Status of off-shell Higgs studies

Eleni Vryonidou
University of Manchester

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25/05/23

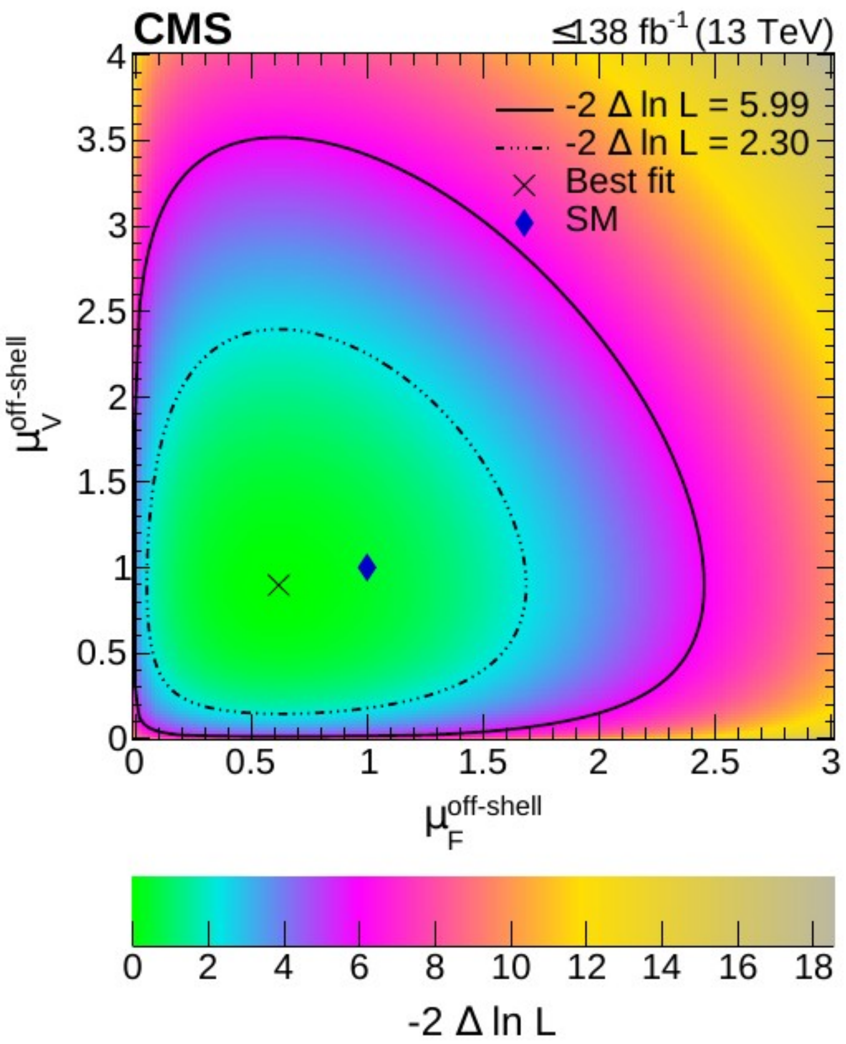
Why off-shell Higgs?

A probe of the Higgs width:

$$\sigma^{\text{onshell}}_{gg\to H\to VV} \sim \frac{c^2_{ggH}c^2_{VVH}}{m_H\Gamma_H}$$

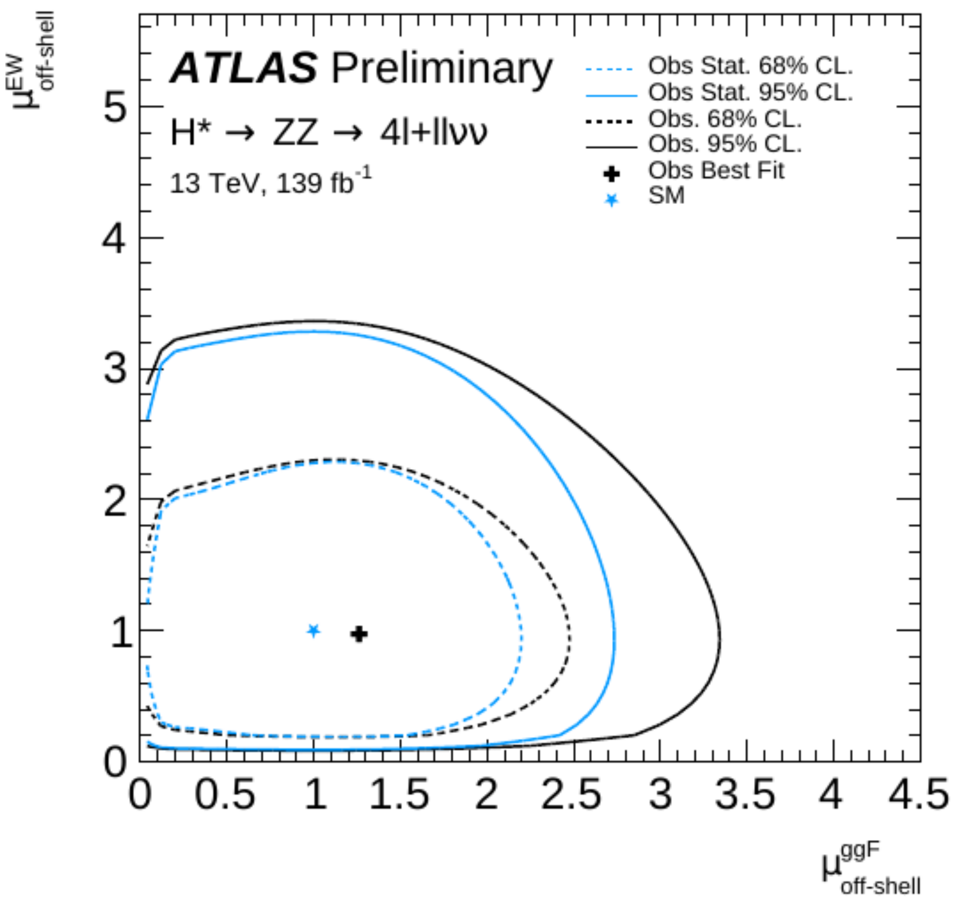
$$\sigma^{\text{offshell}}_{gg\to H\to VV} \sim \frac{c^2_{ggH}c^2_{VVH}}{m^2_{ZZ}}$$

Caola and Melnikov arXiv:1307.4935



$\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

CMS, 2202.06923

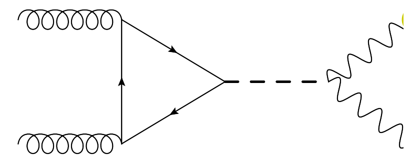


$\Gamma_H = 4.6^{+2.6}_{-2.5}$ MeV

ATLAS-CONF-2022-068

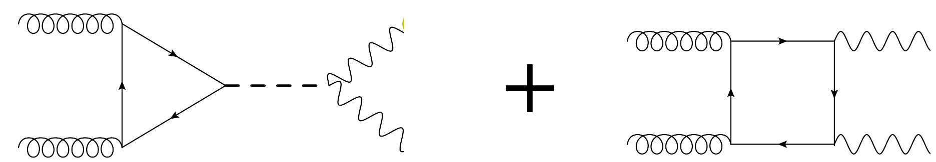
Off-shell Higgs

Why is this process interesting?

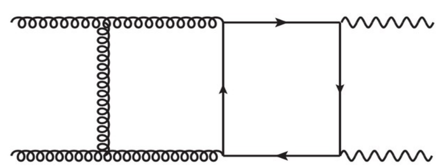


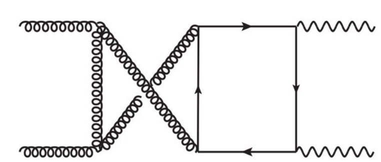
- Crucial for Higgs width determination
- Access to high energy regions due to large invariant masses:
  - Models with new heavy resonances
  - **Sensitivity to SMEFT operators**

Why is this process tough?



- Signal background interference
- Loop induced: hard to compute higher order corrections





Full top amplitudes only recently computed:

Agarwal, Jones, von Manteuffel 2011.15113, Brønnum-Hansen, Wang 2009.03742, 2101.12095

- **Complex EFT structure**

LHCHWG Off-Shell Task Force

LHCHWG-2022-001

May 16, 2022

LHC Higgs Working Group[a]

Public Note

Off-shell Higgs Interpretations Task Force[b]

Models and Effective Field Theories Subgroup Report

Aleksandr Azatov [1,2,c], Jorge de Blas [3,d], Adam Falkowski[4,e], Andrei V. Gritsan[5,f], Christophe Grojean[6,7,g], Lucas Kang[5,h], Nikolas Kauer[8,i] (ed.), Ennio Salvioni[9,10,j], Ulascan Sarica[11,k], Marion Thomas[12,l] and Eleni Vryonidou[12,m]

arXiv:2203.02418

Contents

Some highlights from this report to follow

Off-shell in Universal directions models

Golden rule:

$$\sigma^{\text{onshell}}_{gg\to H\to VV} \sim \frac{c^2_{ggH} c^2_{VVH}}{m_H \Gamma_H}$$

$$\sigma^{\text{offshell}}_{gg\to H\to VV} \sim \frac{c^2_{ggH} c^2_{VVH}}{m^2_{ZZ}}$$

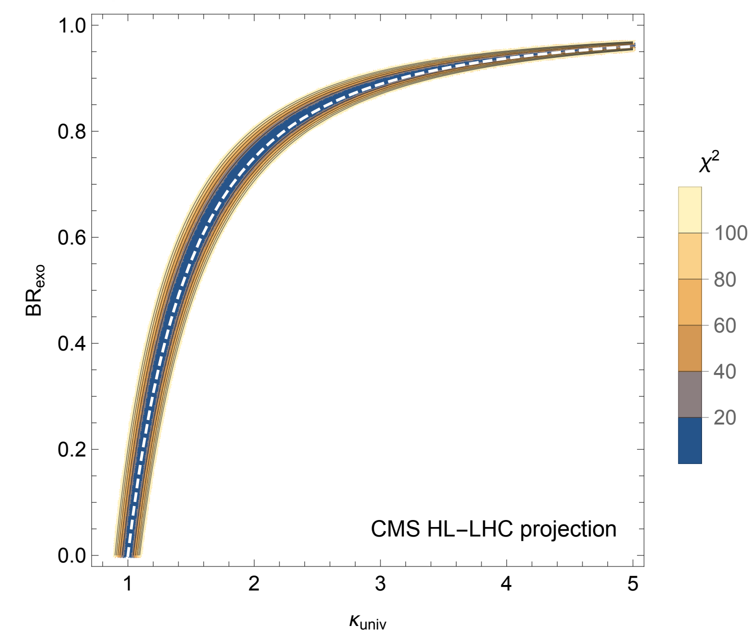
Universal direction:

$$g_{hii} = \kappa_{\text{univ}}\, g^{\text{SM}}_{hii} \qquad \Gamma_h = \kappa^4_{\text{univ}} \Gamma^{\text{SM}}_h$$

