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

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Outline

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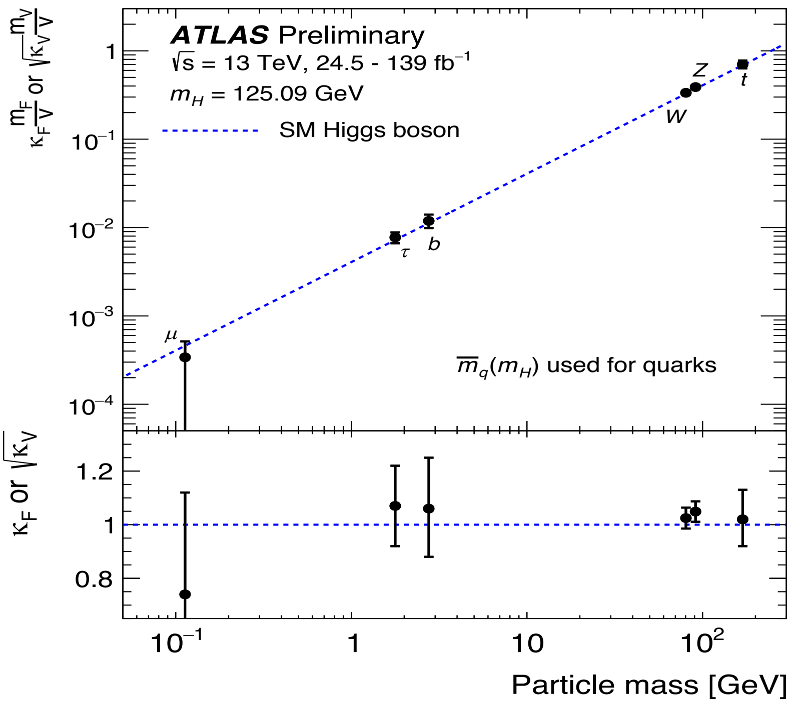
Motivation



with the SM

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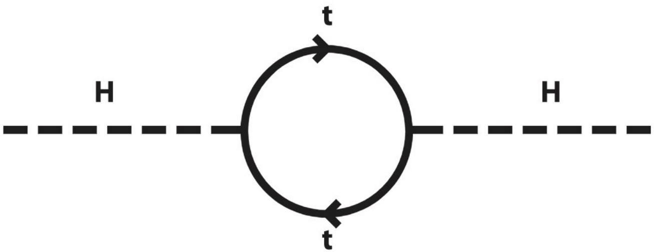
scale Q, the

[Phys. Rev. D 101 (2020) 012002]

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.

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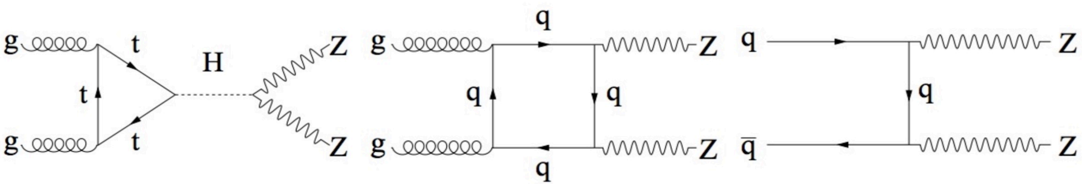
Signal Chanel

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



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

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Higgs Width

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

$$\sigma^{\text{on-shell}}_{i\to H\to f} \propto \frac{g_i^2\left(m_H\right) g_f^2\left(m_H\right)}{\Gamma_H}$$

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

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

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

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[1] JHEP, 08:116, 2012; Phys. Rev., D88:054024, 2013.

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($gg \to H^* \to ZZ$) and GGF continuum background ($gg \to ZZ$) is obtained by $\sigma_{int} = \sigma_{gg\to(H^*\to)ZZ} - \sigma_{gg\to H^*\to ZZ} - \sigma_{gg\to ZZ}$

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Selection Cuts

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

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

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

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

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

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

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

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

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

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

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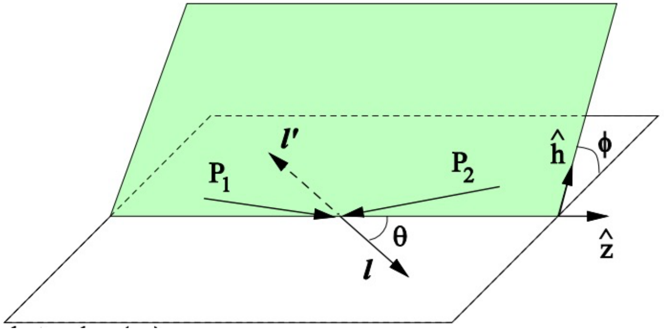
BDT

To further distinguish signal and background, we built a boosted decision tree (BDT).
Two of the observables we used are $cos\theta \ \ cos\varphi$, where θ and φ are the polar and azimuthal angles of the charged lepton in Z boson rest frame (Collins-Soper frame).

