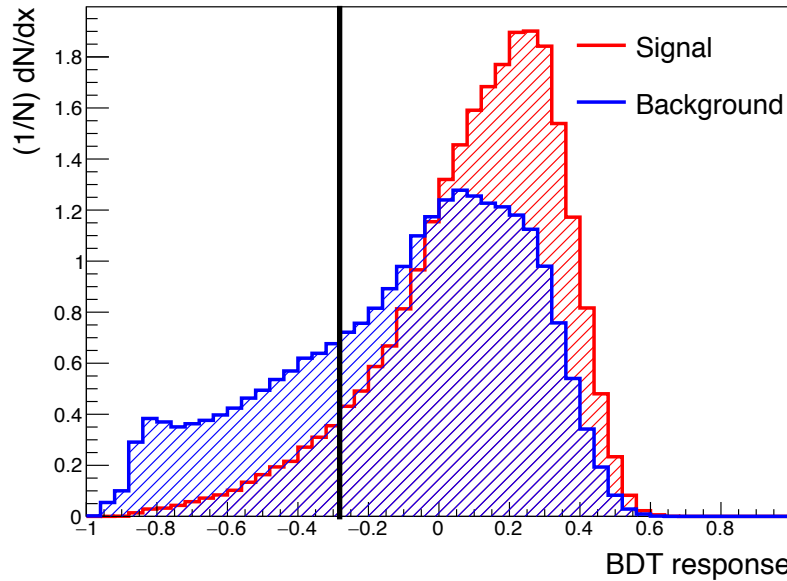
$$\cos\theta = \frac{2|q^0 p_\ell^3 - q^3 p_\ell^0|}{Q\sqrt{Q^2 + |\vec{q}_T|^2}} \quad \cos\phi = \frac{2}{\sin\theta} \frac{|Q^2 \vec{p}_{T\ell} \cdot \vec{q}_T - |\vec{q}_T|^2 p_\ell \cdot q|}{Q^2 |\vec{q}_T| \sqrt{Q^2 + |\vec{q}_T|^2}}$$





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

BDT Results



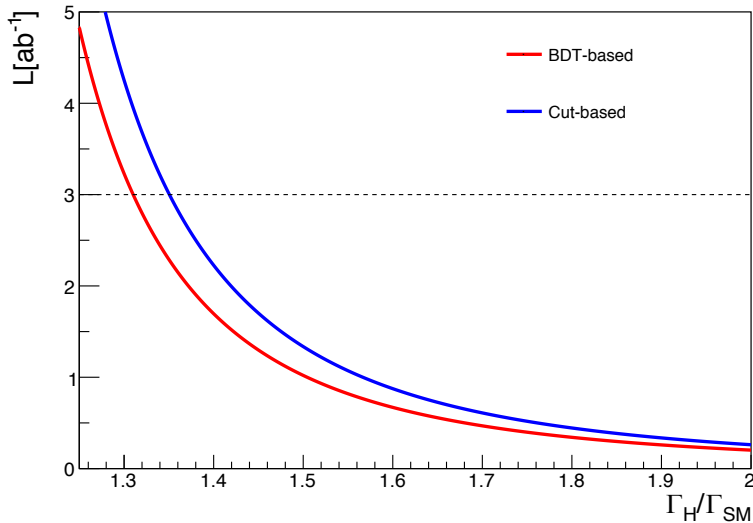
To maximize $S/\sqrt{S+B}$ at 3 ab^{-1} , we choose a BDT cut at -0.26 with signal efficiency 88% and background rejection of 34% .

