CP violation in SMEFT loop-induced diboson production

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YOUNGST@RS - EFTs and Beyond

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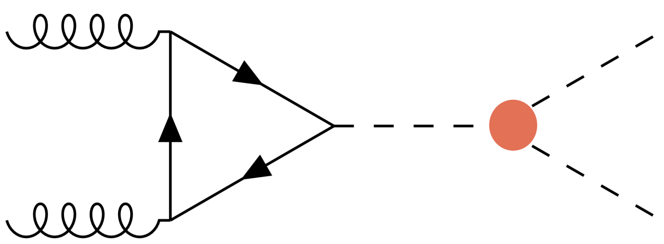
Based on arXiv:2411.00959, in collaboration with Eleni Vryonidou

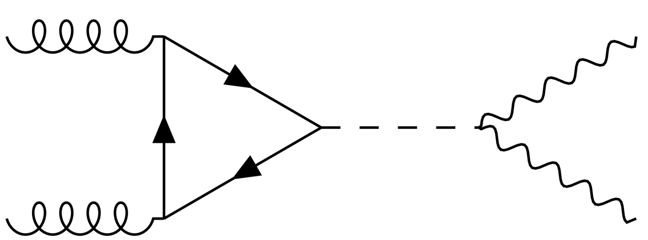
Why gluon-induced diboson production?

Diboson processes probe Higgs properties...

- $gg \to HH$: probes the **Higgs trilinear coupling**



- $gg \to ZZ, WW$: measurements of the **Higgs width**



$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggF}} g^2_{\text{HZZ}}}{m^2_{ZZ}}$$

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggF}} g^2_{\text{HZZ}}}{m_H \Gamma_H}$$

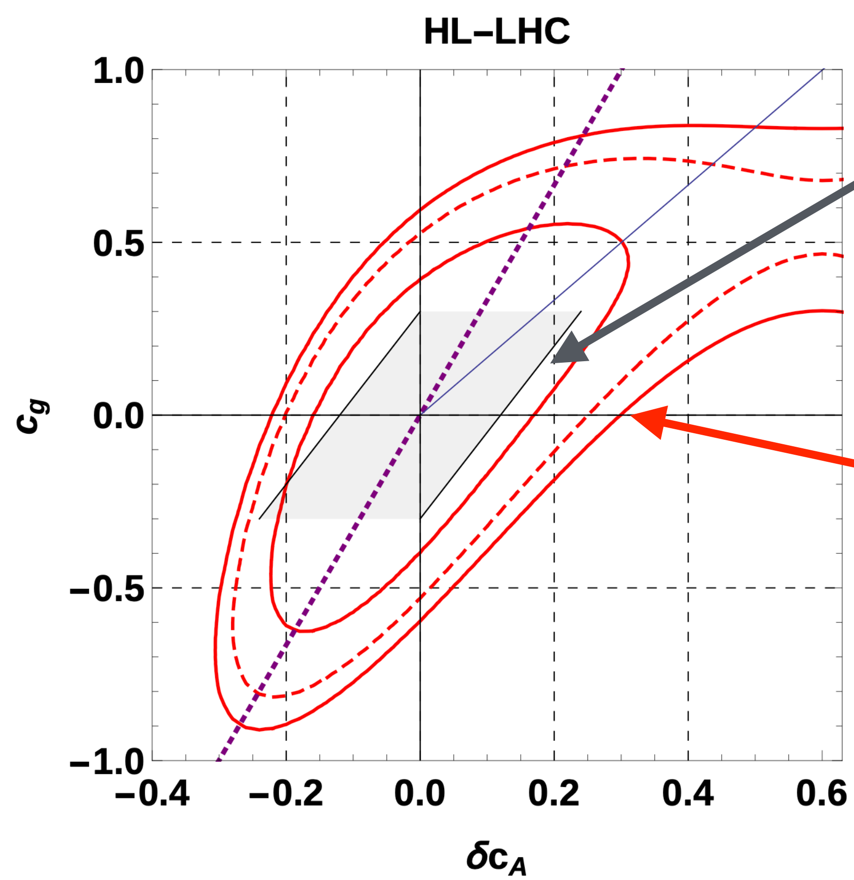
$$\to \quad \frac{\sigma^{\text{off-shell}}}{\sigma^{\text{on-shell}}} \sim \Gamma_H$$

ATLAS EXPERIMENT [arXiv:2304.01532] $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV

CMS [arXiv:2409.13663] $\Gamma_H = 3.0^{+2.0}_{-1.5}$ MeV

Why gluon-induced diboson production?

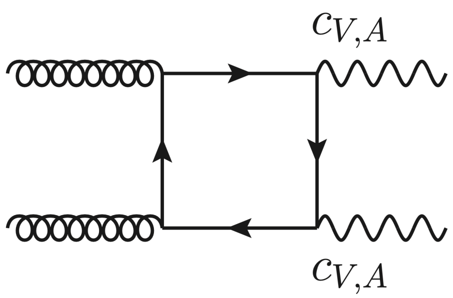
… and are also sensitive to top couplings

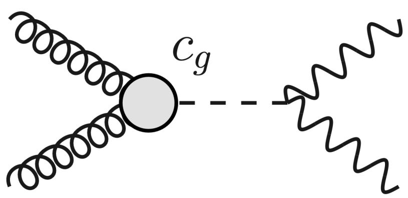


Constraints from $gg \to ZH$
Englert et al, [arXiv:1603.05304]

Constraints from $gg \to ZZ$

Azatov, Grojean, Paul, Salvioni [arXiv:1608.00977]





See also: Englert, Soreq, Spannowsky [arXiv:1410.5440]
Cao, Yan, Yuan and Zhang, [arXiv:2004.02031]

- Amplitudes dominated by top loops → probe poorly constrained top operators

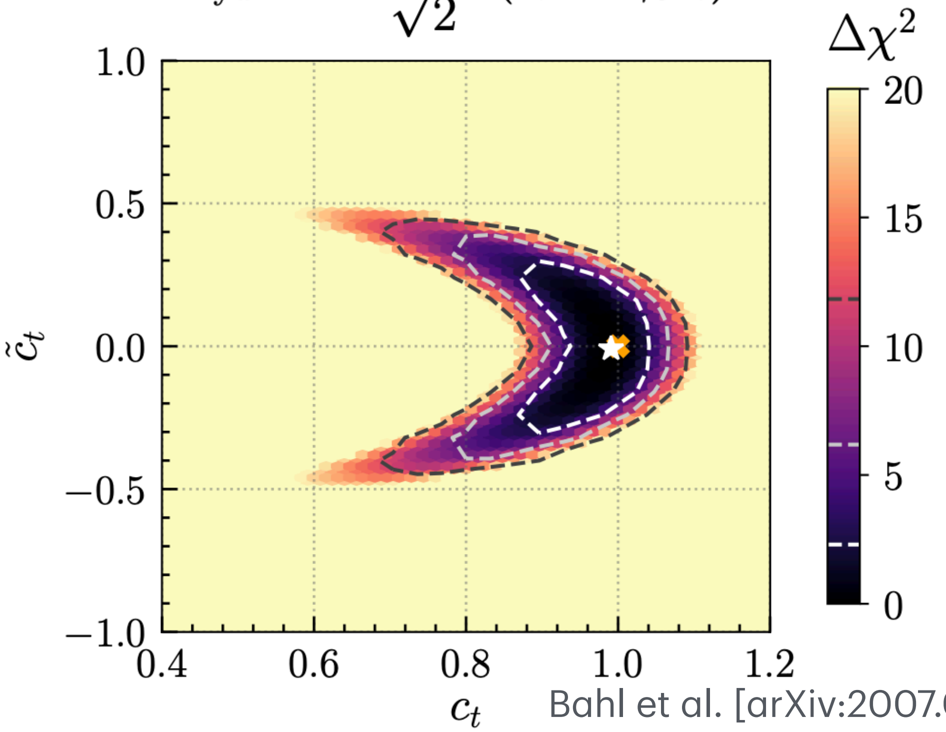
CP violation in the SMEFT

- **CP-odd** component of **Higgs interactions not ruled out** by measurements

  CP mixing angle in top Yukawa in $t\bar{t}H$ and tH production [arXiv:2303.05974]

  CP-odd contribution to $t\bar{t}H$ in $H \to \gamma\gamma$ [arXiv:2003.10866] + many more

$$\mathcal{L}_{\text{yuk}} = -\frac{y_t^{\text{SM}}}{\sqrt{2}}\bar{t}\,(c_t + i\gamma_5\tilde{c}_t)\,tH$$



Bahl et al. [arXiv:2007.08542]

- So far **CP violation in EFTs at one-loop** studied mostly in **Higgs sector**, eg. with Higgs Characterisation framework. [arXiv:1306.6464] [arXiv:1407.5089]

What about a more general treatment?