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



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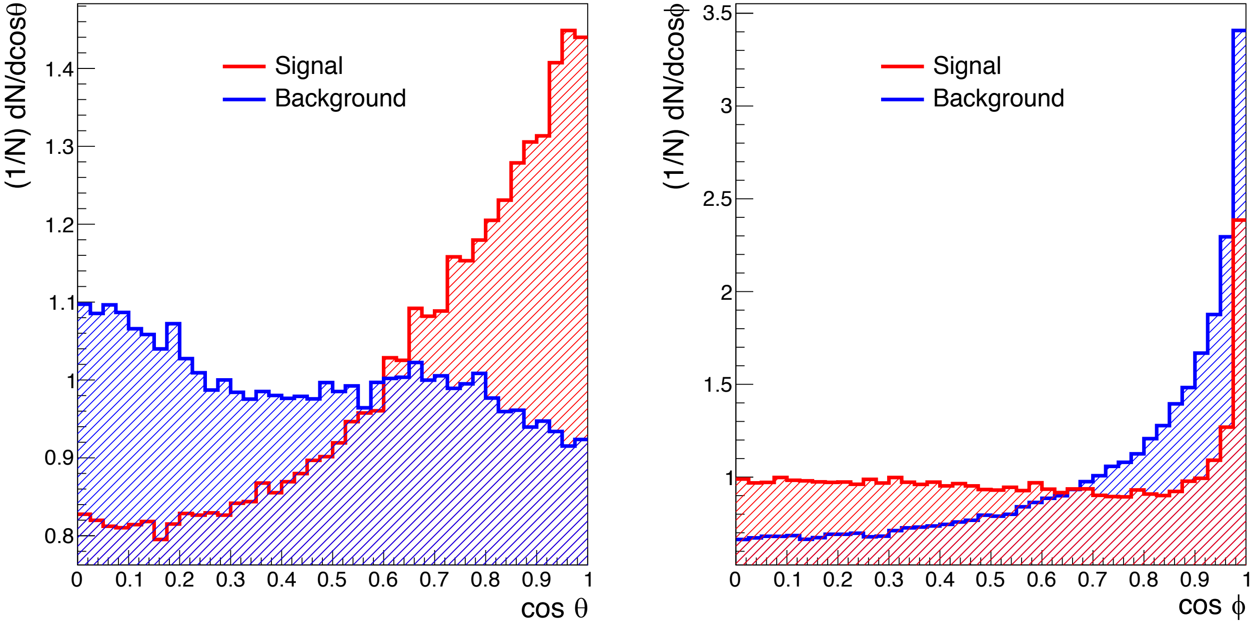

The difference arises from the different Z boson polarizations for the signal and background components at large diboson invariant mass. The s-channel Higgs tends to have Z_L dominance, while the background is mostly Z_T dominated

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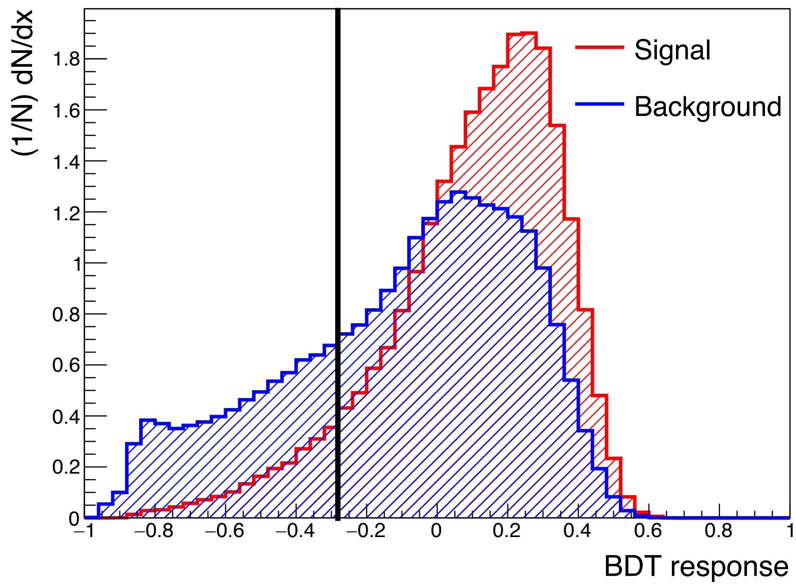
BDT Results



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% .

