What can off-shell Higgs tell us?

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Off-shell interpretations task force

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What can off-shell Higgs production tell us?

off-shell

width

exact flat direction

difficult

UV models
($\kappa_V > 1$, tuning)

approx. flat direction?

· still need $\kappa_V > 1$?
· need to relax Vh(h→bb)
· which deviation of on-shell rate will give more freedom?

top/Higgs couplings

κ_t vs κ_g

weaker than
tth
~ (40% vs. 10% @HL-LHC)

top EW couplings

weaker than
ttZ
~ (30% vs. 10%)

top CPV?

Flat direction in on-shell Higgs measurements

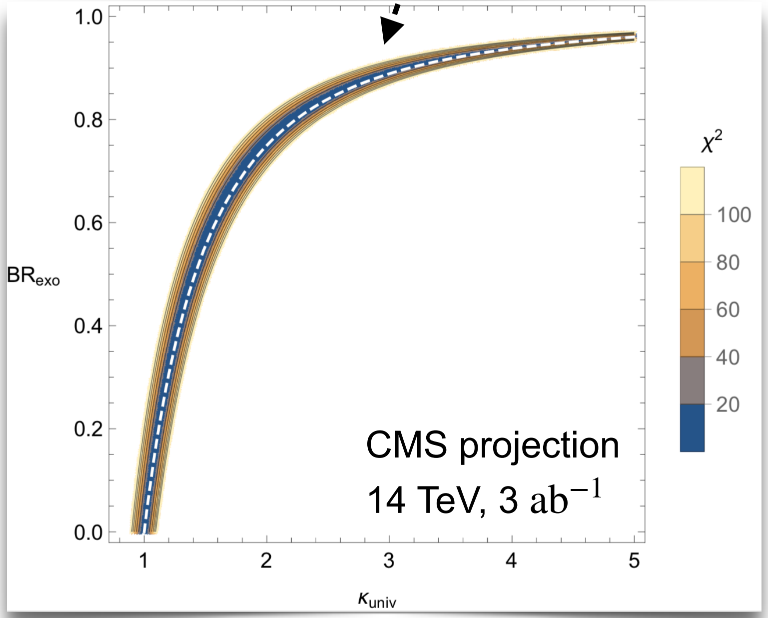
$$\sigma(XX \to h)\,\mathrm{BR}(h \to YY) \;\propto\; g_{hXX}^2 \frac{g_{hYY}^2}{\Gamma_h}$$

$$g_{hii} = \kappa_{\rm univ}\, g_{hii}^{\rm SM}$$

$$\Gamma_h = \kappa_{\rm univ}^4 \Gamma_h^{\rm SM}$$

all on-shell rates unchanged

$$\Gamma_h = \kappa_{\rm univ}^2 \Gamma_h^{\rm SM} + \Gamma_h^{\rm exo} \quad \to \quad \mathrm{BR}_{\rm exo} = \frac{\kappa_{\rm univ}^2 - 1}{\kappa_{\rm univ}^2}$$



untagged BR gives most leeway,
invisible BR already strongly constrained

$$\mathrm{BR}(\mathrm{Higgs} \to \mathrm{invisible}) < 13\% \quad (95\%\ \mathrm{CL})$$

[ATLAS-CONF-2020-008]

thanks to Jorge de Blas for providing the likelihood from [1905.03764]

Flat direction vs off-shell Higgs

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Going to off-shell region:

$$\frac{d\sigma_{gg\to h^*\to ZZ}}{ds} \;\propto\; \frac{g_{hgg}^2 g_{hZZ}^2}{(s-m_h^2)^2 + \Gamma_h^2 m_h^2} \sim \frac{g_{hgg}^2 g_{hZZ}^2}{s^2}$$

which grows as $\kappa_{\rm univ}^4$

➡ upper bound on off-shell cross section translates to upper bound on width

[Caola and Melnikov 1307.4935]

Universal flat direction

How to realize a **universal** flat direction? Toy setup:

$$\mathcal{L}_{\rm BSM} = \frac{c_H}{f^2}\left(\partial_\mu |H|^2\right)^2 + \lambda_{H\phi}|H|^2\phi^2$$