→ on-shell unaffected
off-shell affected

Flat direction from on-shell:

$$\text{BR}_{\text{exo}} = \frac{\kappa^2_{\text{univ}} - 1}{\kappa^2_{\text{univ}}}$$



Off-shell measurement gives a bound on κ_{univ}

Realised in particular BSM scenarios with specific couplings

$$\mathcal{L}_{\text{BSM}} \ni \frac{c_H}{2f^2}(\partial_\mu |H|^2)^2 - \lambda_{H\varphi}|H|^2\varphi^2$$ e.g. Triplet scalars

Azatov, de Blas, Grojean, Salvioni

arXiv:2203.02418

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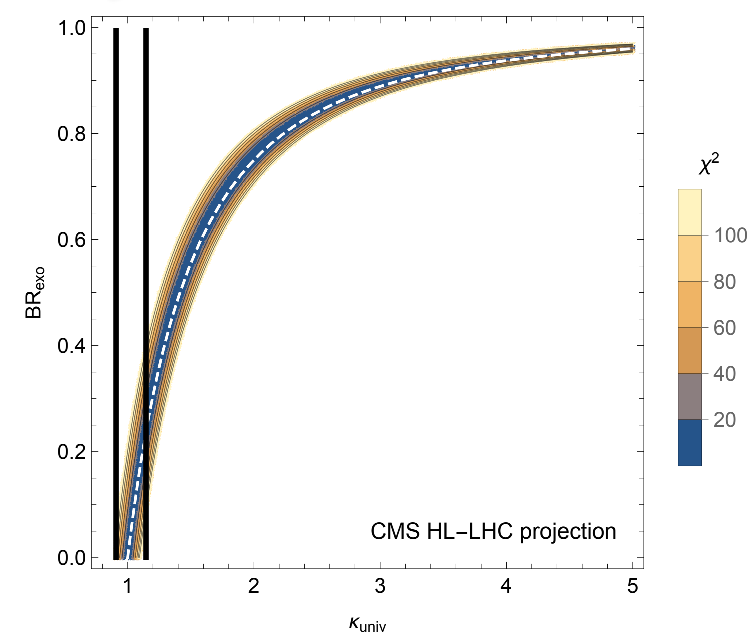

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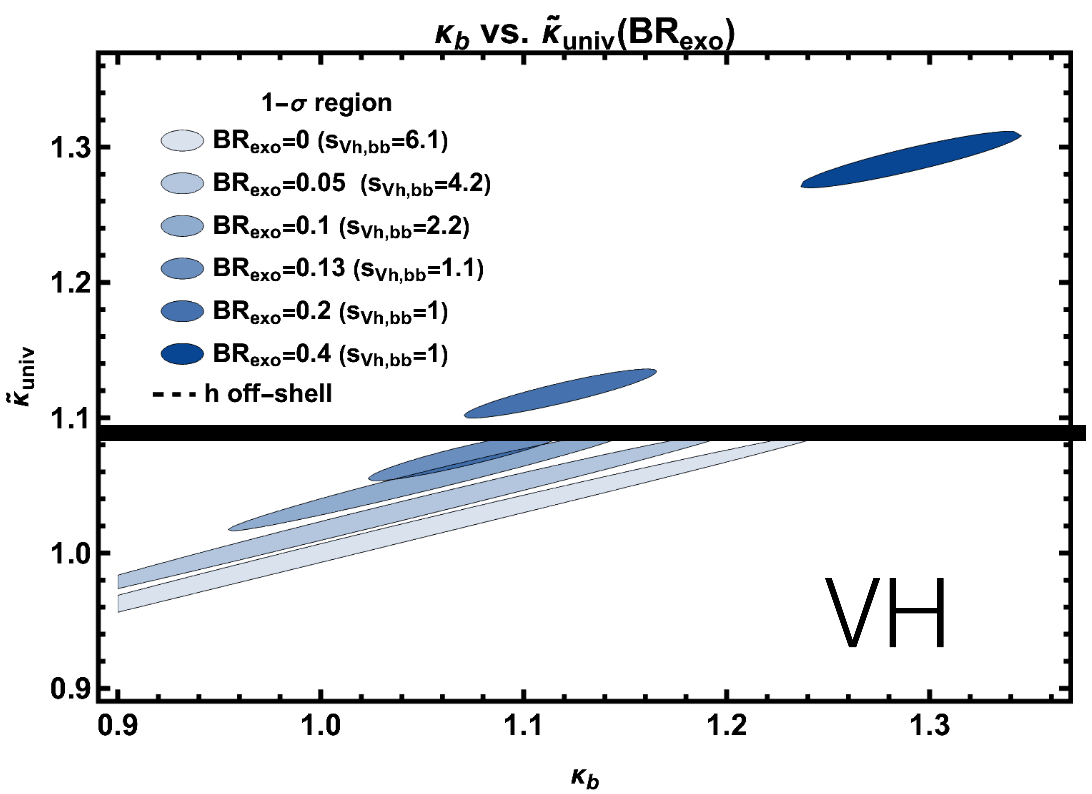
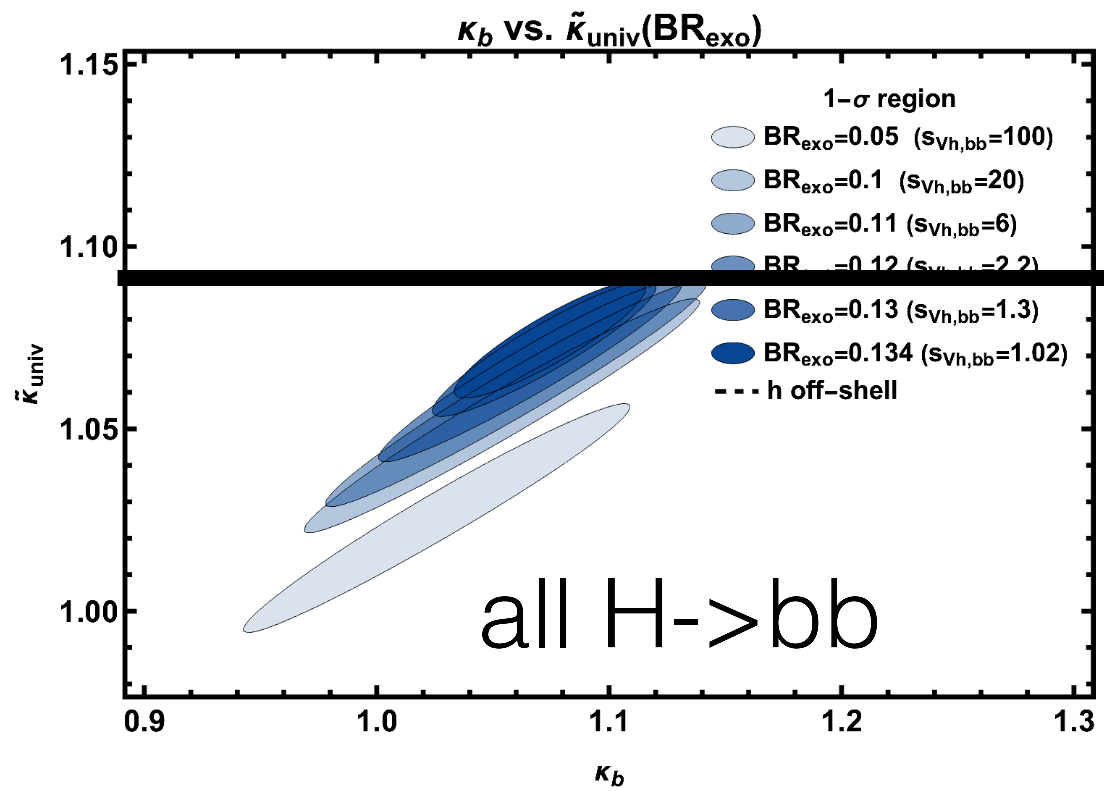
Beyond Universal directions

Relaxing universality assumption: $\tilde{\kappa}_{\rm univ}, \kappa_b, {\rm BR}_{\rm exo}$

Hbb coupling

Use on-shell VH, ttH with Higgs to bb and off-shell





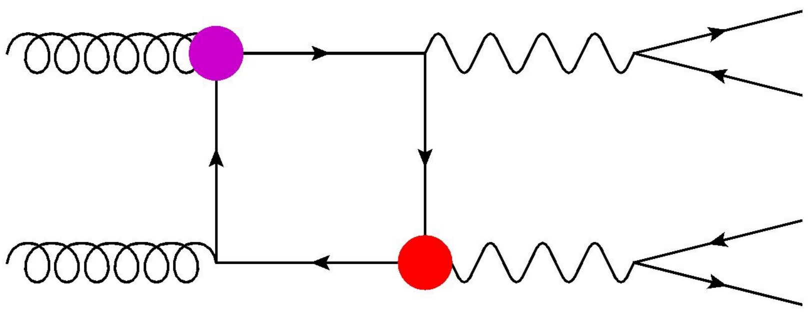
$$ {\rm BR}_{\rm exo} = 1 - \mu_{\rm on}\frac{\tilde{\kappa}^2_{\rm univ}(1-{\rm BR}^{b\bar{b}}_{\rm SM}) + \kappa_b^2{\rm BR}^{b\bar{b}}_{\rm SM}}{\tilde{\kappa}^4_{\rm univ}}\,, \quad \kappa_b^2 = \frac{\mu_{Vh,b\bar{b}}}{\mu_{\rm on}}\,\tilde{\kappa}^2_{\rm univ} \qquad \mu_{\rm off} = a + b\tilde{\kappa}^2_{\rm univ} + c\tilde{\kappa}^4_{\rm univ} $$