CP violation in the SMEFT

- **CP-odd** component of **Higgs interactions not ruled out** by measurements

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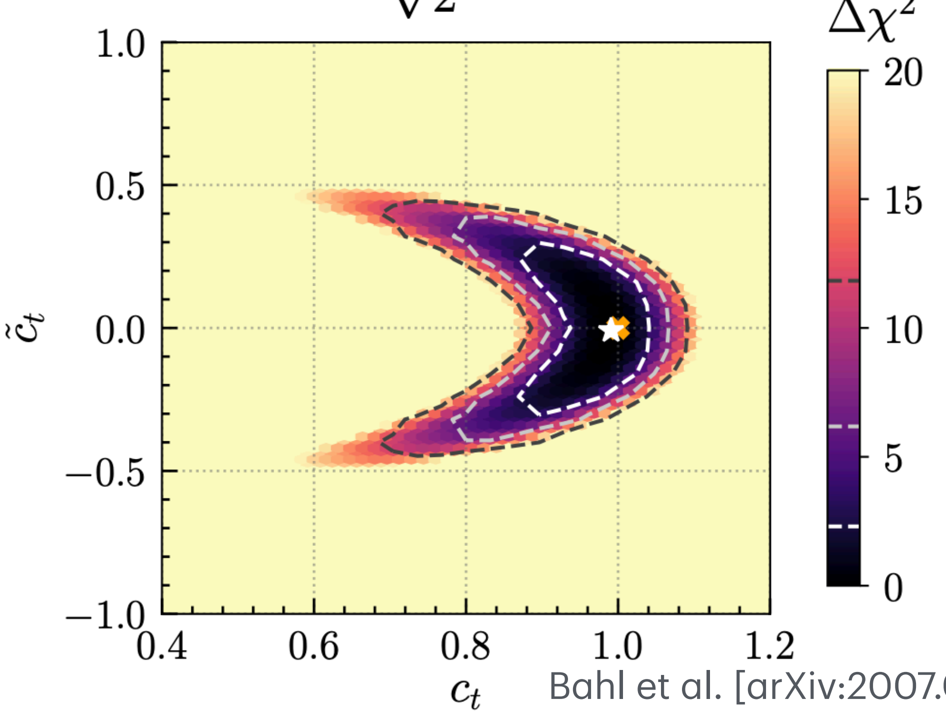

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- So far **CP violation in EFTs at one-loop** studied mostly in **Higgs sector**, eg. with Higgs Characterisation framework. [arXiv:1306.6464] [arXiv:1407.5089]

What about a more general treatment?

We extend the SMEFT@NLO UFO to **include dim-6 CP-odd SMEFT operators** entering **gluon-induced diboson production** and **study their impact** on kinematic distributions.

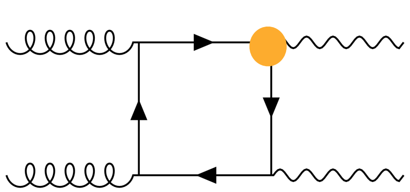
CP-violating SMEFT operators

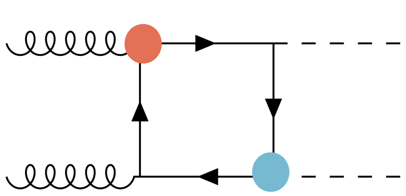
Warsaw basis of dim-6 SMEFT operators
Flavour symmetry: $U(2)_q \times U(3)_d \times U(2)_u$

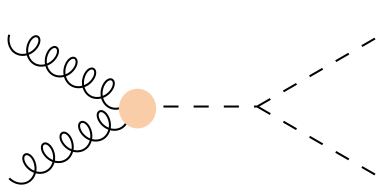
Hermitian operators

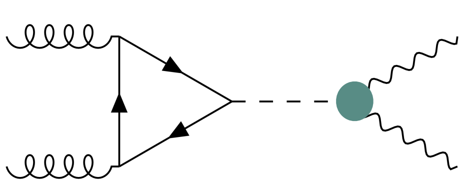
$$c_i = \mathtt{RE}c_i$$

$\mathcal{O}_{\varphi\tilde{G}}$	$c_{\varphi\tilde{G}}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \widetilde{G}^{\mu\nu}_A \, G^A_{\mu\nu}$
$\mathcal{O}_{\varphi\tilde{W}}$	$c_{\varphi\tilde{W}}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \widetilde{W}^{\mu\nu}_I \, W^I_{\mu\nu}$









Non-hermitian operators

$$c_i = \mathtt{RE}c_i + i\,\mathtt{IM}c_i$$

$\mathcal{O}_{tG}$	c_{tG}	$ig_s\,(\bar{Q}\sigma^{\mu\nu}\,T_A\,t)\,\tilde{\varphi}\,G^A_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{t\varphi}$	$c_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q}\,t\,\tilde{\varphi} + \text{h.c.}$
$\mathcal{O}_{tW}$	c_{tW}	$(\bar{Q}\sigma^{\mu\nu}\,\tau_I\,t)\,\tilde{\varphi}\,W^I_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{tB}$	c_{tB}	$(\bar{Q}\sigma^{\mu\nu}\,t)\,\tilde{\varphi}\,B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{tZ}$	c_{tZ}	$-\sin\theta_W\,c_{tB} + \cos\theta_W\,c_{tW}$

$$\widetilde{X}_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}X^{\rho\sigma}$$

Adding CP-odd operators in SMEFT@NLO

3 ingredients to add to UFO

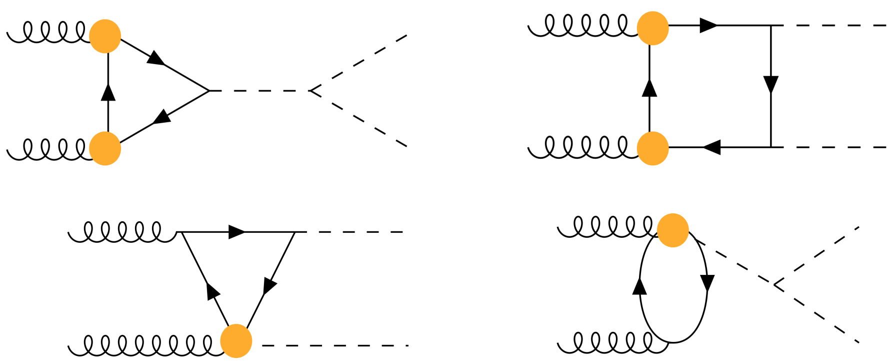
Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang, [arXiv:2008.11743]

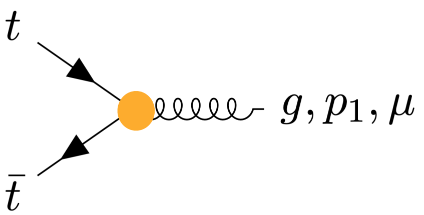
▶ Feynman rules

Read from the SMEFT Lagrangian

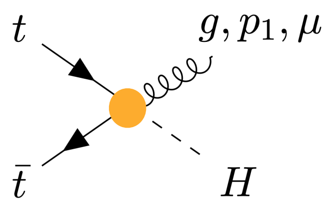
Example: $\mathtt{IM}c_{tG}$ in $gg \to HH$

$\mathcal{O}_{tG} \quad c_{tG} \quad i g_s \left(\bar{Q}\sigma^{\mu\nu} T_A\, t\right) \tilde{\varphi}\, G^A_{\mu\nu} + \text{h.c.}$





$$= -\frac{\mathtt{IM}c_{tG}\, v\, g_s}{\sqrt{2}\,\Lambda^2}[\gamma^\mu, \not{p}_1]\gamma_5$$



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Example: $\mathtt{IM}c_{tG}$ in $gg \to HH$

- Feynman rules

  Read from the SMEFT Lagrangian

- Rational terms R_2

  Calculated from one-particle irreducible diagrams

What are the rational terms?