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

Higgs Width Limit

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

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



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

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

or

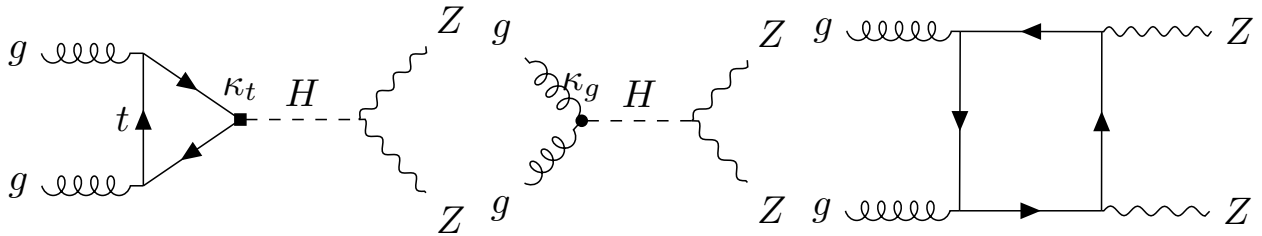
$$\Gamma_H < 5.33 \text{ MeV}$$

EFT Framework

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

↓ EWSB

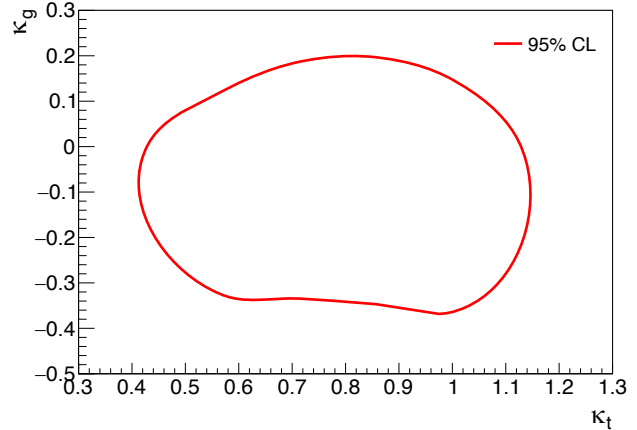
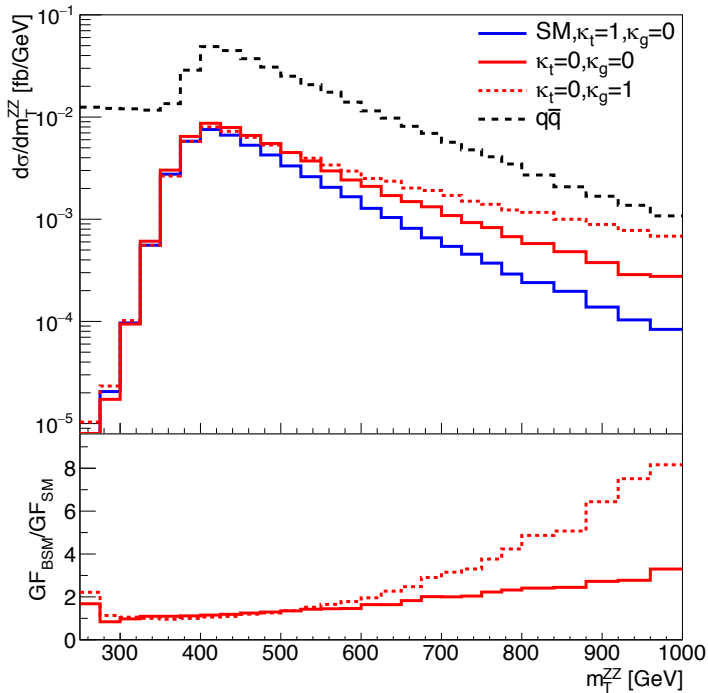
$$\mathcal{L} \supset \kappa_g \frac{\alpha_s}{12\pi v} H G_{\mu\nu} G^{\mu\nu} - \kappa_t \frac{m_t}{v} H (\bar{t}_R t_L + \text{h.c.})$$



$$\mathcal{M}_t^{++00} \approx + \frac{m_t^2}{2m_Z^2} \log^2 \frac{m_{ZZ}^2}{m_t^2}$$

$$\mathcal{M}_g^{++00} \approx - \frac{m_{ZZ}^2}{2m_Z^2}$$

$$\mathcal{M}_c^{++00} \approx - \frac{m_t^2}{2m_Z^2} \log^2 \frac{m_{ZZ}^2}{m_t^2}$$



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

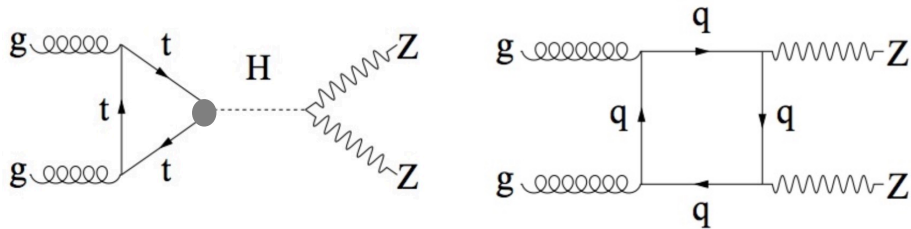
Higgs boson could be a bound state of a strongly interacting sector with composite scale Λ . In addition, the top quark can also be composite.

