CP violation in gluon-induced diboson production

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In collaboration with Eleni Vryonidou, in preparation

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CP violation in the SMEFT

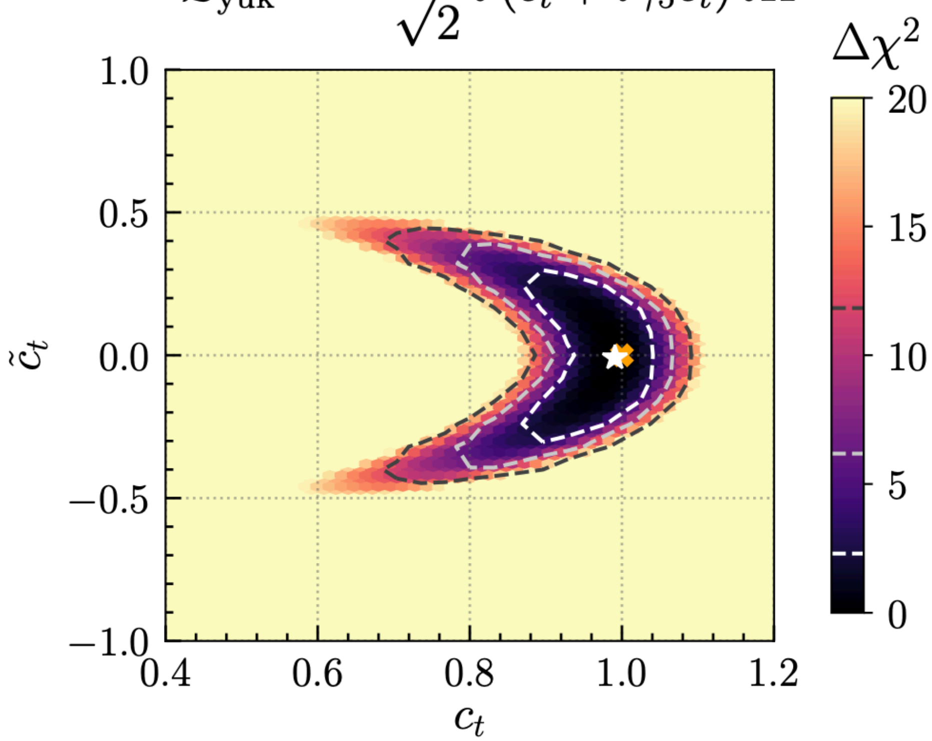
CP-odd component of Higgs interactions not ruled out by measurements

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. in arXiv:2007.08542

EFT studies of Higgs interactions at one-loop, eg. with Higgs Characterisation framework [arXiv:1306.6464] [arXiv:1407.5089]

→ So far focus on CP-violation in HVV and Hff interactions

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.