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

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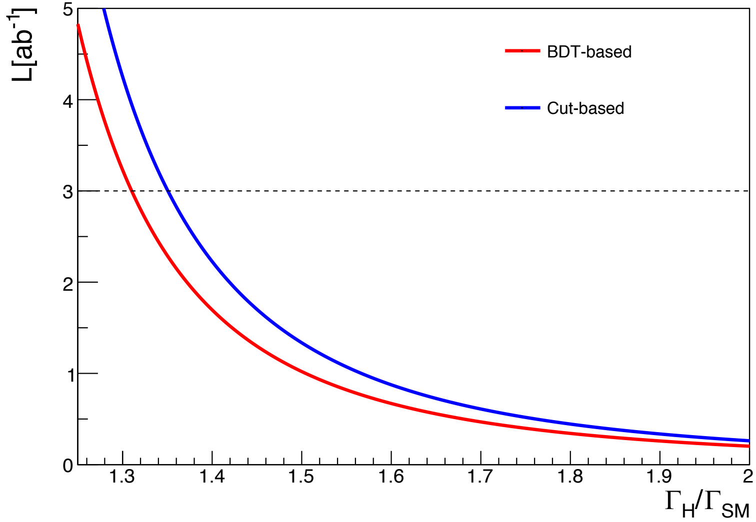
Higgs Width Limit

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

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



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

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

or

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

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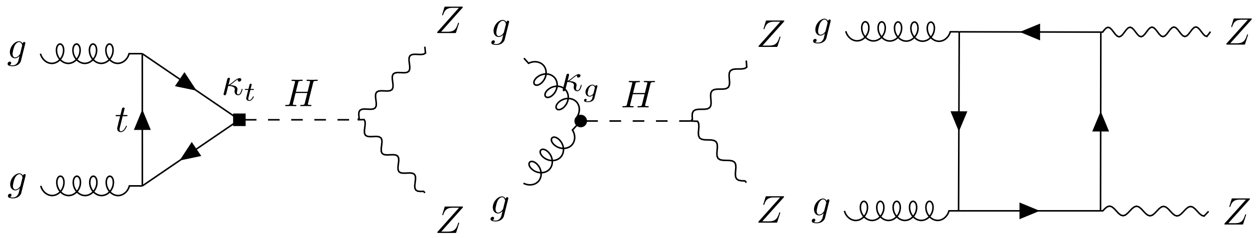
EFT Framework

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

EWSB

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



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

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

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

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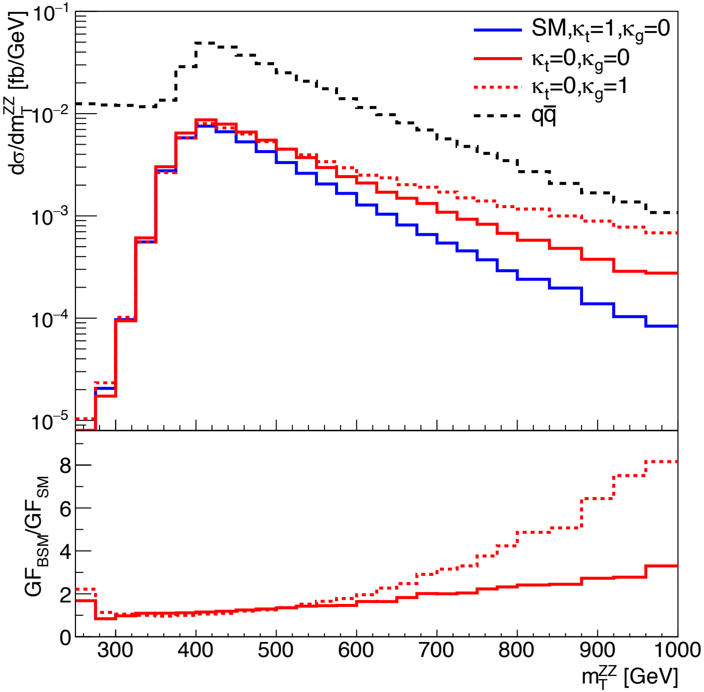

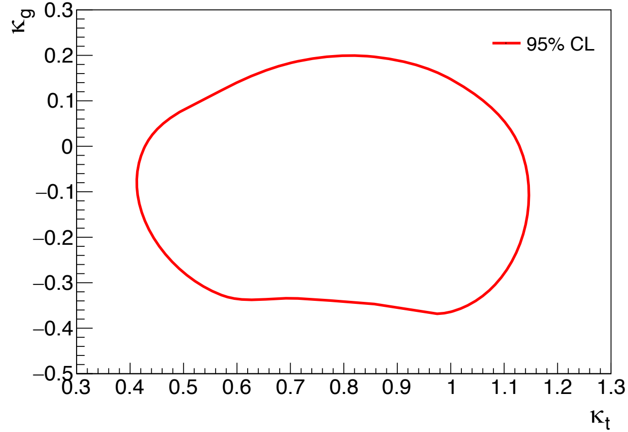

HL-LHC can bound the top Yukawa within $\kappa_t \approx [0.4, 1.1]$ at 95% CL using this single off-shell channel.