- Implementation of one-loop QCD calculations in MadLoop relies on Ossola-Papadopoulos-Pittau (OPP) reduction method.
- In d-dimension, write m-point amplitude for 1-particle irreducible diagrams:

4-dimensional numerator

4- and (d-4)-dimensional objects

$$\mathcal{A} = \frac{1}{(2\pi)^4} \int d^d\bar{q} \, \frac{N(q) + \tilde{N}(\tilde{q}, q)}{\bar{D}_0 \, \bar{D}_1 \ldots \, \bar{D}_{m-1}}$$

d-dimensional integral

d-dimensional denominator

$$\begin{aligned} \bar{q} &= q + \tilde{q}, \\ \bar{\gamma}_{\bar{\mu}} &= \gamma_{\mu} + \tilde{\gamma}_{\tilde{\mu}}, \\ \bar{g}^{\bar{\mu}\bar{\nu}} &= g^{\mu\nu} + \tilde{g}^{\tilde{\mu}\tilde{\nu}} \end{aligned}$$

$$R_2 \equiv \frac{1}{(2\pi)^4} \int d^d\bar{q} \, \frac{\tilde{N}(\tilde{q}, q)}{\bar{D}_0 \, \bar{D}_1 \ldots \, \bar{D}_{m-1}}$$

Ossola, Papadopoulos, Pittau in arXiv:0609007, 0711.3596, 0802.1876
Hirschi et al. in arXiv:1103.0621

Adding CP-odd operators in SMEFT@NLO

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- ▶ Feynman rules

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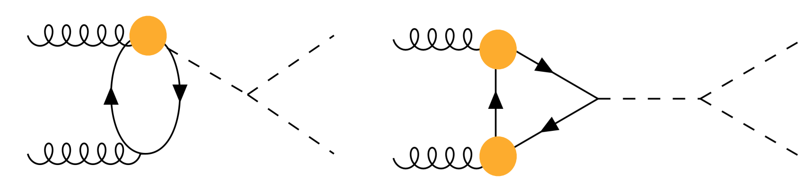
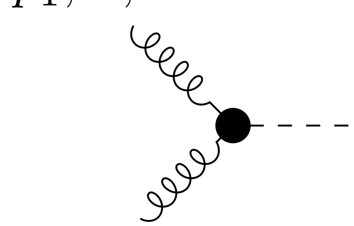
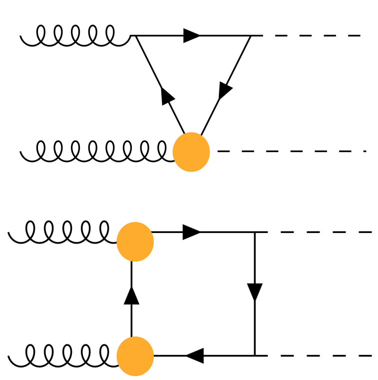
Example: $\mathtt{IM}c_{tG}$ in $gg \to HH$



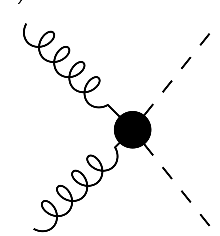
→ Need underlying ggH R_2



$$= \frac{\mathtt{IM}c_{tG}}{\Lambda^2}\frac{\sqrt{2}\,i\,g_s^2\,m_t}{3\pi^2}\varepsilon^{\alpha\beta p_1 p_2}\delta_{ab}$$



One-particle irreducible diagrams for $gg \to HH$ →



$$= \frac{\mathtt{IM}c_{tG}}{\Lambda^2}\frac{i\,g_s^2\,m_t}{\sqrt{2}\pi^2 v}\varepsilon^{\alpha\beta p_1 p_2}\delta_{ab}$$

Adding CP-odd operators in SMEFT@NLO

3 ingredients to add to UFO

Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang, [arXiv:2008.11743]

- **Feynman rules**

  Read from the SMEFT Lagrangian

- **Rational terms R_2**

  Calculated from one-particle irreducible diagrams

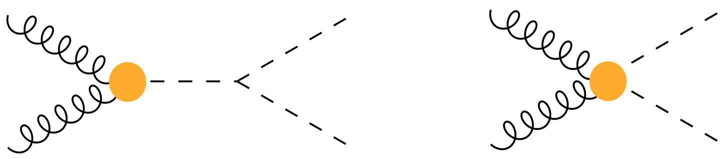
- **UV Counterterms**

  Checked against the Renormalisation Group Evolution

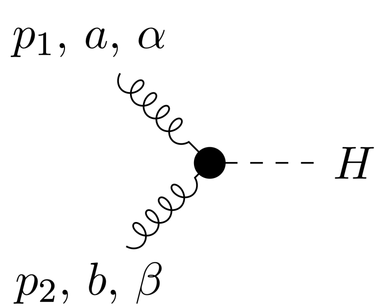
  Alonso, Jenkins, Manohar and Trott in arXiv:1308.2627, 1310.4838, 1312.2014

Example: $\texttt{IM}c_{tG}$ in $gg \to HH$

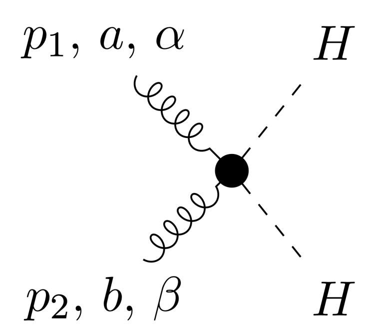
Renormalised with $\mathcal{O}_{\varphi\tilde{G}}$



ggH and $ggHH$ UV counterterms:



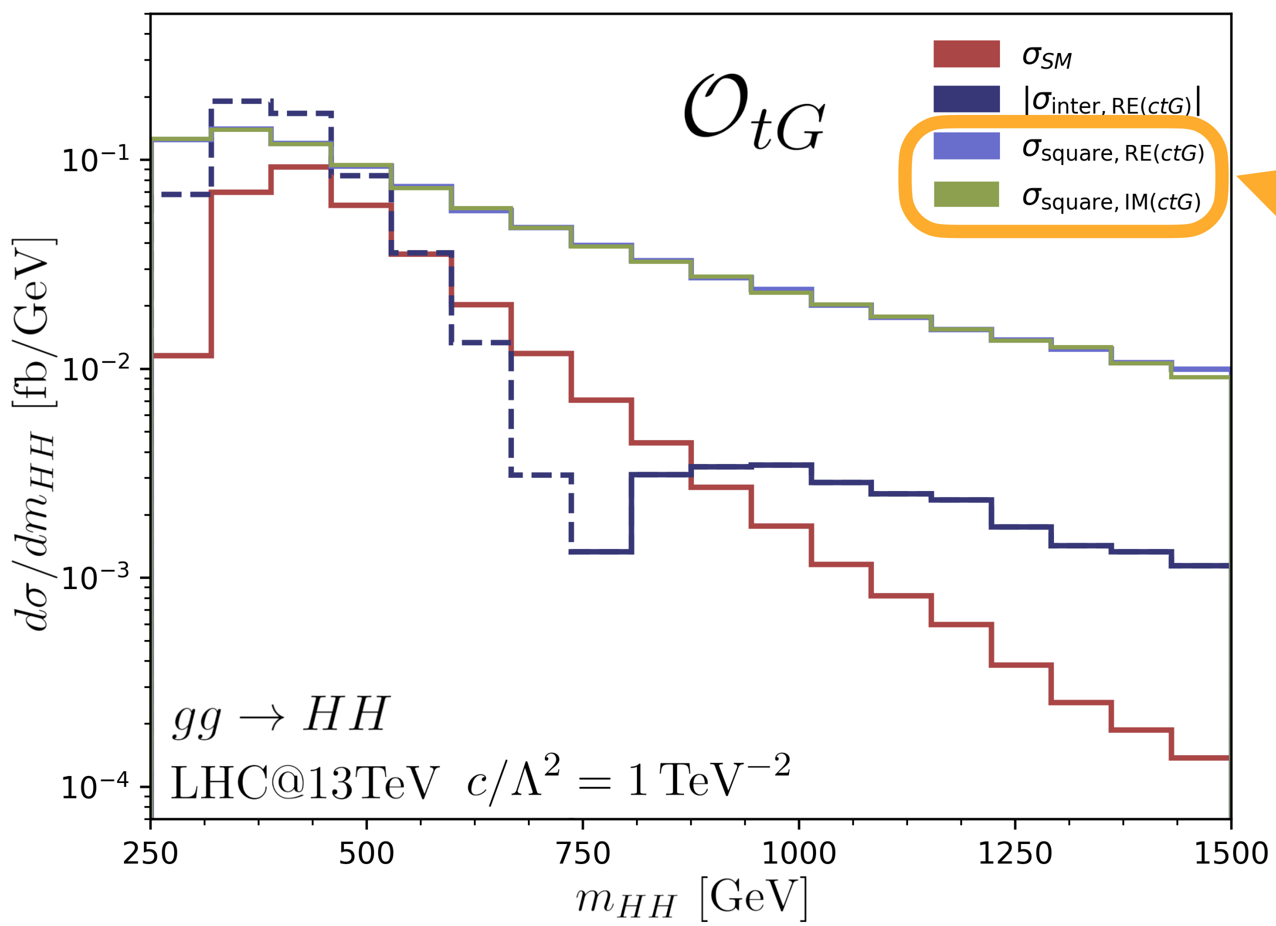
$$= \frac{\texttt{IM}c_{tG}}{\Lambda^2}\frac{i\,g_s^2\,m_t}{\sqrt{2}\pi^2}\left(\frac{1}{\epsilon} - \log\left(\frac{\mu_{EFT}^2}{\mu_R^2}\right)\right)\varepsilon^{p_1 p_2 \alpha\beta}\delta_{ab}$$