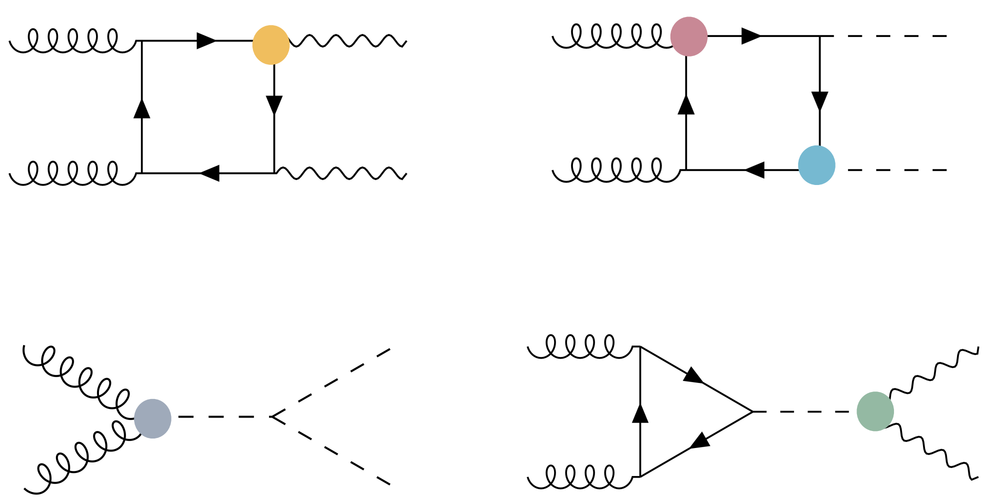
CP-violating SMEFT operators

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

Hermitian operators

$$c_i = \texttt{RE}c_i$$

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



Non-hermitian operators

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

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

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

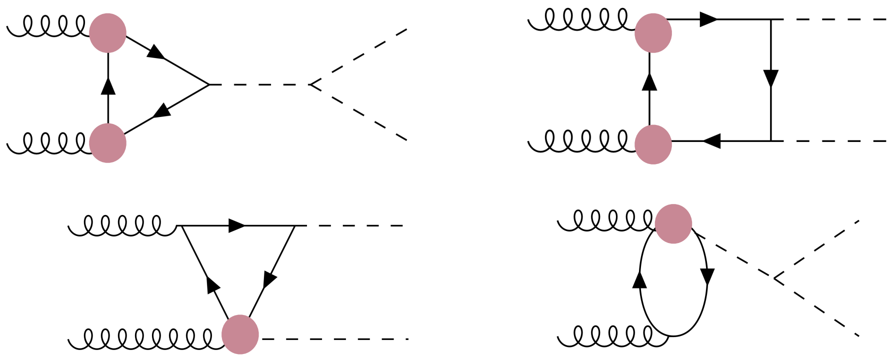
Adding CP-odd operators in SMEFT@NLO

3 ingredients to add to UFO

Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang in arXiv:2008.11743

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

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



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1. Feynman rules

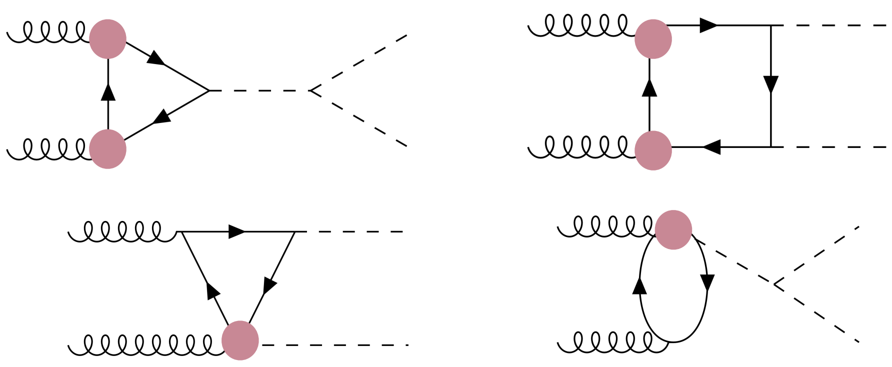
Read from the SMEFT Lagrangian

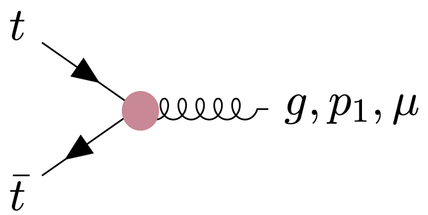
Checked against SMEFTsim implementation

Brivio in arXiv:2012.11343

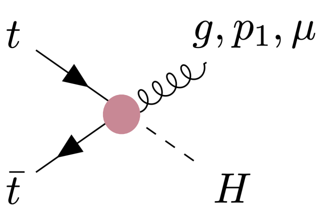
Example: $\mathtt{IM}c_{tG}$ in $gg \to HH$

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





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



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

1. Feynman rules

Read from the SMEFT Lagrangian

2. Rational Terms R_2

Calculated from one-loop irreducible diagrams

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

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

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
Hirschi et al. in arXiv:1103.0621

Adding CP-odd operators in SMEFT@NLO

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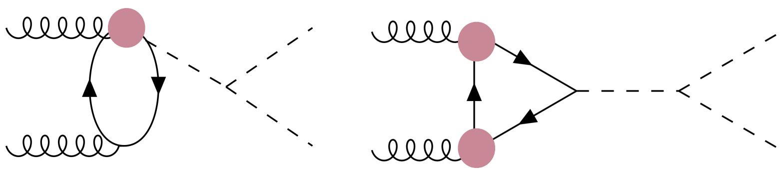
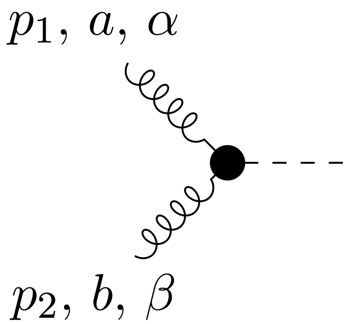
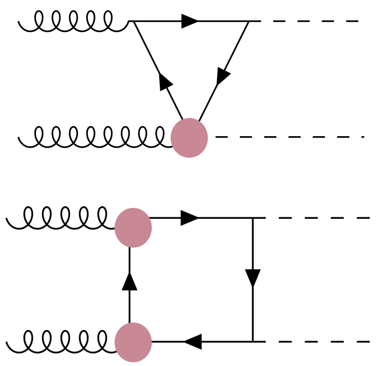