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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

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

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.

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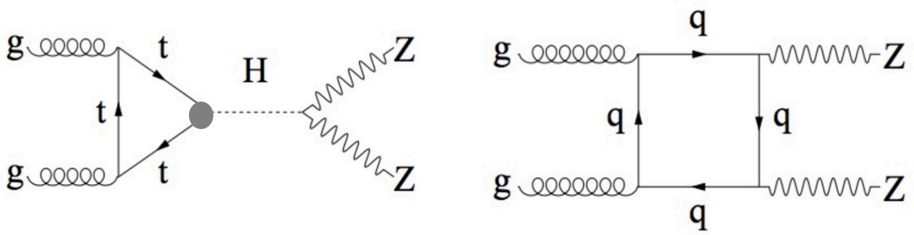
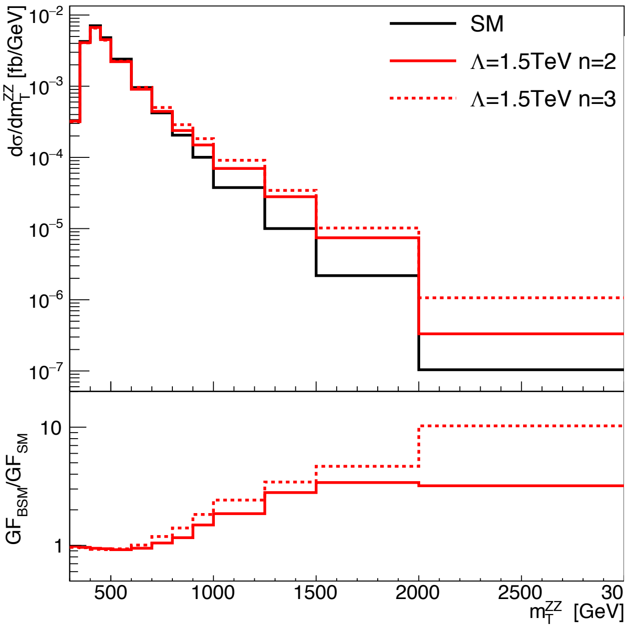
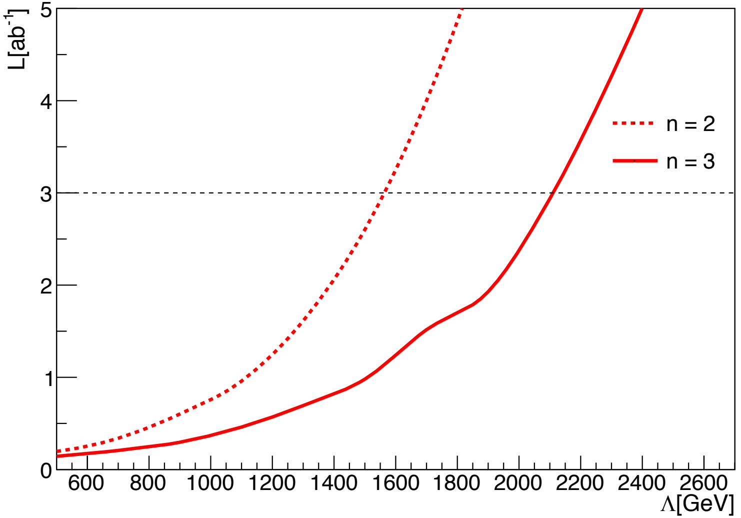


$$\sigma_{\text{full ggf}} = \Gamma^2\left(Q^2/\Lambda^2\right)\sigma^{\text{SM}}_{\text{triangle}} + \Gamma\left(Q^2/\Lambda^2\right)\boxed{\sigma^{\text{SM}}_{\text{int}}} + \sigma^{\text{SM}}_{\text{box}}$$

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

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Summary and Outlook

	Γ_H/Γ_H^{SM}	Λ_{EFT}	$\Lambda^{n=2}_{\text{Composite}}$
$H^* \to ZZ \to \ell\ell\nu\nu$	1.31	0.8TeV	1.5TeV
$H^* \to ZZ \to 4\ell$	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*→ZZ→ℓℓvv 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

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Thank You!