Off-shell can help for large untagged widths

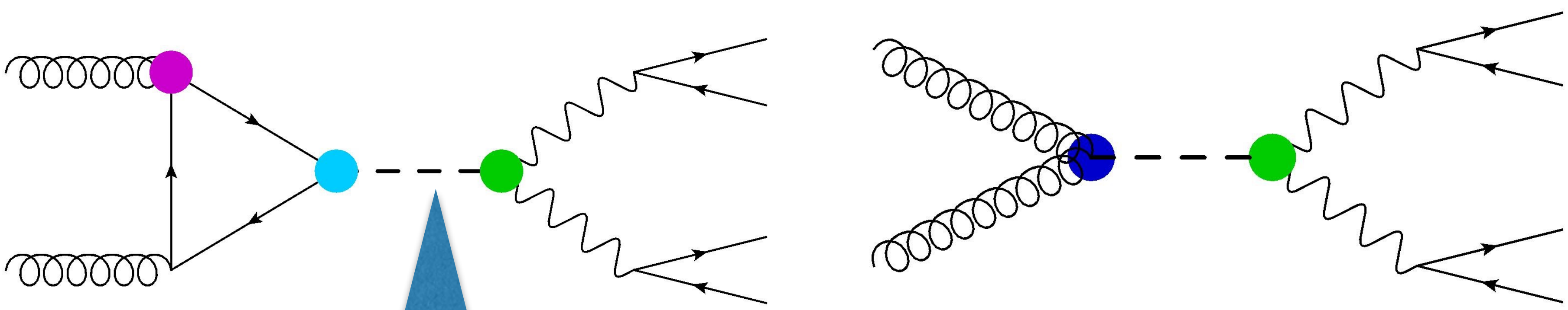
Azatov, de Blas, Grojean, Salvioni

arXiv:2203.02418

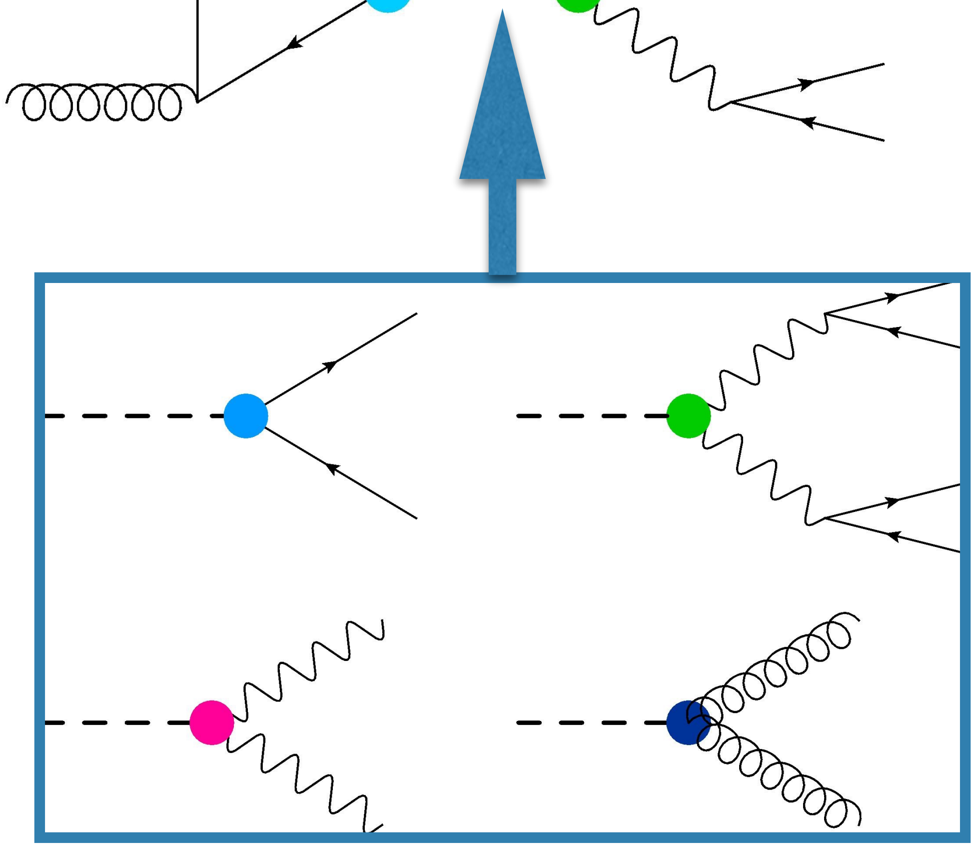
Going more general: SMEFT



The background

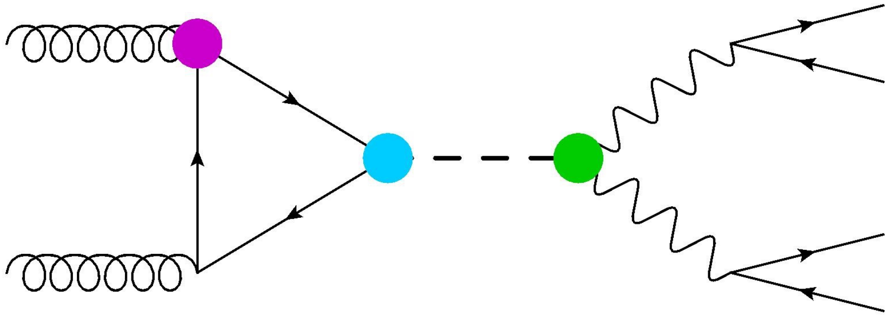


The signal



The Higgs width

The Higgs propagator



$$\mathcal{M} \propto \frac{c_i}{s - M_H^2 + i\Gamma_H(c_i)M_H}$$

$$s \gg M_H^2 \qquad \mathcal{M} \propto \frac{c_i}{s - M_H^2}$$

$$s \sim M_H^2 \qquad \sigma_H(c_i) \cdot \frac{\Gamma_H^{4l}(c_i)}{\Gamma_H(c_i)}$$

Off-shell Higgs in SMEFT

Higgs basis: Top and Higgs interactions

$$\Delta\mathcal{L} = \frac{h}{v}\Big(c_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}G^{\mu\nu\,a} - m_t\underline{[\delta y_u]_{33}}\bar{t}_L t_R + \text{h.c.} + \delta c_z\frac{g_Z^2 v^2}{4}Z_\mu Z^\mu + c_{zz}\frac{g_Z^2}{4}Z_{\mu\nu}Z^{\mu\nu} + c_{z\Box}g_L^2 Z_\mu\partial_\nu Z^{\mu\nu}$$
$$+\tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\widetilde{G}^a_{\mu\nu} + \tilde{c}_{zz}\frac{g_Z^2}{4}Z_{\mu\nu}\widetilde{Z}_{\mu\nu}\Big) - g_Z(\delta g_L^{Zu})_{33}Z_\mu\bar{t}_L\gamma^\mu t_L - g_Z(\delta g_R^{Zu})_{33}Z_\mu\bar{t}_R\gamma^\mu t_R$$
$$-\frac{m_t}{4v^2}\Big(1+\frac{h}{v}\Big)\Big(g_s\bar{t}_R\sigma^{\mu\nu}T^a\underline{[d_{Gu}]_{33}}t_L G^a_{\mu\nu} + g_Z\bar{t}_R\sigma^{\mu\nu}T^a\underline{[d_{Zu}]_{33}}t_L Z_{\mu\nu}\Big) + \text{h.c.},$$

red: CP odd, blue: CP even

- Top Yukawa
- Higgs-gluon

$$\frac{\sigma_{gg\to h}}{\sigma^{\text{SM}}_{gg\to h}} \simeq \Big(1 + 12\pi^2 c_{gg} + \text{Re}\,[\delta y_u]_{33}\Big)^2$$

Degeneracy

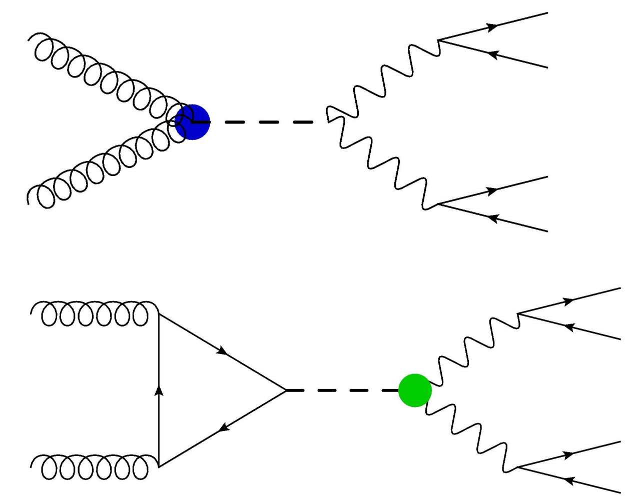
- Higgs couplings to gauge bosons: Probed in VH, VBF, Higgs decays
- Top couplings to the Z: Probed in tZ, ttZ
- Top-gluon interactions: Probed in top pair production

See global fits: Ethier, et al arXiv:2105.00006
Ellis et al arXiv:2012.02779

The operators: Warsaw basis

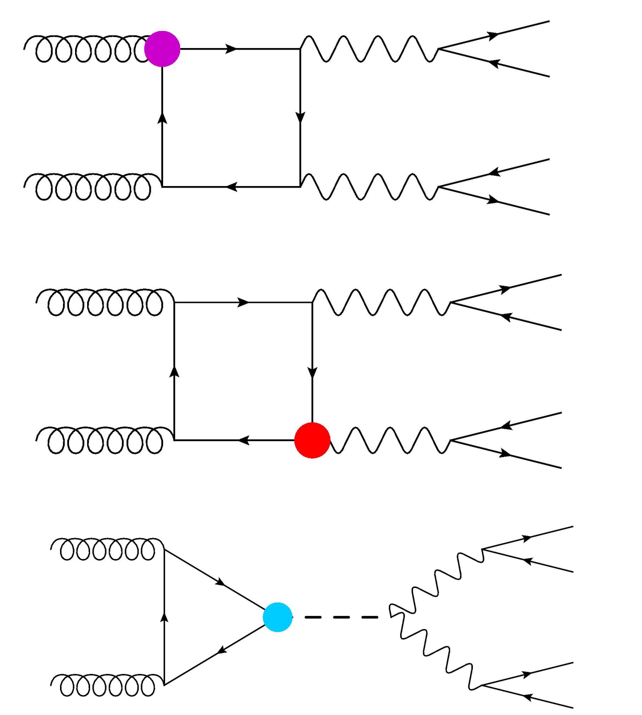
Higgs operators

$\mathcal{O}_{\varphi G}$	cpG	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) G_A^{\mu\nu}\, G^A_{\mu\nu}$	$\mathcal{O}_{\varphi W}$	cpW	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu}\, W^I_{\mu\nu}$
$\mathcal{O}_{\varphi B}$	cpBB	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu}\, B_{\mu\nu}$	$\mathcal{O}_{\varphi WB}$	cpWB	$(\varphi^\dagger\tau_I\varphi)\, B^{\mu\nu} W^I_{\mu\nu}$
$\mathcal{O}_{\varphi}$	cp	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3$	$\mathcal{O}_{\varphi d}$	cdp	$\partial_\mu(\varphi^\dagger\varphi)\partial^\mu(\varphi^\dagger\varphi)$
$\mathcal{O}_{\varphi D}$	cpDC	$(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$			