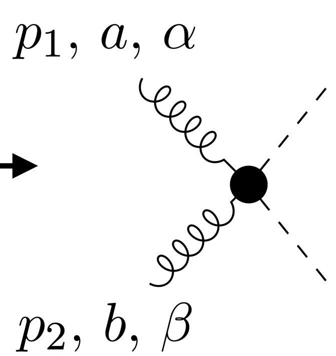
Need underlying ggH R_2



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



One-loop 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

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1. **Feynman rules**

Read from the SMEFT Lagrangian

2. **Rational Terms R_2**

Calculated from one-loop irreducible diagrams

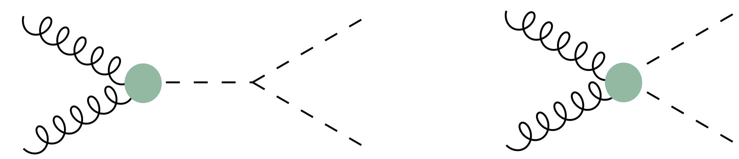
3. **UV Counterterms**

Checked against the Renormalisation Group Evolution (RGE)

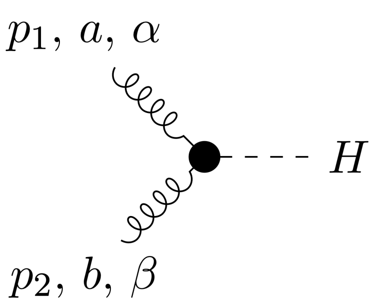
Alonso, Jenkins, Manohar and Trott in arXiv:1308.2627, 1310.4838, 1312.2014

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

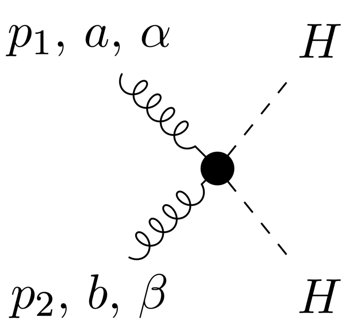
Renormalised with $\mathcal{O}_{\varphi\tilde{G}}$



ggH and $ggHH$ UV counterterms:



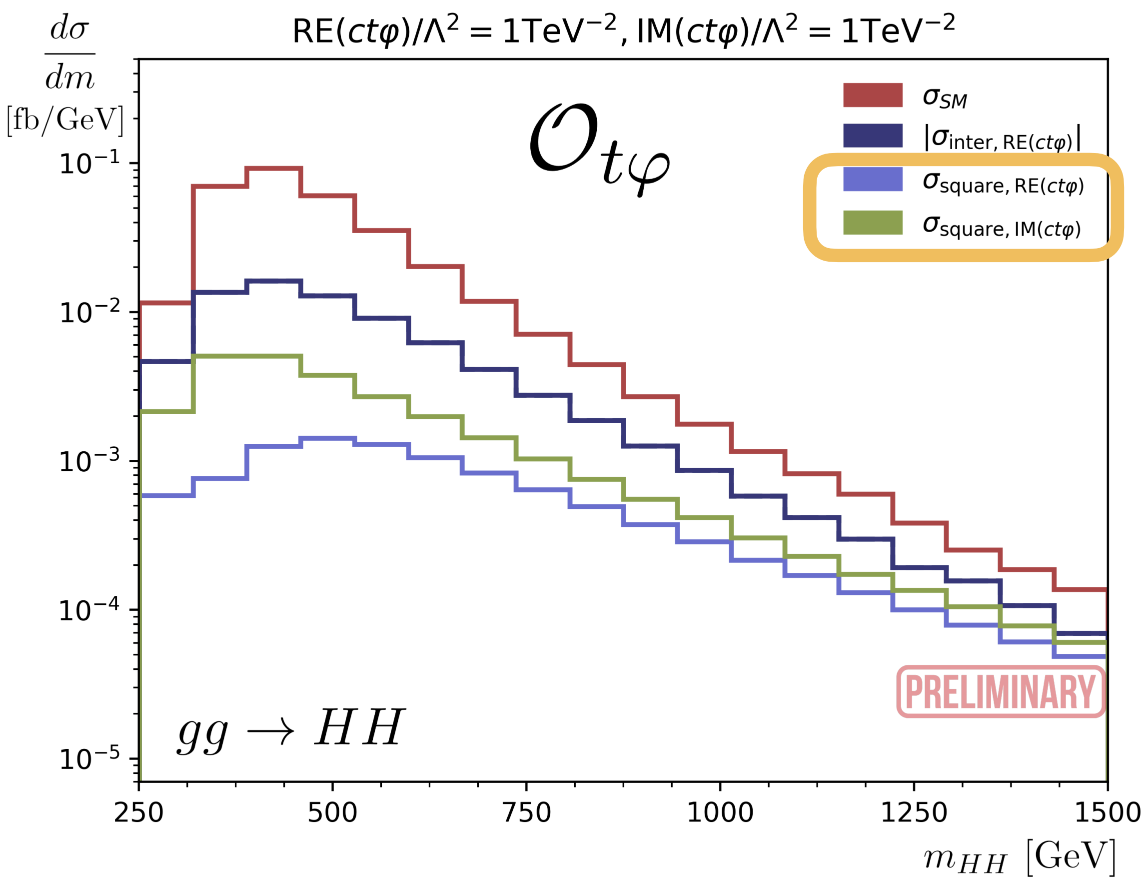
$$= \frac{\mathtt{IM}c_{tG}}{\Lambda^2}\frac{i\,g_s^2\,m_t}{\sqrt{2}\pi^2}\left(\frac{1}{\epsilon} - \log\left(\frac{\mu_{EFT}^2}{\mu_R^2}\right)\right)\varepsilon^{p_1 p_2 \alpha\beta}\delta_{ab}$$