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

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

Phenomenological ansatz motivated by the nucleon form factor.

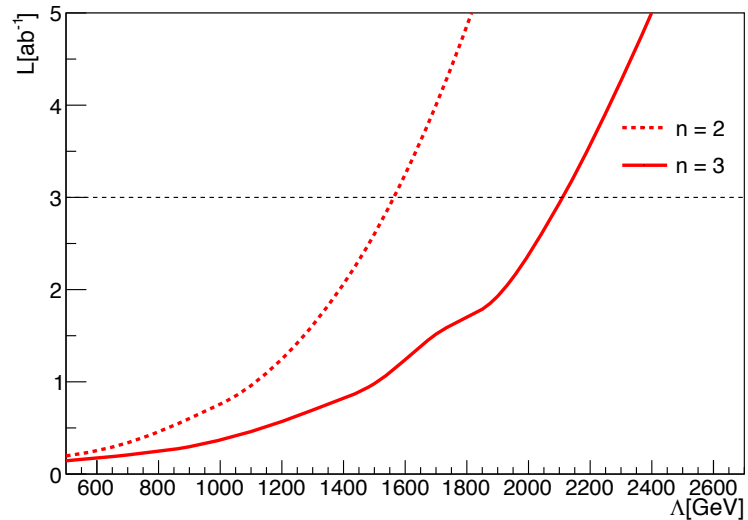
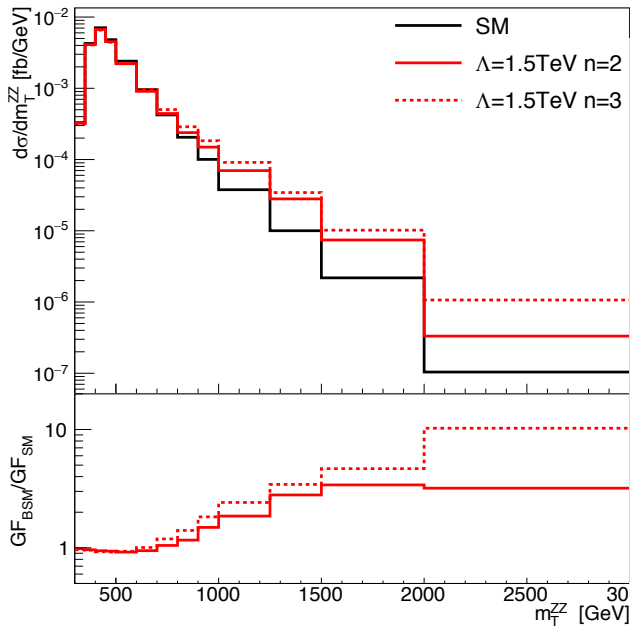
For $n = 2$, it is a dipole-form factor, higher values of n correspond to higher multipoles.



$$\sigma_{\text{full ggf}} = \Gamma^2 (Q^2/\Lambda^2) \sigma_{\text{triangle}}^{\text{SM}} + \Gamma (Q^2/\Lambda^2) \boxed{\sigma_{\text{int}}^{\text{SM}}} + \sigma_{\text{box}}^{\text{SM}}$$

Destructive

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 Λ 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

	Γ_H/Γ_H^{SM}	Λ_{EFT}	$\Lambda_{\text{Composite}}^{n=2}$
$H^* \rightarrow ZZ \rightarrow \ell\ell\nu\nu$	1.31	0.8TeV	1.5TeV
$H^* \rightarrow ZZ \rightarrow 4\ell$	1.3(68%CL)[36]	0.55TeV[37]	0.8TeV[18]

- Off-shell Higgs is essential to probe new physics at ultraviolet regime
- Promising $H^* \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ 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 and in [arXiv:2106.00018](https://arxiv.org/abs/2106.00018)



Thank You!