Top operators

$\mathcal{O}_{t\varphi}$	ctp	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q}\, t\, \tilde{\varphi} + \text{h.c.}$	$\mathcal{O}_{tW}$	ctW	$i(\bar{Q}\tau^{\mu\nu}\, \tau_I\, t)\, \tilde{\varphi}\, W^I_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{tG}$	ctG	$igs\, (\bar{Q}\tau^{\mu\nu}\, T_A\, t)\, \tilde{\varphi}\, G^A_{\mu\nu} + \text{h.c.}$	$\mathcal{O}_{tB}$	-	$i(\bar{Q}\tau^{\mu\nu}\, t)\, \tilde{\varphi}\, B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}^{(3)}_{\varphi Q}$	cpQ3	$i(\varphi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\varphi)(\bar{Q}\,\gamma^\mu\,\tau^I Q)$	$\mathcal{O}_{tZ}$	ctZ	$-\sin\theta_W \mathcal{O}_{tB} + \cos\theta_W \mathcal{O}_{tW}$
$\mathcal{O}^{(-)}_{\varphi Q}$	cpQM	$\mathcal{O}^{(1)}_{\varphi Q} - \mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi t}$	cpt	$i(\varphi^\dagger\, \overleftrightarrow{D}_\mu\, \varphi)(\bar{t}\,\gamma^\mu\, t)$



See also: Englert, Soreq, Spannowsky arXiv:1410.5440
Azatov et al arXiv:1406.6338,1608.00977

SMEFT analysis of off-shell production

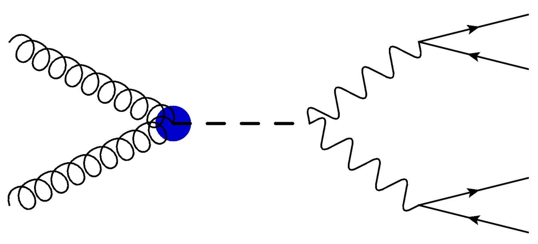
Things to consider:

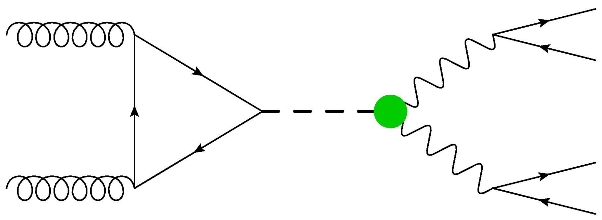
- The relevant operators modifying the signal:
    - Higgs couplings
- The operators entering the gg → ZZ background
    - The constraints on the top-operators
    - Well-constrained operators → small impact
    - Unconstrained operators → to be taken into account

What should we expect?

Helicity amplitude computation:

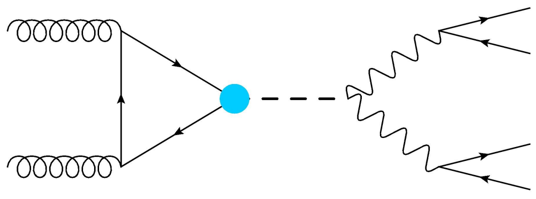
$\lambda_{g_1}, \lambda_{g_2}, \lambda_{Z_1}, \lambda_{Z_2}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi G}$
$+,+,+,+$	$\frac{m_t^2\, s_{\rm w}^2\, g_s^2}{8\sqrt{2}\,\pi^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2\, c_{\rm w}^2\, g_s^2}{8\sqrt{2}\,\pi^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$-$
$+,+,-,-$	$\frac{m_t^2\, s_{\rm w}^2\, g_s^2}{8\sqrt{2}\,\pi^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2\, c_{\rm w}^2\, g_s^2}{8\sqrt{2}\,\pi^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$-$
$+,+,0,0$	$-$	$-$	$s\,\frac{v^2\, e^2}{2\sqrt{2}\, m_Z^2\, c_{\rm w}^2\, s_{\rm w}^2}$

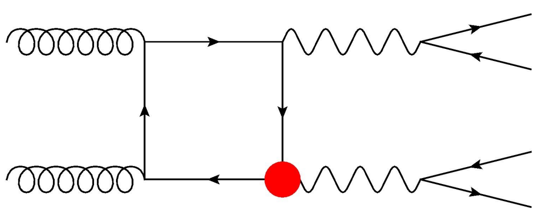




$\lambda_{g_1}, \lambda_{g_2}, \lambda_{Z_1}, \lambda_{Z_2}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi Q}^{(-)}$
$+,+,0,0$	$\frac{m_t\, v^3\, e^2\, g_s^2}{128\pi^2\, m_Z^2\, c_{\rm w}^2\, s_{\rm w}^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2\, v^2\, e^2\, g_s^2}{32\sqrt{2}\pi^2\, m_Z^2\, c_{\rm w}^2\, s_{\rm w}^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2\, v^2\, e^2\, g_s^2}{32\sqrt{2}\,\pi^2\, m_Z^2\, c_{\rm w}^2\, s_{\rm w}^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$

Logarithmic growth





Rossia, Thomas, EV soon

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$+,+,-,-$	$\frac{m_t^2\, s_{\rm w}^2\, g_s^2}{8\sqrt{2}\,\pi^2}\left[\log\left(\frac{s}{m_t^2}\right)-i\pi\right]^2$	$\frac{m_t^2\, c_{\rm w}^2\, g_s^2}{8\sqrt{2}\,\pi^2}\left[\log\left(\frac{s}{m_t^2}\right)-i\pi\right]^2$	$-$
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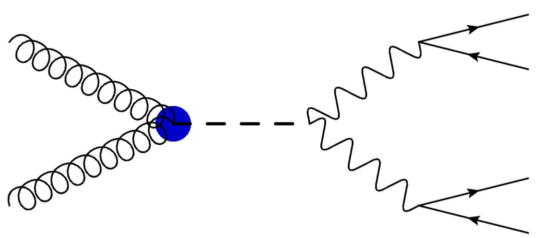

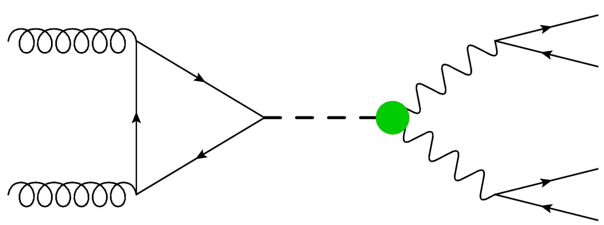

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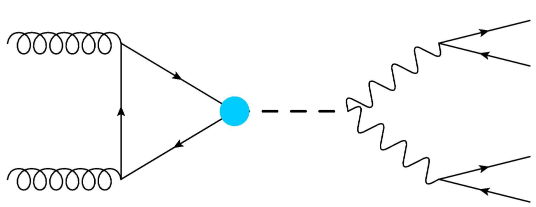
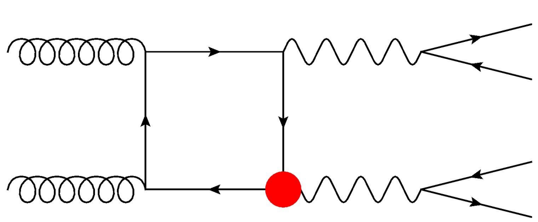
Logarithmic growth