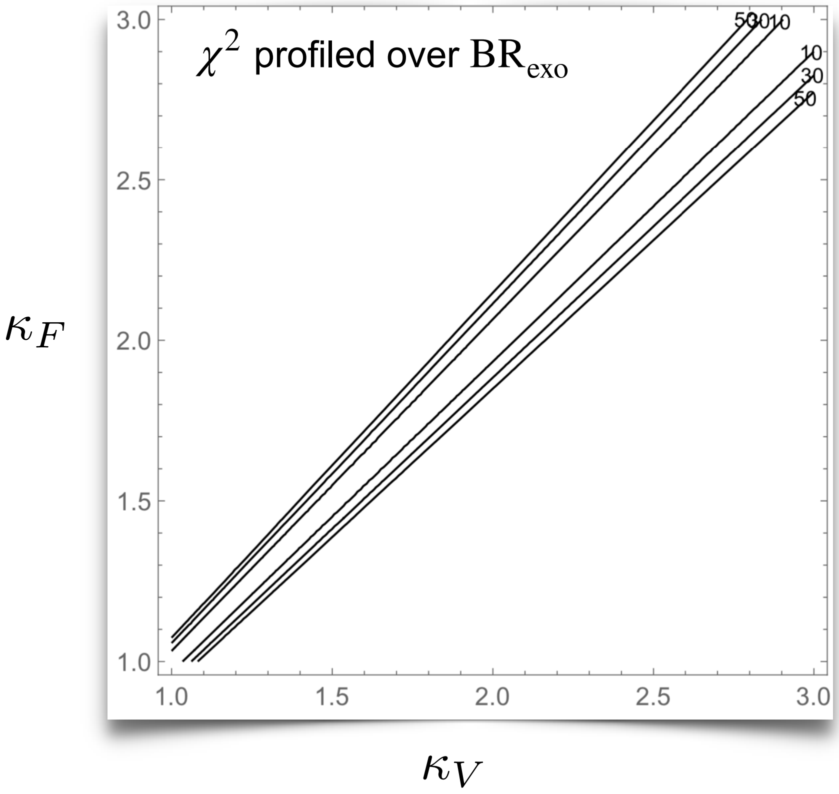
$$\frac{g_{hii}}{g_{hii}^{\rm SM}} = 1 - c_H \frac{v^2}{f^2}$$

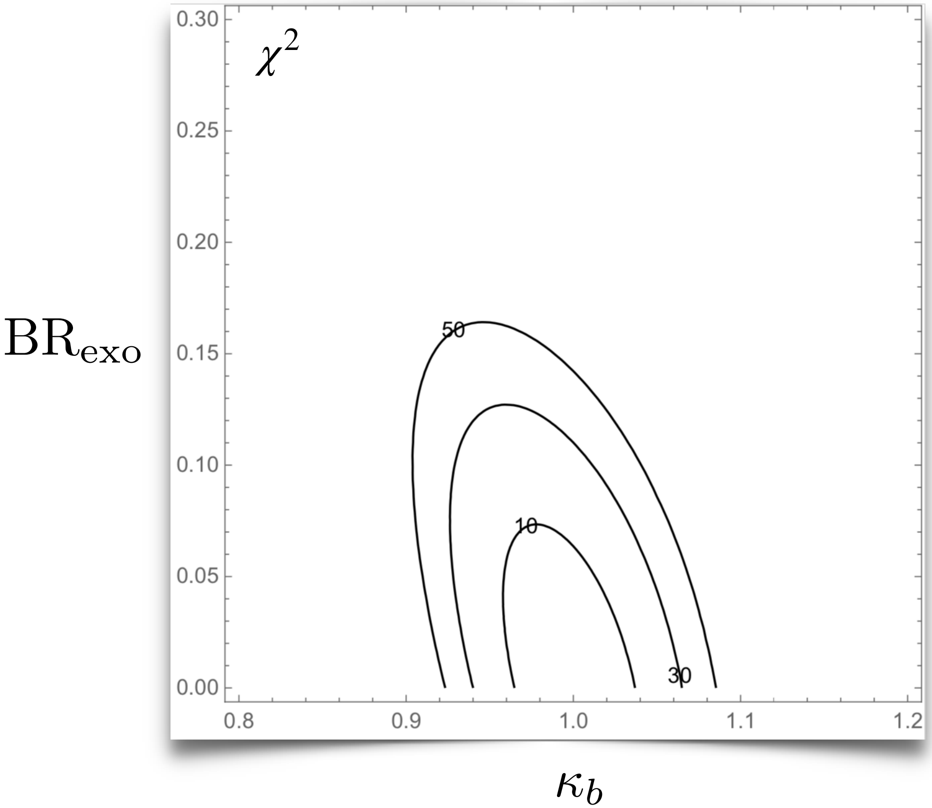
$$\Gamma(h \to \phi\phi) \sim \frac{\lambda_{H\phi}^2 v^2}{8\pi m_h}$$

Requires:

- $c_H < 0$, possible but somewhat exotic. for example [Georgi and Machacek 1985]
  E.g., pNGB of non-compact coset, or models with larger scalar reps.
- ϕ decays to hadrons, for example color octet or singlet $\to gg$
- A "conspiracy" relating c_H and $\lambda_{H\phi}$

Relaxing coupling universality?