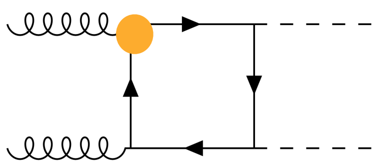
$$= \frac{\texttt{IM}c_{tG}}{\Lambda^2}\frac{i\,g_s^2\,m_t}{\sqrt{2}\pi^2 v}\left(\frac{1}{\epsilon} - \log\left(\frac{\mu_{EFT}^2}{\mu_R^2}\right)\right)\varepsilon^{p_1 p_2 \alpha\beta}\delta_{ab}$$

Growing amplitudes and tail effects

Modified top-gluon interactions in $gg \to HH$



Overlapping $\mathcal{O}(\Lambda^{-4})$ distributions



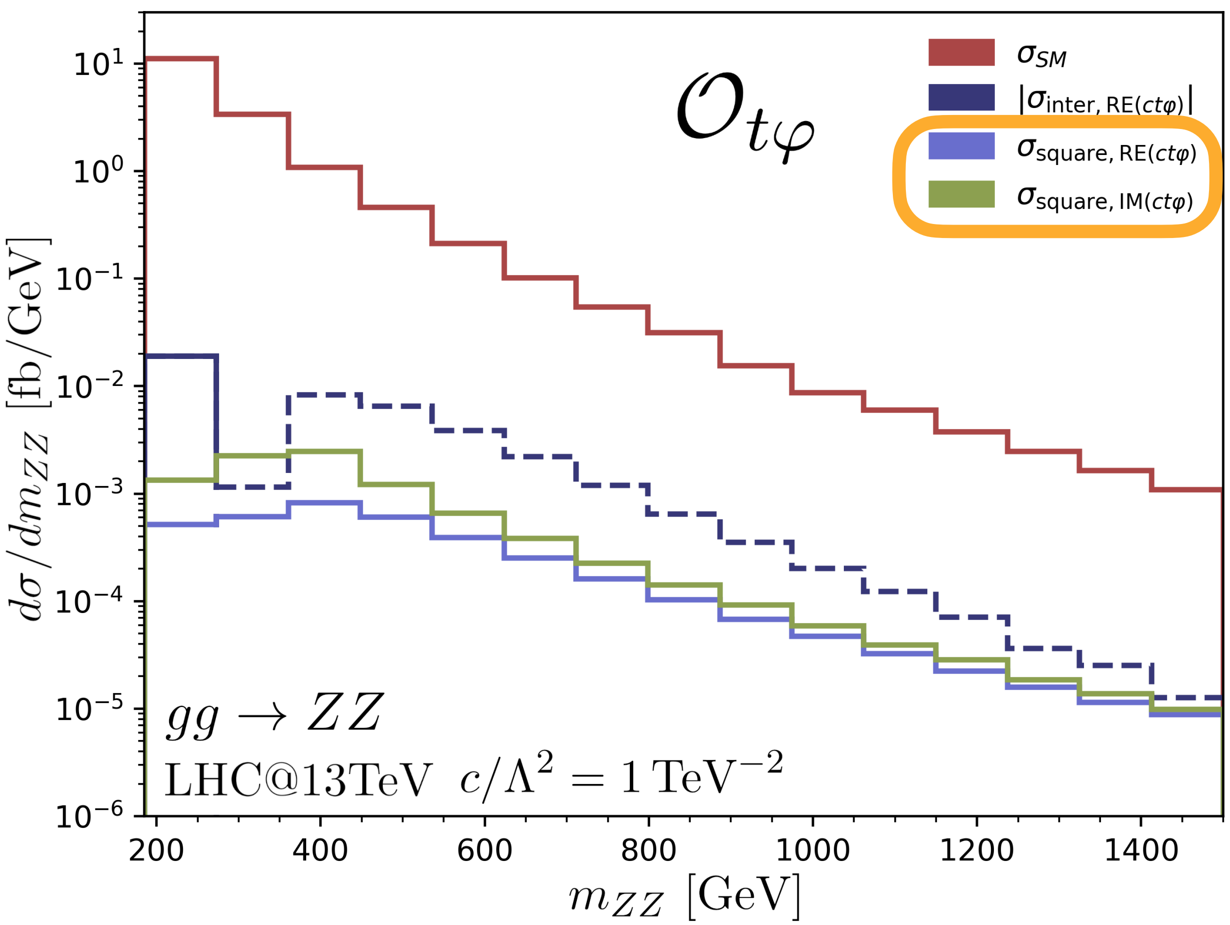
Total IM/RE c_{tG} amplitudes dominated by:

$\lambda_{g_1}, \lambda_{g_2}, \lambda_{H_1}, \lambda_{H_2}$	$(+,+,0,0)$
REc_{tG}	$s\,\frac{m_t\, g_s^2}{4\pi^2 v}\left[\log\left(\frac{s}{\mu_{EFT}^2}\frac{\sqrt{1-c\theta^2}}{2}\right) - 2\right]$
IMc_{tG}	$s\,\frac{m_t\, g_s^2\, i}{4\pi^2 v}\left[\log\left(\frac{s}{\mu_{EFT}^2}\frac{\sqrt{1-c\theta^2}}{2}\right) - 2\right]$

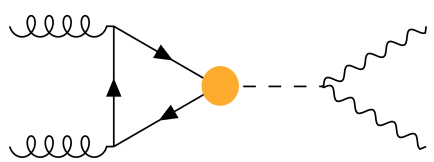
- IMc_{tG} **interference vanishes** at amplitude level.
- **Hard to distinguish** between CP-even and CP-odd contributions.

Growing amplitudes and tail effects

Modified top-Higgs interactions in $gg \to ZZ$



Similar situation:
distributions converge at high energies



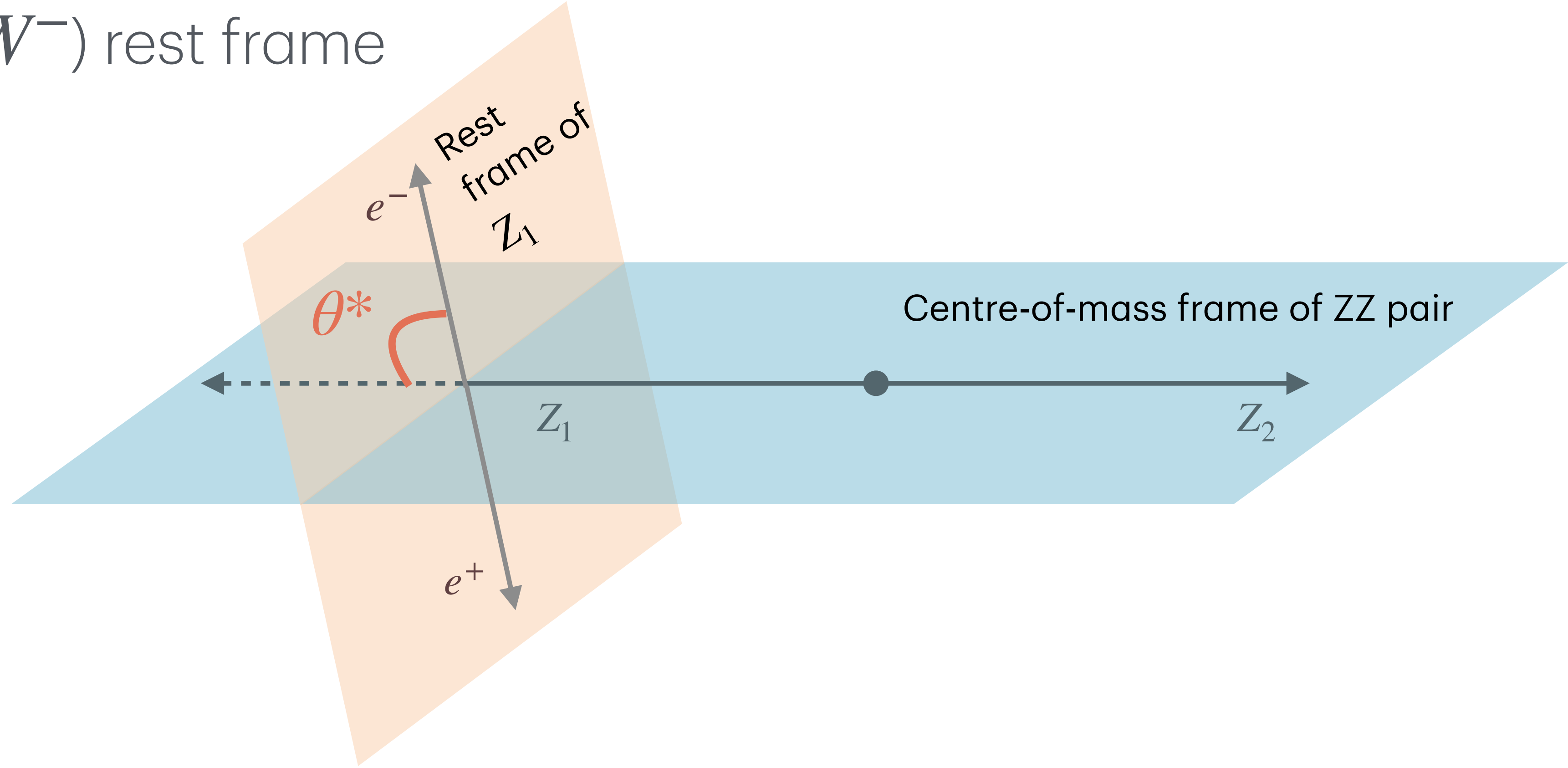
- For all the operators and processes considered the $\mathcal{O}(\Lambda^{-4})$ distributions **either overlap or converge** → we **need other observables.**