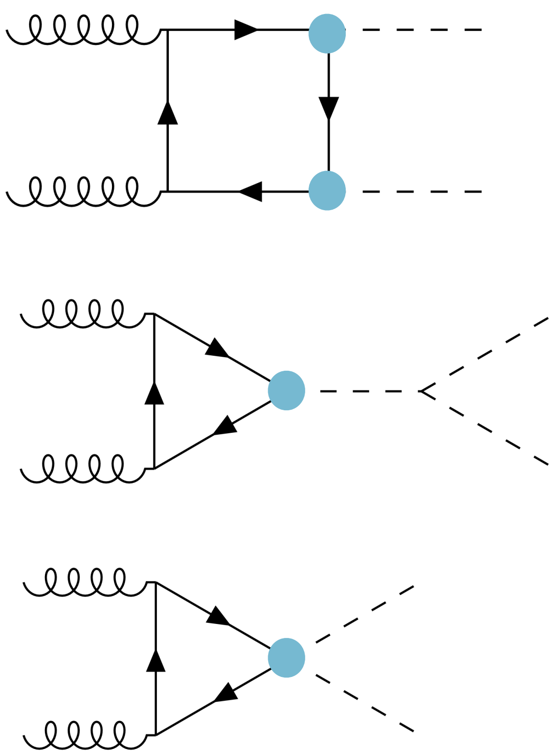
$$= \frac{\mathtt{IM}c_{tG}}{\Lambda^2}\frac{i\,g_s^2\,m_t}{\sqrt{2}\pi^2 v}\left(\frac{1}{\epsilon} - \log\left(\frac{\mu_{EFT}^2}{\mu_R^2}\right)\right)\varepsilon^{p_1 p_2 \alpha\beta}\delta_{ab}$$