Rossia, Thomas, EV soon

Higgs-gauge interactions

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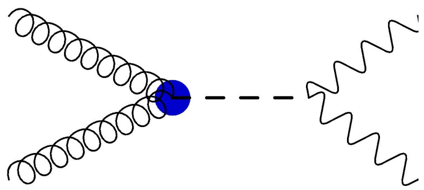
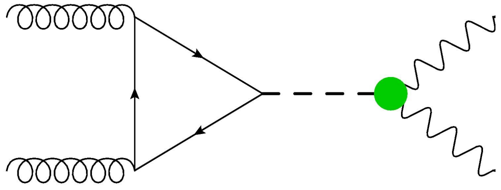
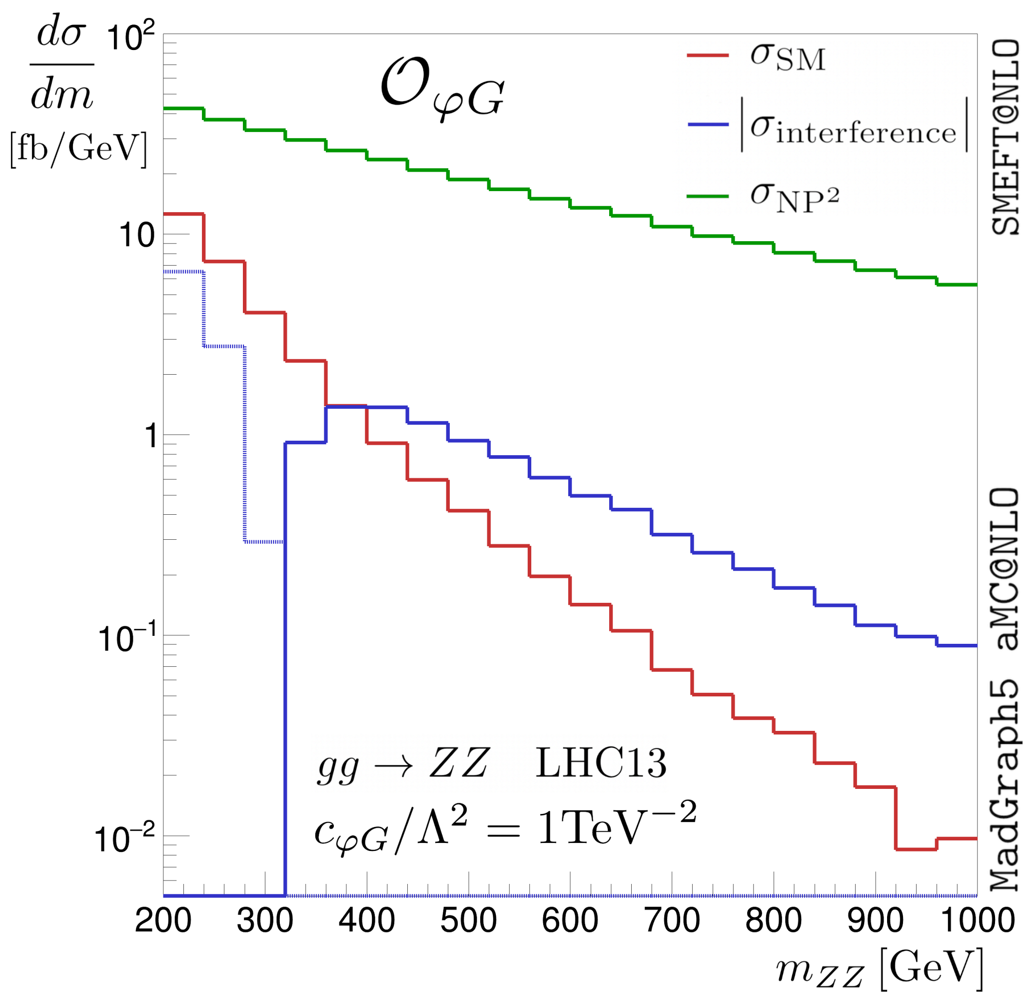
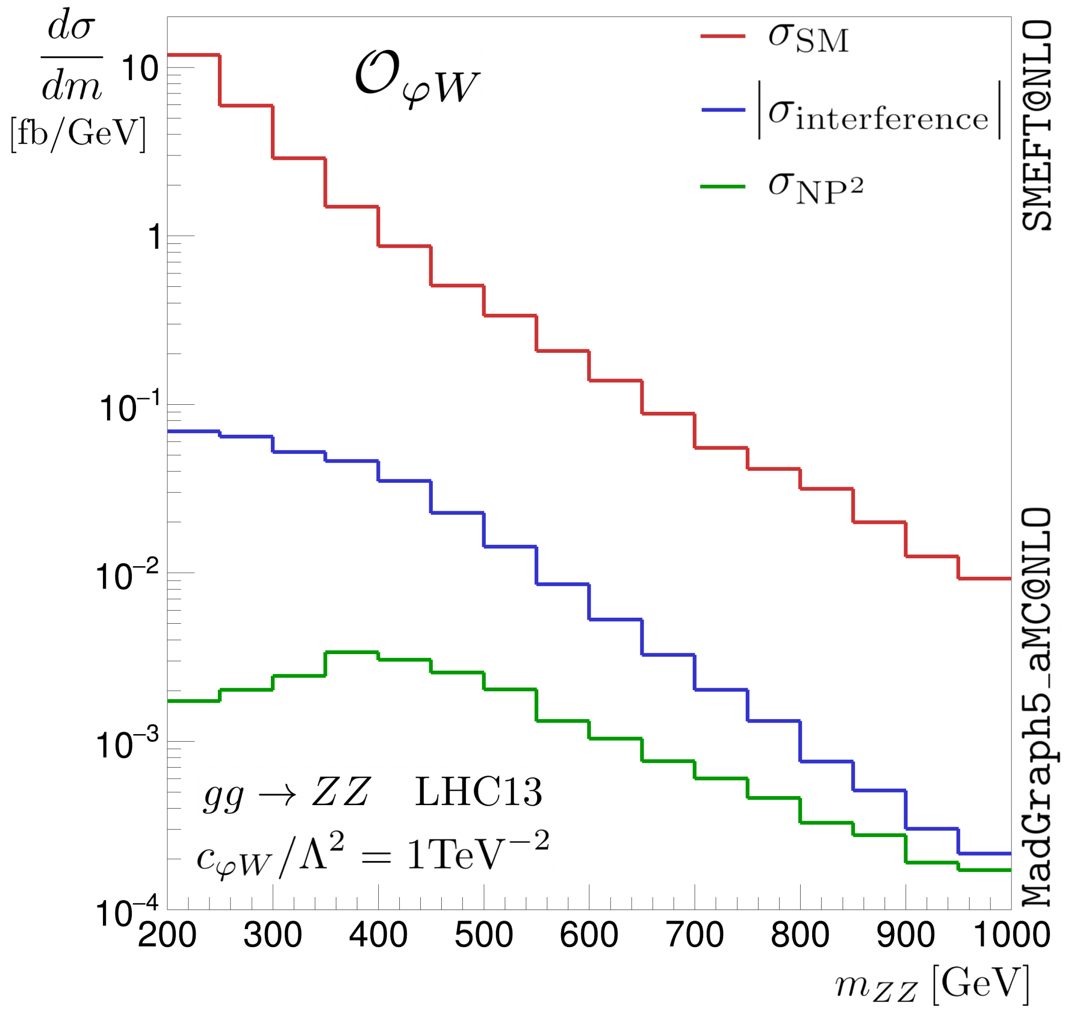


$\mathcal{O}_{\varphi W}$ **cpW** $\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu}\, W^I_{\mu\nu}$







Thomas, EV in arXiv:2203.02418

Top Yukawa

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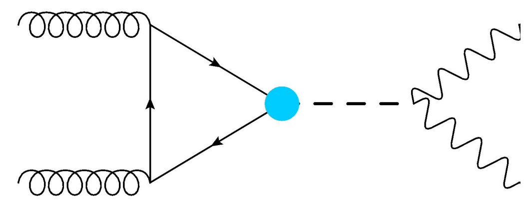