Total IM/RE $c_{t\varphi}$ amplitudes dominated by:

$\lambda_{g_1}, \lambda_{g_2}, \lambda_{Z_1}, \lambda_{Z_2}$	$(+,+,0,0)$
RE$c_{t\varphi}$	$\frac{m_t\, v^3\, e^2\, g_s^2 \delta_{ab}}{128\pi^2\, m_Z^2\, c_w^2\, s_w^2}\left[\left(\log\left(\frac{s}{m_t^2}\right) - i\pi\right)^2 - 4\right]$
IM$c_{t\varphi}$	$i\,\frac{m_t\, v^3\, e^2\, g_s^2 \delta_{ab}}{128\pi^2\, m_Z^2\, c_w^2\, s_w^2}\left(\log\left(\frac{s}{m_t^2}\right) - i\pi\right)^2$

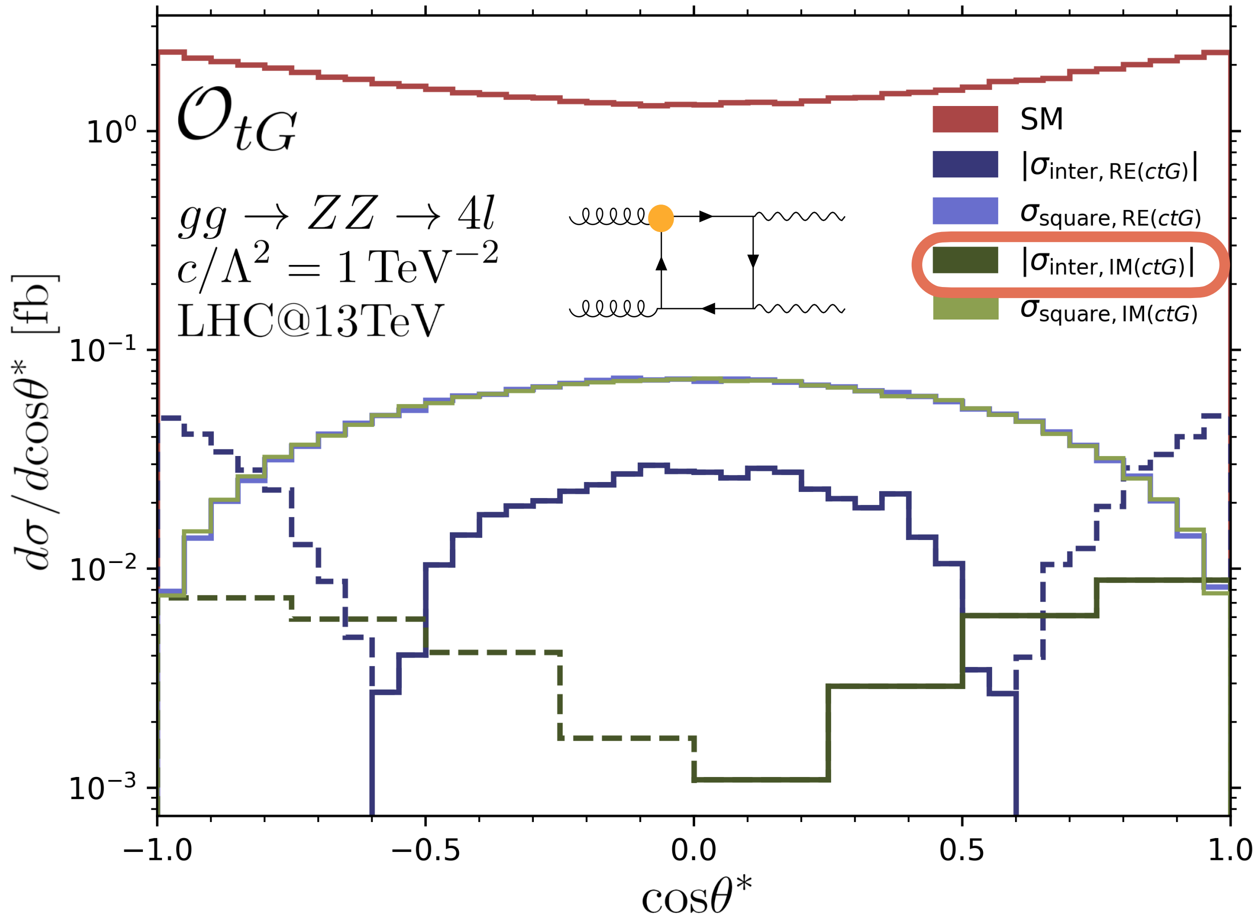
Distinguishing CP-odd contributions with angular observables

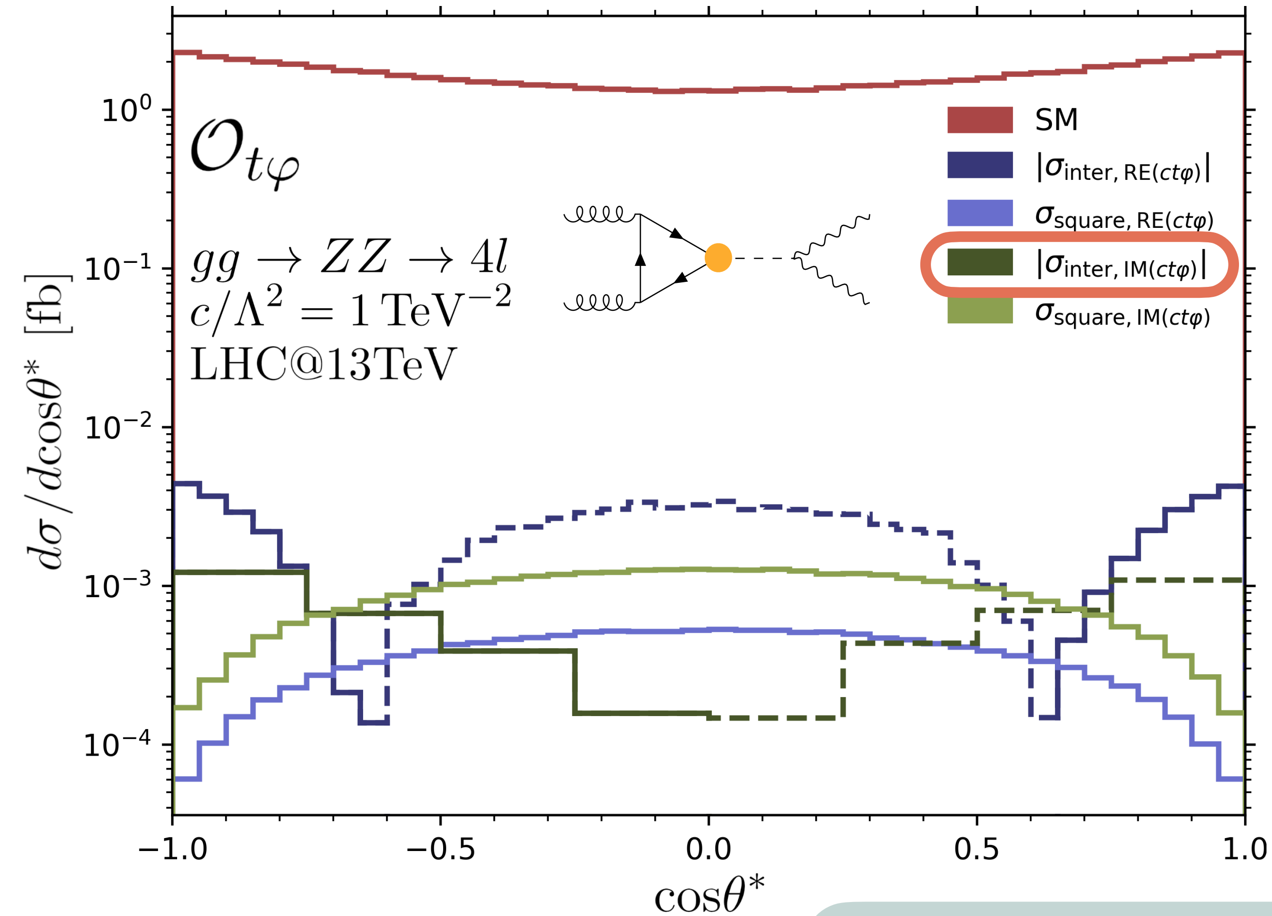
- Consider $gg \to ZZ \to e^+e^-\mu^+\mu^-$ and $gg \to W^+W^- \to \mu^+\nu_\mu e^-\bar{\nu}_e$
- No kinematic cuts except to keep Z and W bosons on-shell
- θ^* : angle between $Z\,(W^-)$ boson momentum in $ZZ\,(WW)$ pair centre-of-mass frame and momentum of e^- in $Z\,(W^-)$ rest frame