Flat direction is lifted very rapidly when we depart from universal rescaling of Higgs couplings

Preliminary - in progress

Beyond the Higgs width: (SM)EFT

- $gg \to ZZ$ [Higgs-mediated + continuum] is sensitive to Higgs/top operators. In Higgs basis:

9 CP-even coefficients

$$\{c_{gg},\ (\delta y_u)_{33},\ \delta c_z,\ c_{zz},\ c_{z\Box},\ (\delta g_L^{Zu})_{33},\ (\delta g_R^{Zu})_{33},\ \mathrm{Re}\,(d_{Zu})_{33},\ \mathrm{Re}\,(d_{Gu})_{33}\}$$

5 CP-odd coefficients

$$\{\tilde{c}_{gg},\ (\phi_u)_{33},\ \tilde{c}_{zz},\ \mathrm{Im}(d_{Zu})_{33},\ \mathrm{Im}(d_{Gu})_{33}\}$$

$$\mathcal{L} = \frac{h}{v}\Big[\tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\widetilde{G}^a_{\mu\nu} - m_t\,(\delta y_u)_{33}e^{i(\phi_u)_{33}}\bar{t}_R t_L + \mathrm{h.c.} + \delta c_z\,\frac{g_Z^2 v^2}{4}Z_\mu Z^\mu + c_{zz}\frac{g_Z^2}{4}Z_{\mu\nu}Z^{\mu\nu} + c_{z\Box}g^2 Z_\mu\partial_\nu Z^{\mu\nu} + \tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\widetilde{G}^a_{\mu\nu} + \tilde{c}_{zz}\frac{g_Z^2}{4}Z_{\mu\nu}\widetilde{Z}^{\mu\nu}\Big]$$

$$+ g_Z(\delta g_L^{Zu})_{33}Z_\mu\bar{t}_L\gamma^\mu t_L + g_Z(\delta g_R^{Zu})_{33}Z_\mu\bar{t}_R\gamma^\mu t_R - \frac{m_t}{4v^2}\Big[g_s\,\bar{t}_L\sigma^{\mu\nu}T^a\underline{(d_{Gu})_{33}}t_R G^{\mu\nu\,a} + g_Z\,\bar{t}_L\sigma^{\mu\nu}T^a\underline{(d_{Zu})_{33}}t_R Z^{\mu\nu}\Big] + \mathrm{h.c.}$$

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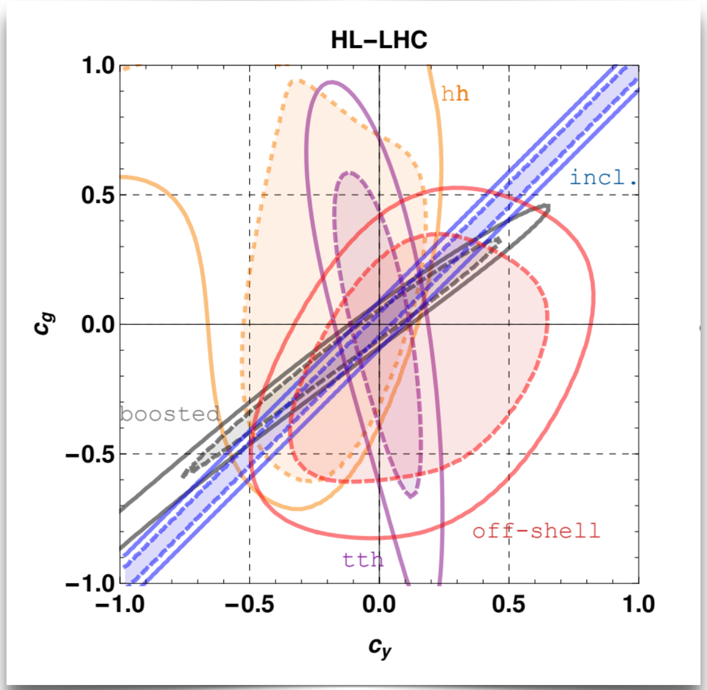
$$\frac{\sigma_{gg\to h}}{\sigma^{\rm SM}_{gg\to h}} \sim [1 + c_{gg} - (\delta y_u)_{33}]^2$$

blind direction in on-shell gluon fusion production



[Azatov, Grojean, Paul, Salvioni 1608.00977]

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68% CL bounds on $\dfrac{\Lambda}{\sqrt{C_i}}$ [TeV]

$$\begin{aligned} C_{\phi Q}^{-} &: [-0.50, 0.37] \\ C_{\phi t} &: [-0.24, 0.55] \\ C_{tZ} &: [-0.66, 0.66] \\ C_{tG} &: [1.2, 1.8] \end{aligned}$$

current bound on $C_{tG} \leftrightarrow \mathrm{Re}\,(d_{Gu})_{33}$ *is significantly stronger than for others*

[Brivio, Bruggisser, Maltoni, Moutafis, Plehn, Vryonidou, Westhoff, Zhang 1910.03606]

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- $gg \to ZZ$ is mostly sensitive to **axial vector** coupling $\propto (\delta g_L^{Zu})_{33} - (\delta g_R^{Zu})_{33}$

[Azatov, Grojean, Paul, Salvioni 1608.00977]

- Angular distributions can be exploited to isolate **LL** pol. mode, which is enhanced for BSM couplings

[Cao, Yan, Yuan, Zhang 2004.02031]

$$\frac{g}{2c_w}\bar{t}\,(v_t - a_t\gamma_5)t\,Z^\mu$$

$$a_t^{\rm SM} = 1/2$$