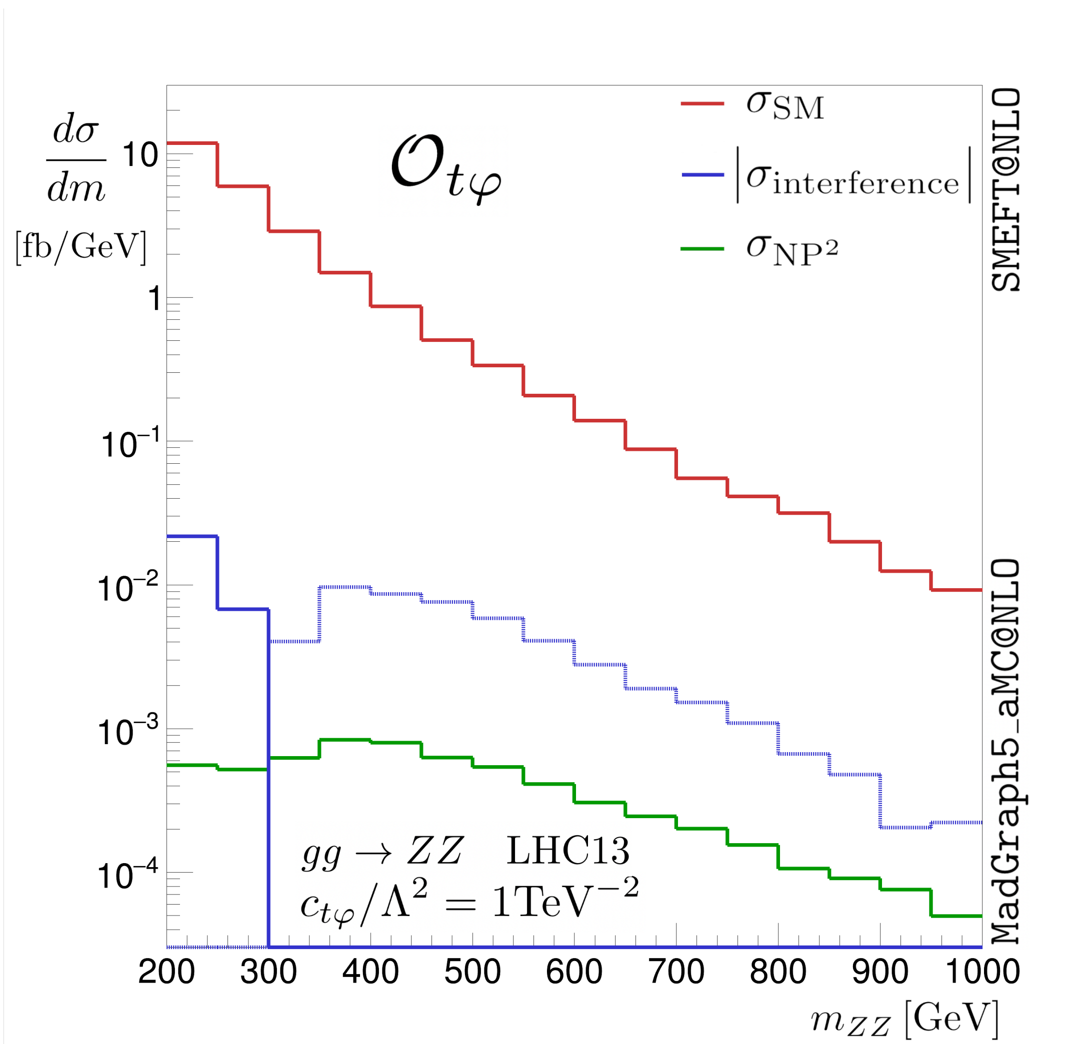

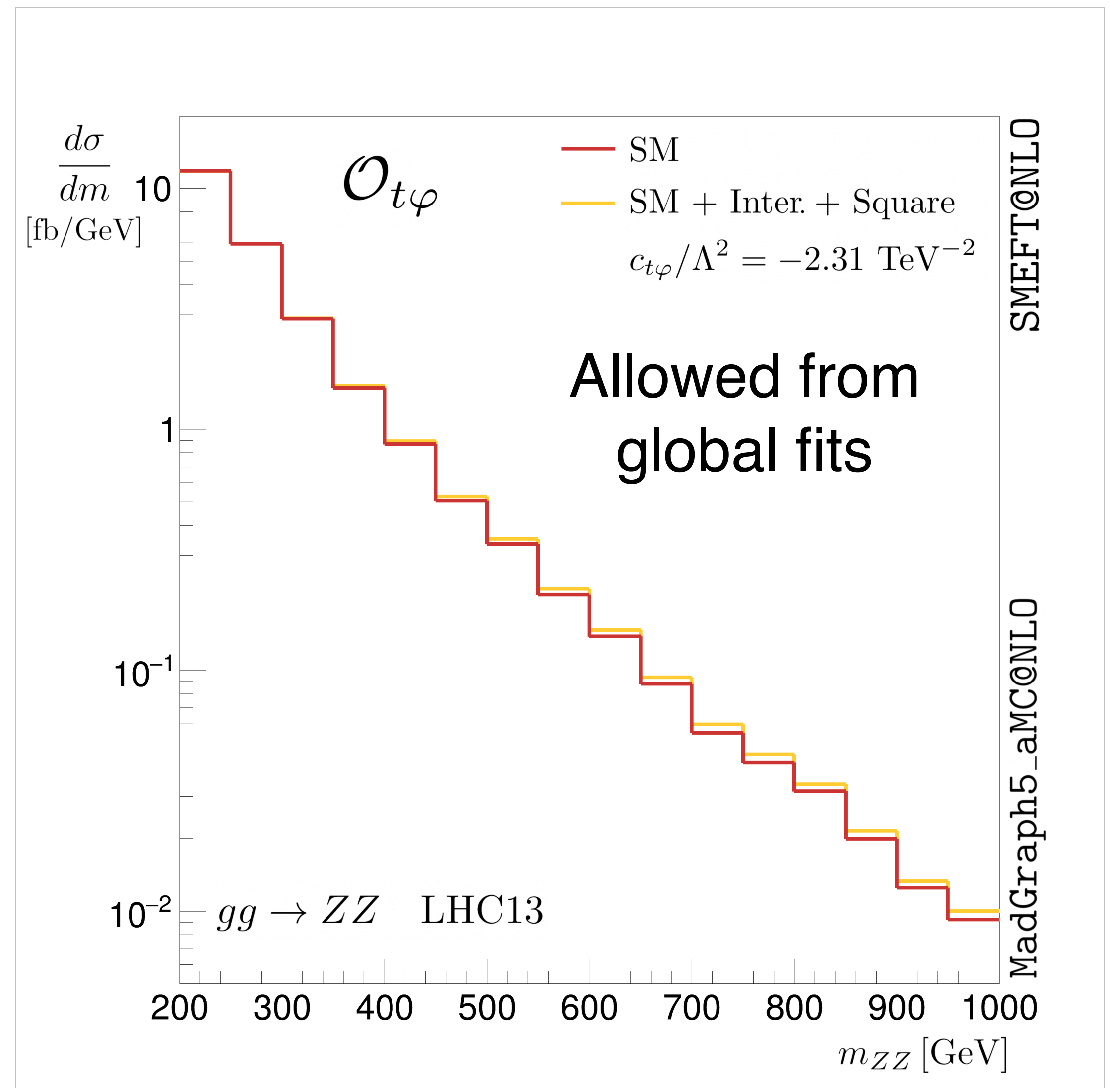

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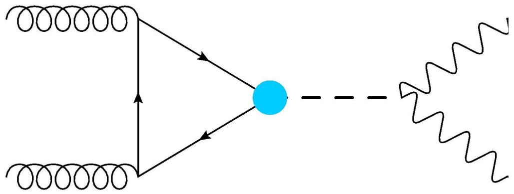
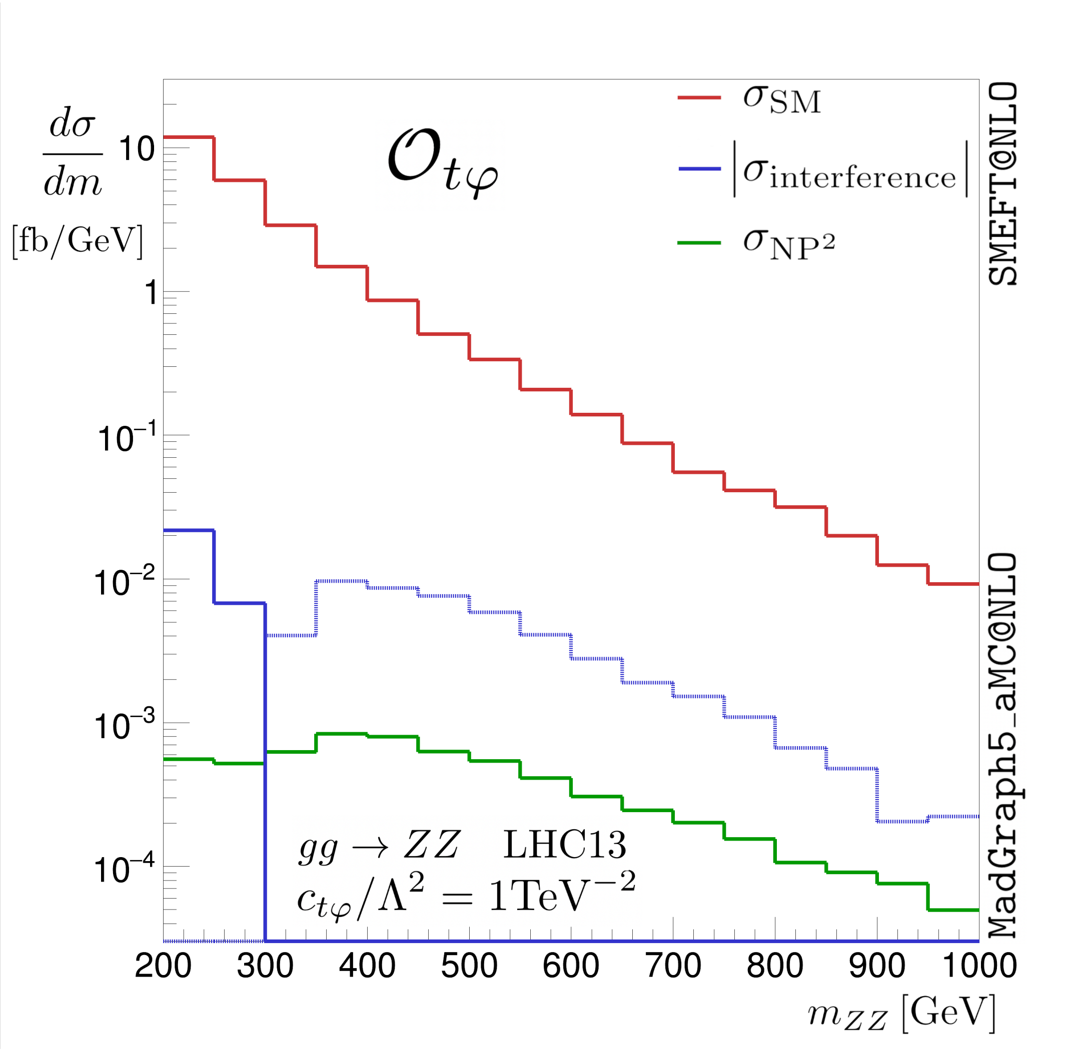
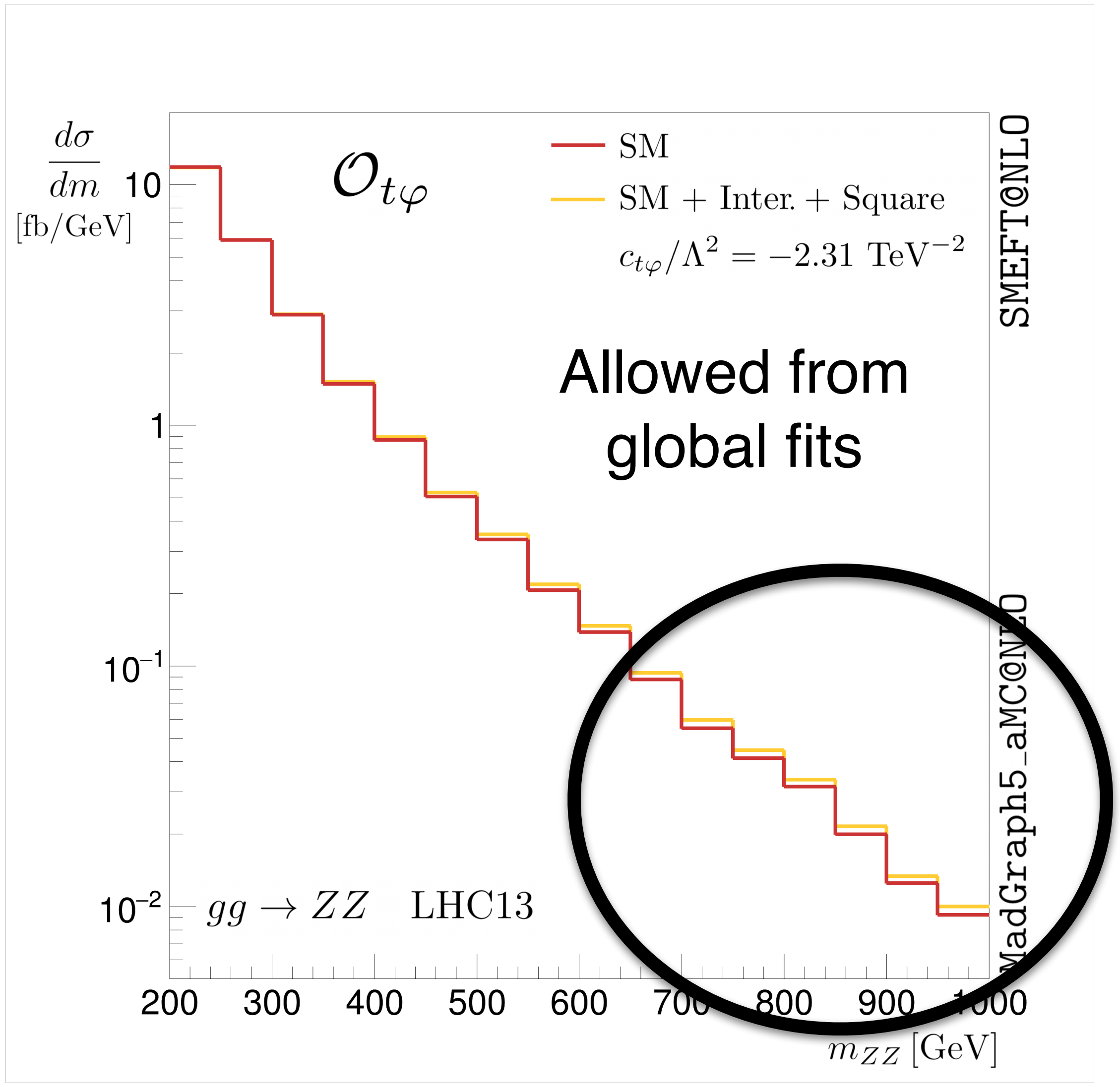