Distinguishing CP-odd contributions with angular observables

$\mathtt{IM}c_{t\varphi}$ and $\mathtt{IM}c_{tG}$ interferences are **non-zero and odd** around $\cos\theta^* = 0$





Dashed line = negative interference

- All other distributions are even around $\cos\theta^* = 0$
- We **can distinguish between CP-even and CP-odd** contributions

Impact on polarisation fractions

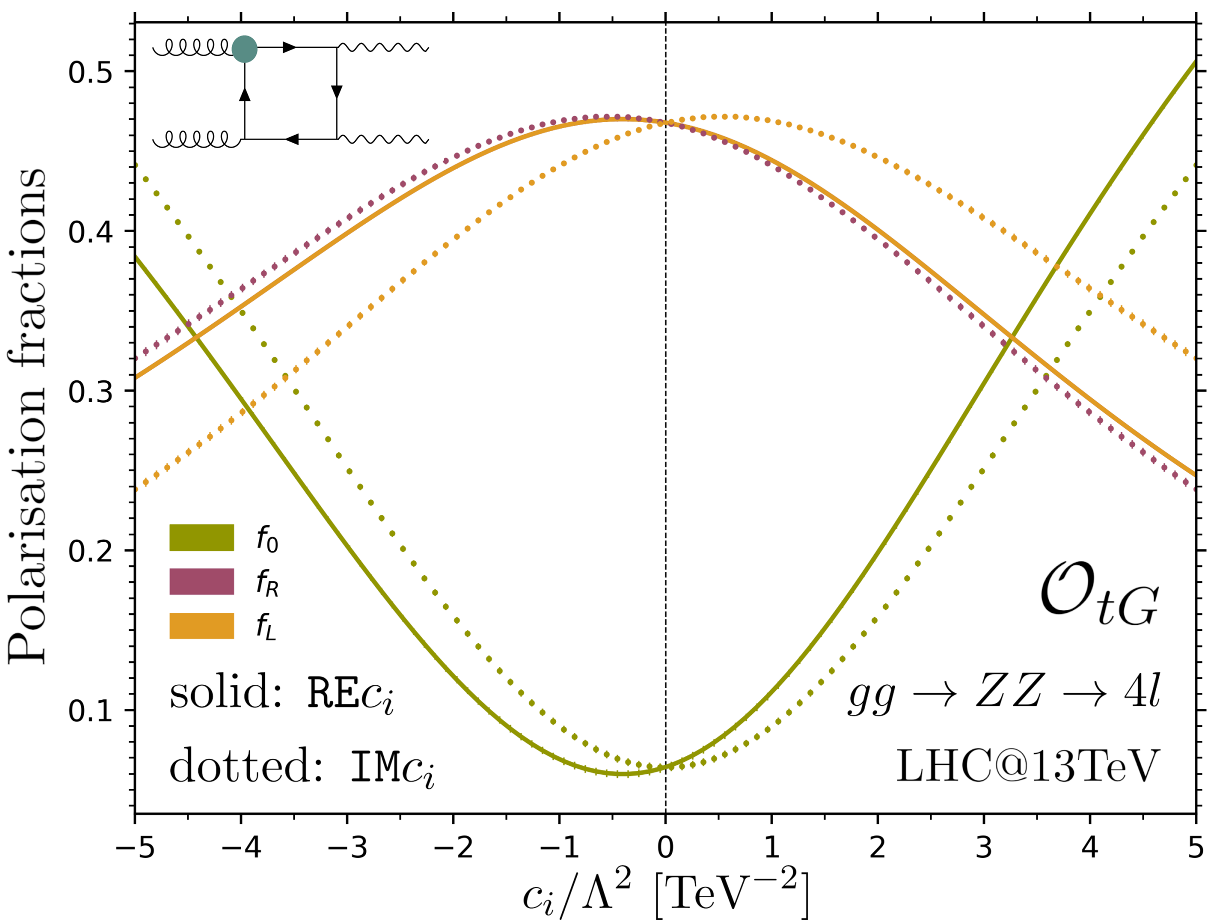
$ZZ \to 4l$ production

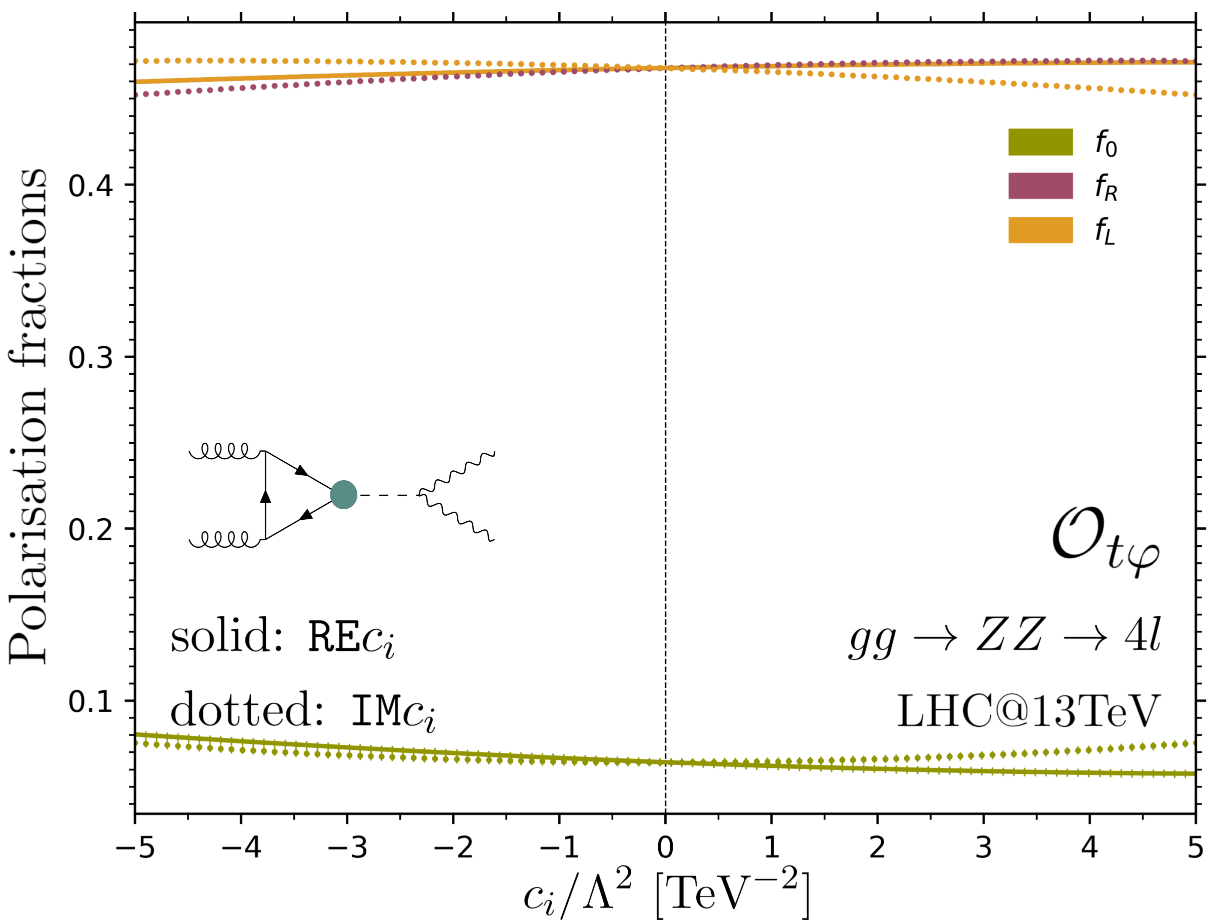
$$f_R = -\frac{1}{2} - \frac{(c_L^2 + c_R^2)}{(c_L^2 - c_R^2)}\langle\cos\theta^*\rangle + \frac{5}{2}\langle\cos^2\theta^*\rangle$$

$$f_L = -\frac{1}{2} + \frac{(c_L^2 + c_R^2)}{(c_L^2 - c_R^2)}\langle\cos\theta^*\rangle + \frac{5}{2}\langle\cos^2\theta^*\rangle$$

$$f_0 = 2 - 5\langle\cos^2\theta^*\rangle$$

- $\langle\cos\theta^*\rangle$, $\langle\cos^2\theta^*\rangle$ are modified by SMEFT coefficients.
- $f_L \neq f_R$ for CP-odd coefficients because $\langle\cos\theta^*\rangle \neq 0$.

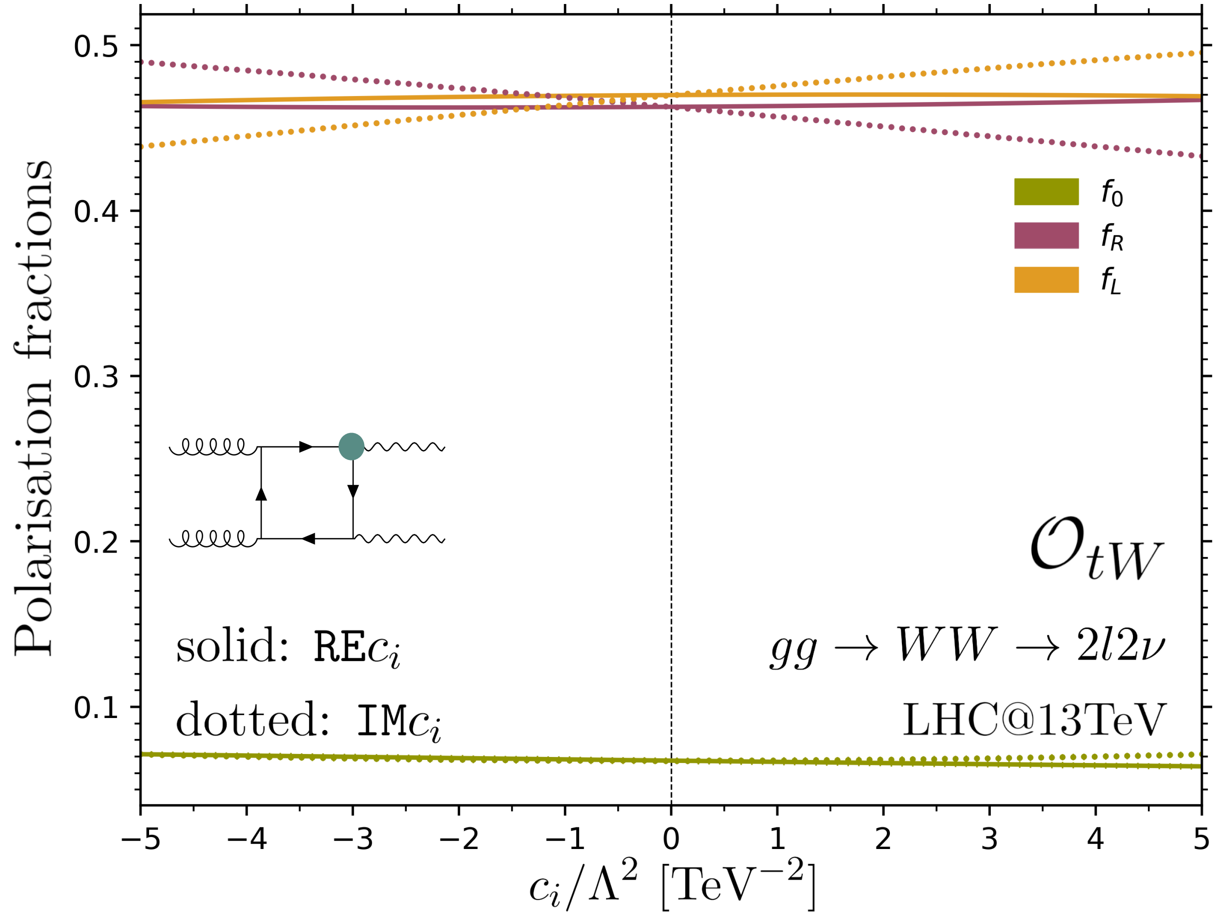


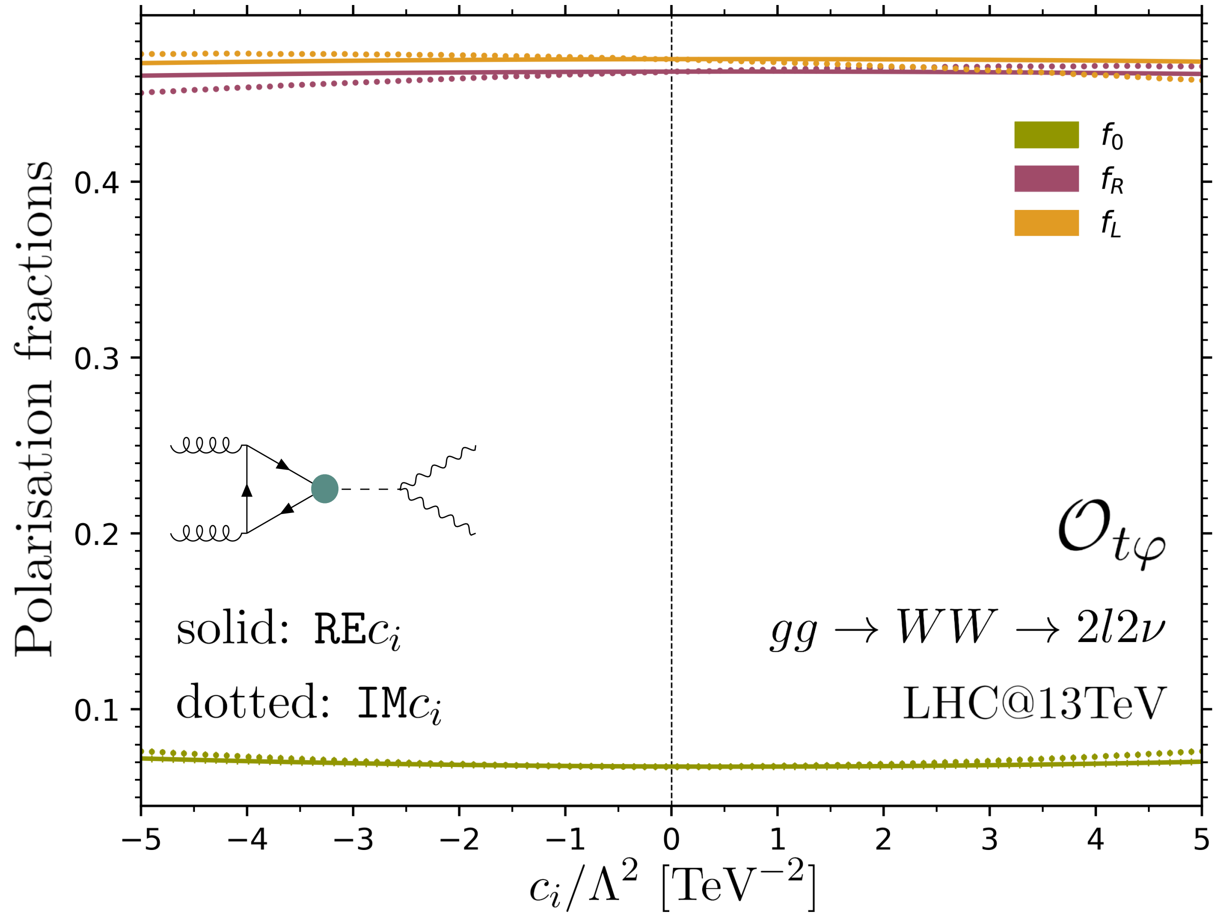


Impact on polarisation fractions

$WW \to 2l2\nu$ production

- $f_L \neq f_R$ also for CP-even coefficients: due to third generation boxes with $m_b \neq m_t$.