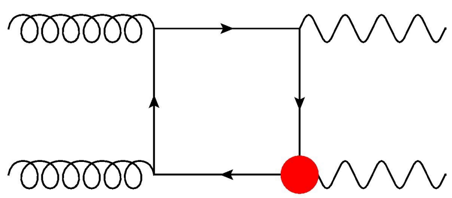




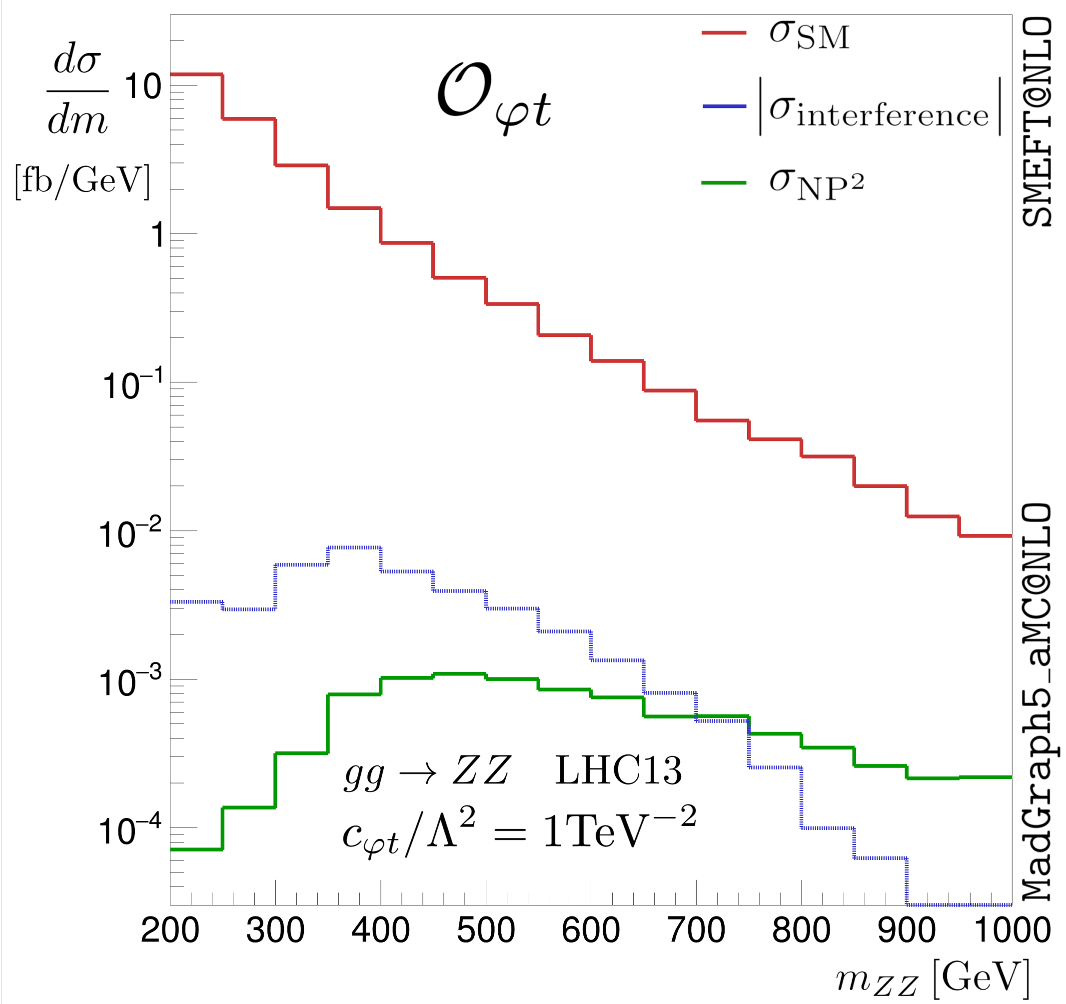
Thomas, EV in arXiv:2203.02418

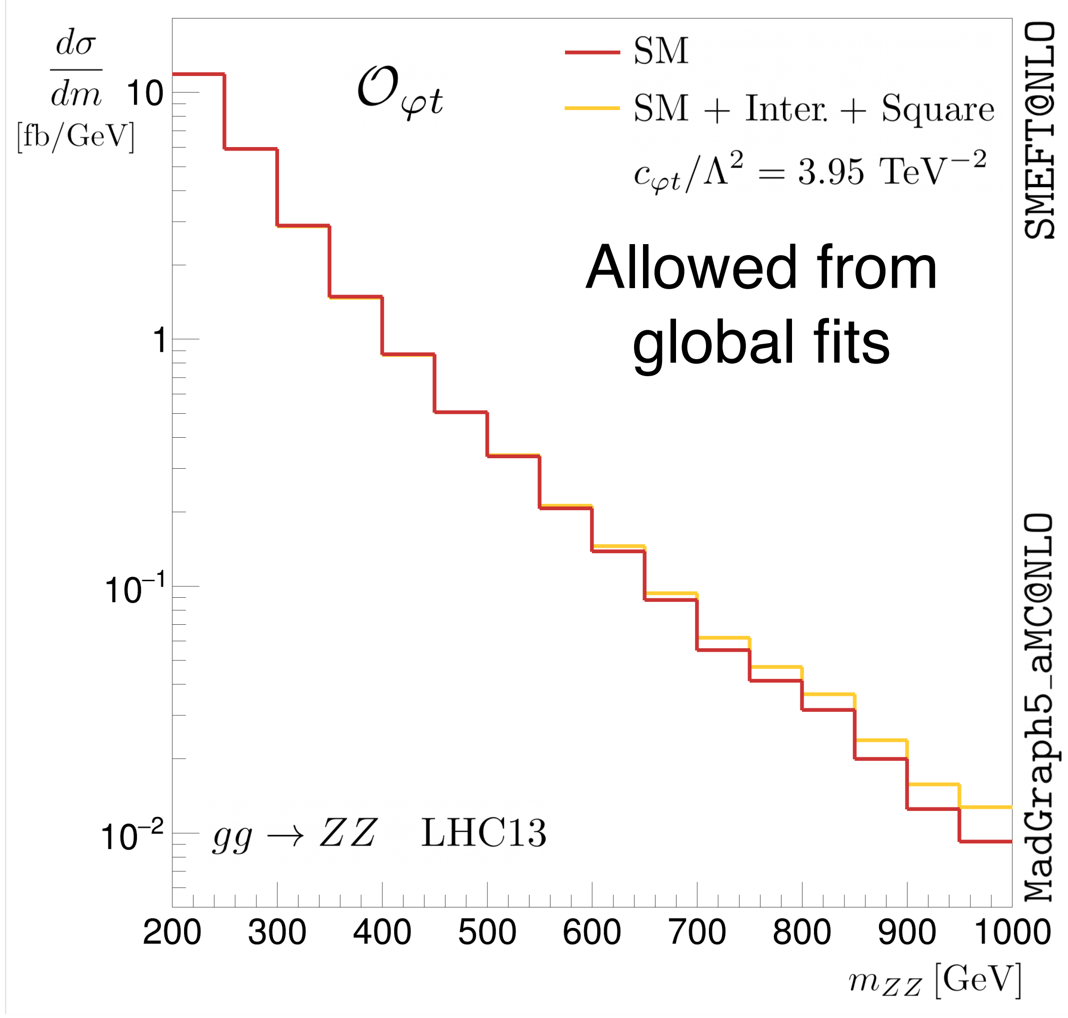
Top-Z couplings

$\mathcal{O}_{\varphi t}$ cpt $i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$



Poorly constrained from top data





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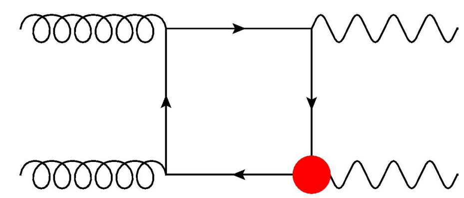
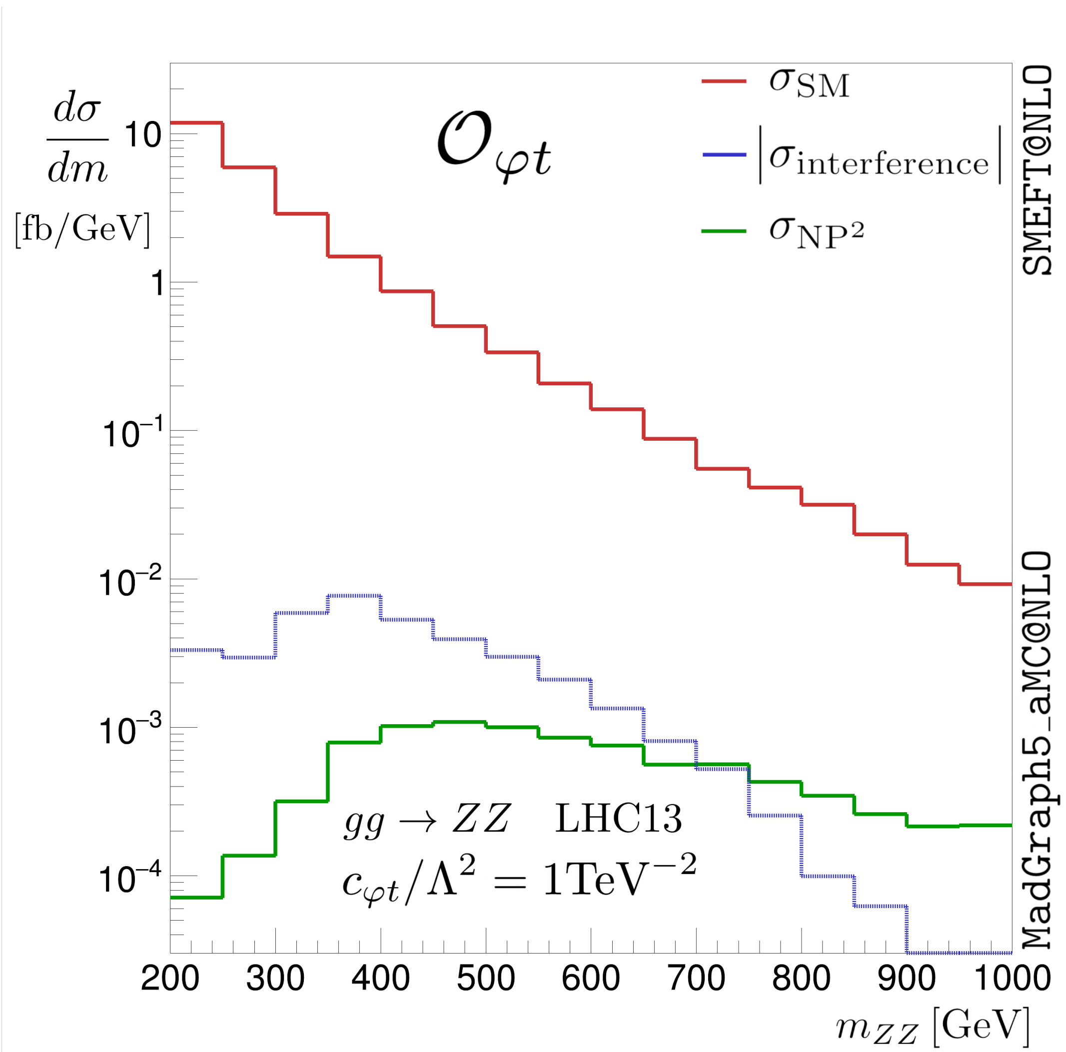
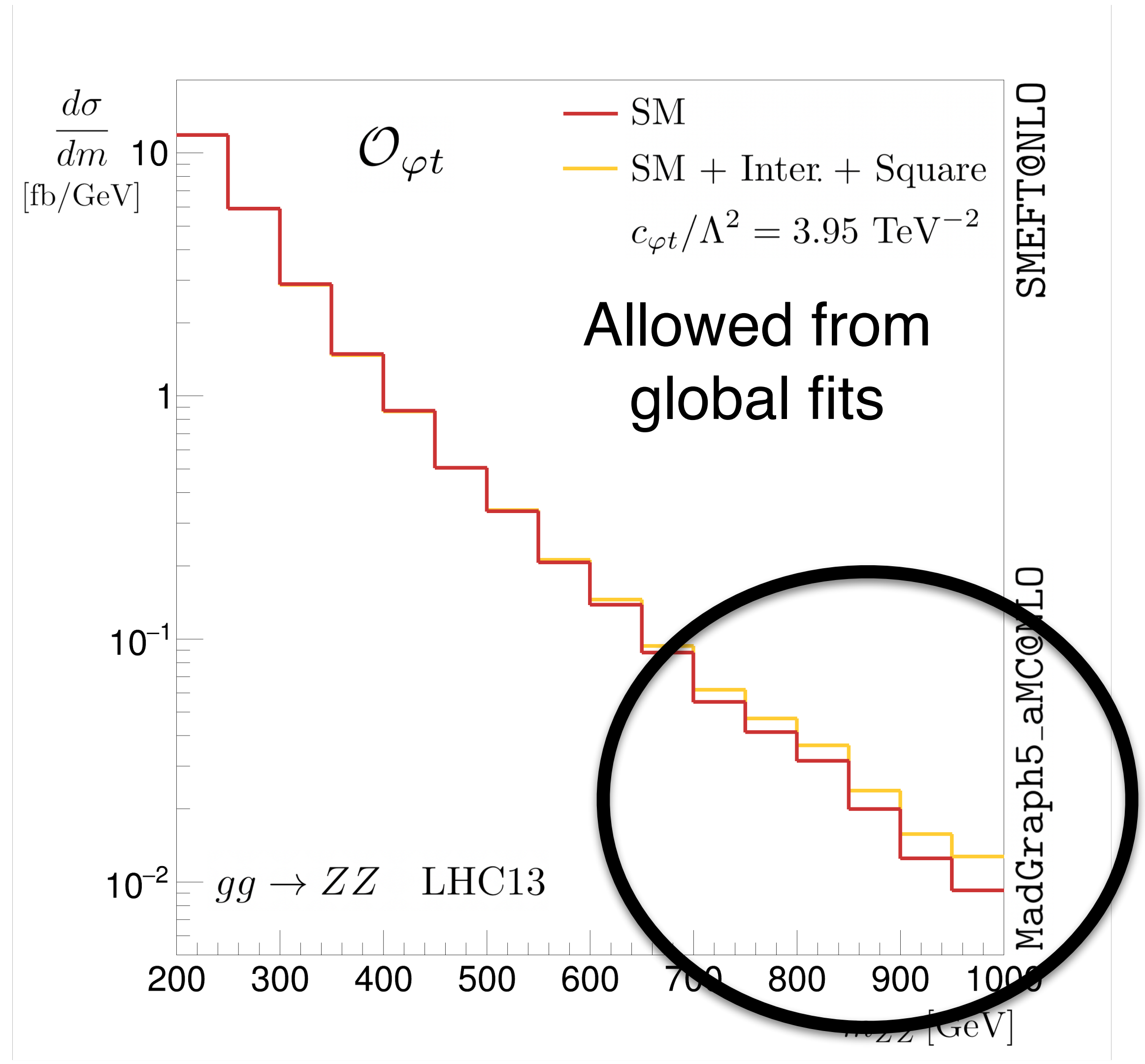