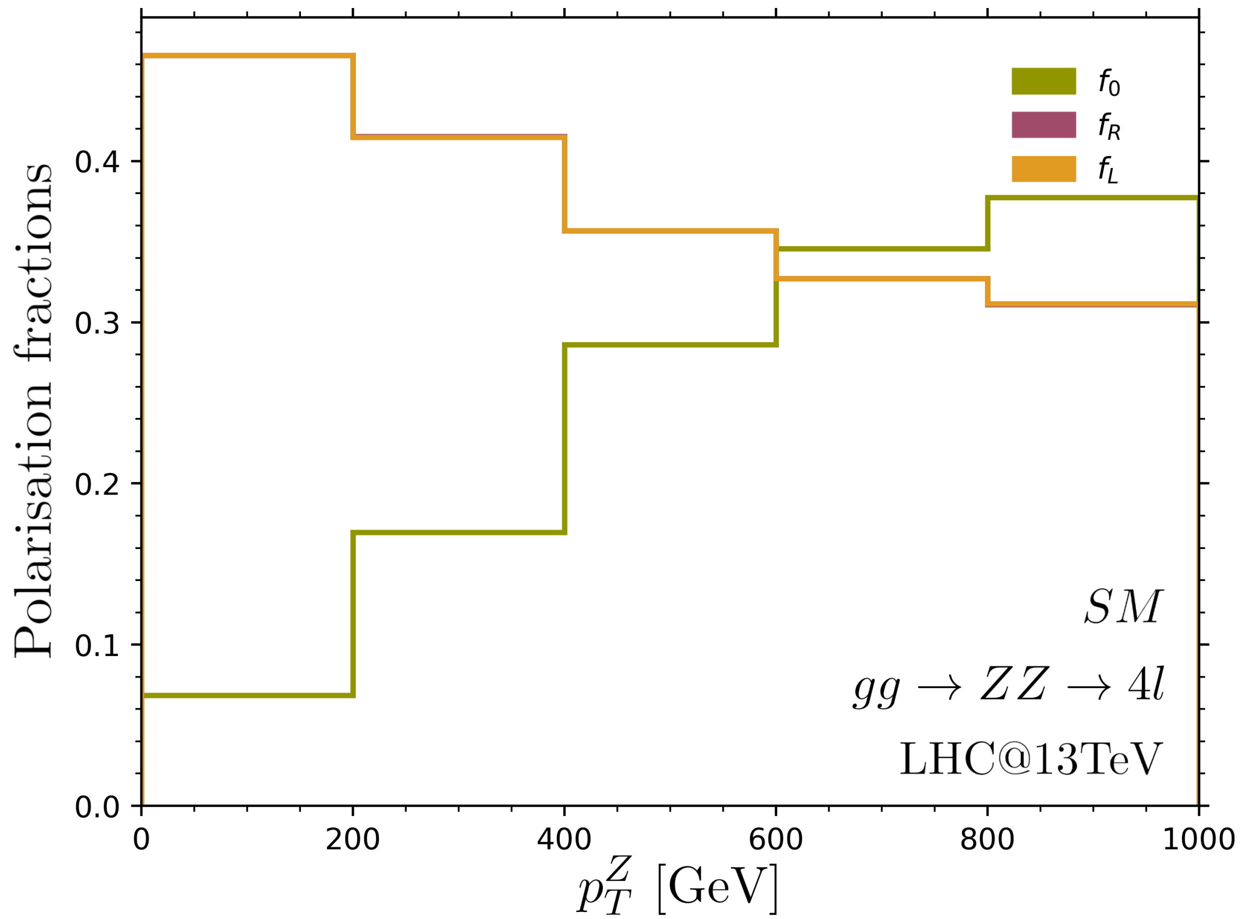


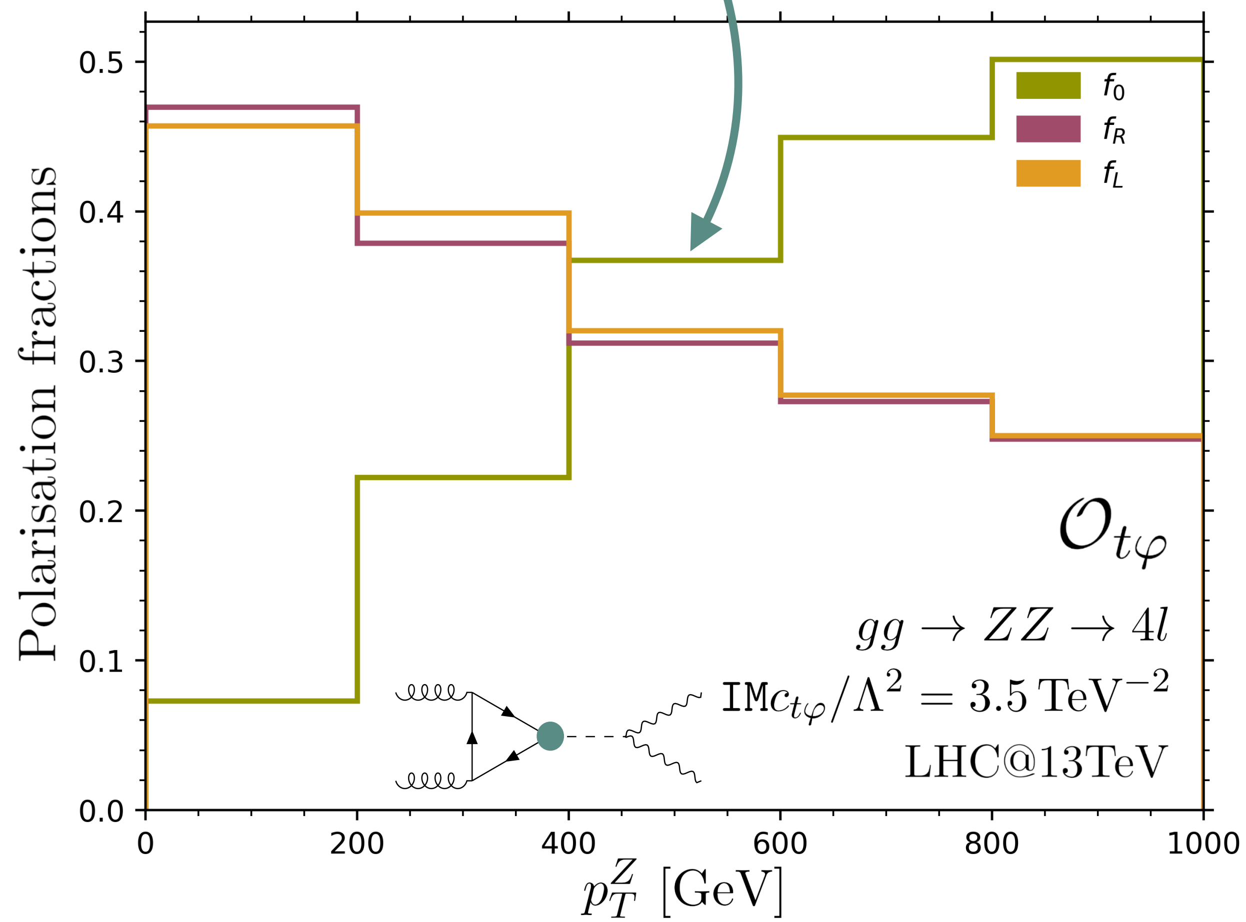
- Overall, **inclusive polarisation fractions moderately impacted** by SMEFT operators, except for $\mathcal{O}_{tG}$ $\to$ **what about the high-energy behaviour?**

Energy behaviour of the polarisation fractions

$\lambda_{g_1}, \lambda_{g_2}, \lambda_{Z_1}, \lambda_{Z_2}$	$(+,+,0,0)$
$\mathtt{IM}c_{t\varphi}$	$i\,\frac{m_t\, v^3\, e^2\, g_s^2 \delta_{ab}}{128\pi^2\, m_Z^2\, c_w^2\, s_w^2}\left(\log\left(\frac{s}{m_t^2}\right) - i\pi\right)^2$

f_0 grows faster than in SM





Conclusions

See also:
[arXiv:2409.00168]
[arXiv:2405.19083]

- Study of CP violation in the SMEFT at one-loop is only beginning.
- We **implemented the dim-6 CP-odd operators** entering in gluon-induced diboson production in SMEFT@NLO ($\rightarrow$ **calculation of rational terms and UV counterterms**).
- **Angular and polarisation observables** are **needed to distinguish between CP-even and CP-odd** contributions.
- **Polarisation fractions can be significantly modified**, especially in the high-energy region.

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- **Polarisation fractions can be significantly modified**, especially in the high-energy region.

Thank you!

What are the rational terms?

- Implementation of one-loop QCD calculations in MadLoop relies on Ossola-Papadopoulos-Pittau (OPP) reduction method.

Calculated automatically in Madgraph

Need to be calculated externally

$$\mathcal{A} = \sum_i d_i \, \text{Box}_i + \sum_i c_i \, \text{Triangle}_i + \sum_i b_i \, \text{Bubble}_i + \sum_i a_i \, \text{Tadpole}_i + R_1 + R_2$$

Known scalar integrals

Rational terms

See 't Hooft, Veltman in Nucl. Phys. B 153 (1979) 365,
Ellis, Zanderighi in arXiv:0712.1851,
Van Hameren in arXiv:1007.4716

Ossola, Papadopoulos, Pittau in arXiv:0609007, 0711.3596, 0802.1876
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