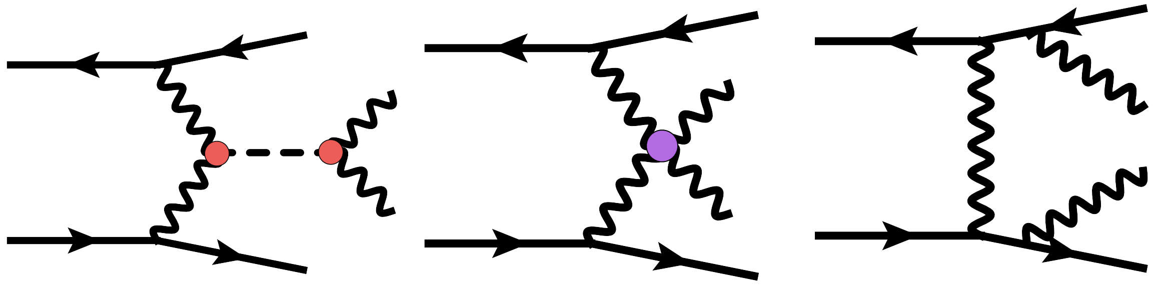
Poorly constrained from top data

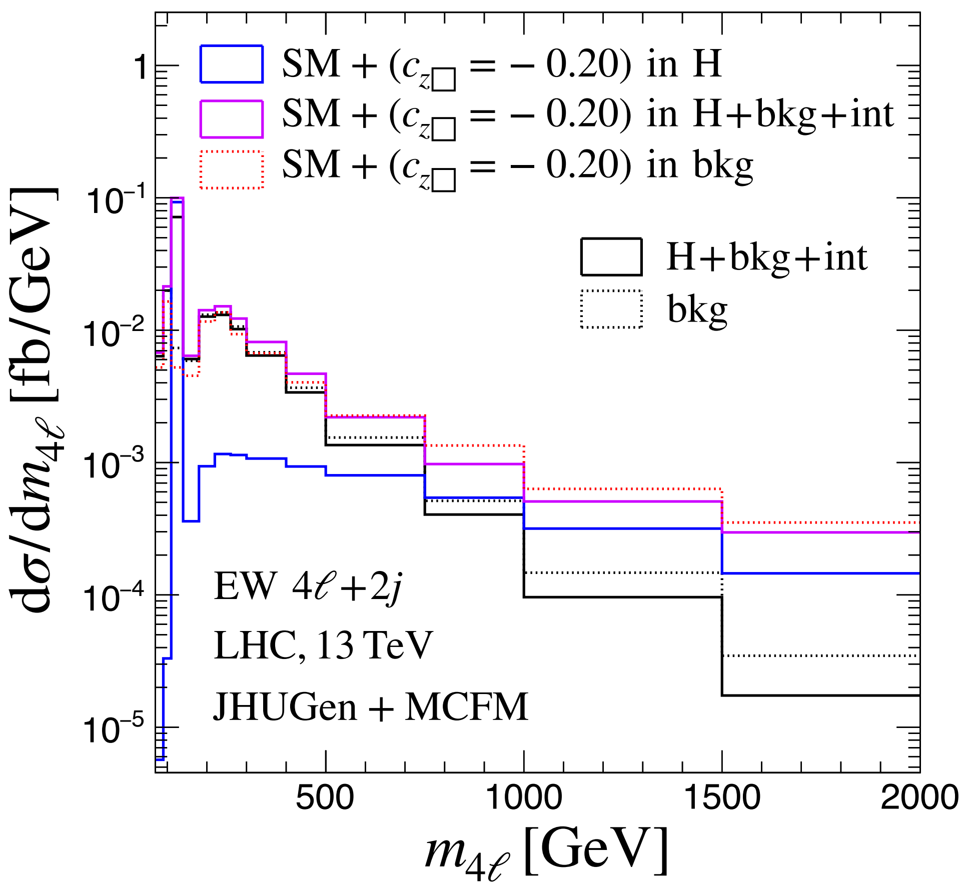


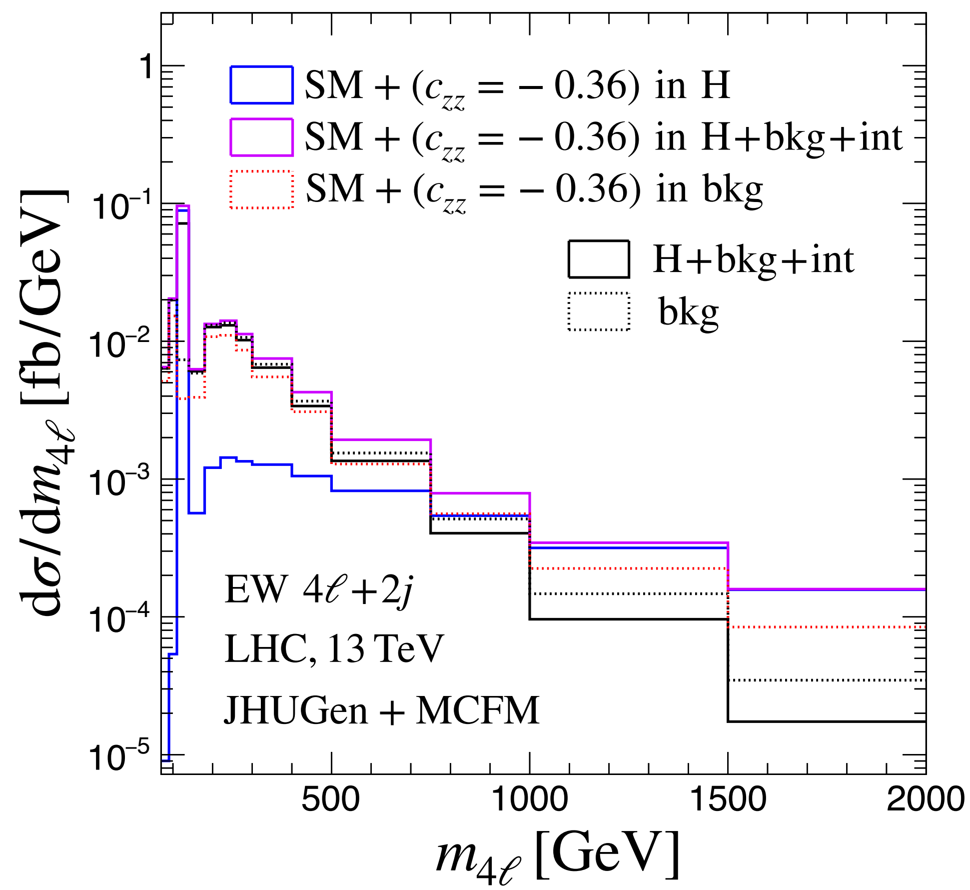


Thomas, EV in arXiv:2203.02418

Going beyond gluon fusion







Also allowing CP odd Higgs couplings

Gritsan, Kang, Sarica in arXiv:2203.02418

Conclusions

- Off-shell Higgs production key in constraining the Higgs width
- Off-shell measurements can break degeneracies from on-shell production
- SMEFT analysis of off-shell Higgs production needs to take into account:
  - Operators modifying the signal
  - Operators modifying the loop-induced background
- Operators modifying the top-Z coupling play a special role, as they are loosely constrained and lead to energy growing amplitudes
- More systematic and realistic studies needed


Thank you for your attention