Growing amplitudes and tail effects

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



Converge at high energies



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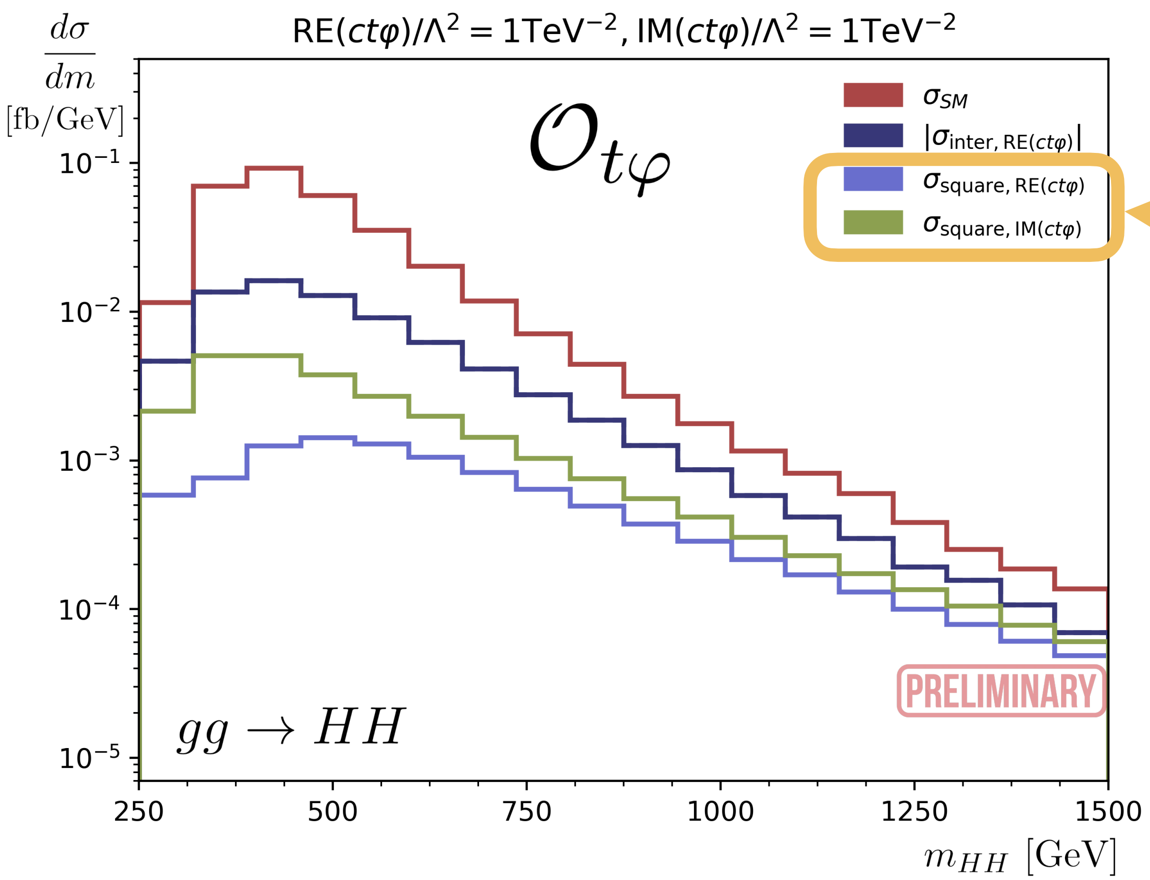

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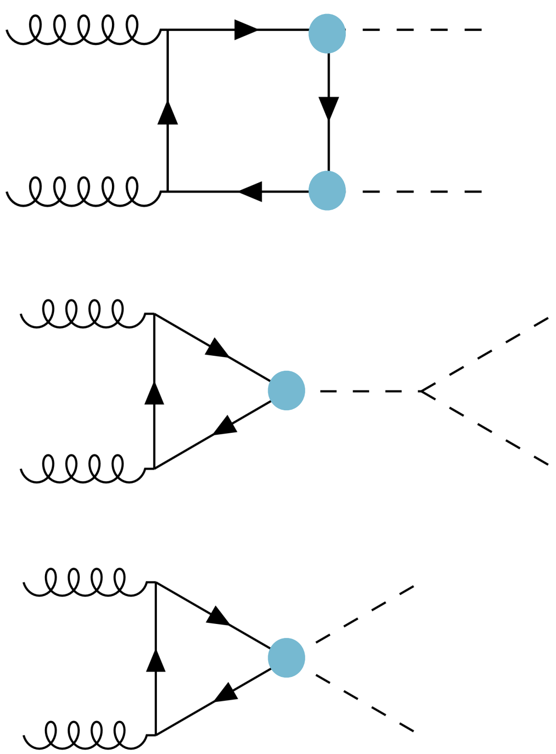


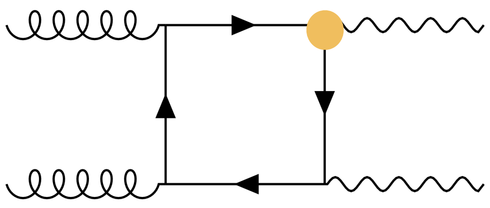
$\lambda_{g_1}, \lambda_{g_2}, \lambda_{H_1}, \lambda_{H_2}$	$(+,+,0,0)$	$(+,-,0,0)$
$\mathtt{RE}c_{t\varphi}$	$\frac{m_t\, v\, g_s^2\, \delta_{ab}}{32\pi^2}\Big[-3\left(\log(\frac{s}{m_t^2})-i\pi\right)^2+20\Big]$	s^0
$\mathtt{IM}c_{t\varphi}$	$\frac{m_t\, v\, g_s^2\, \delta_{ab}}{32\pi^2}\Big[-3i\left(\log(\frac{s}{m_t^2})-i\pi\right)^2\Big]$	0

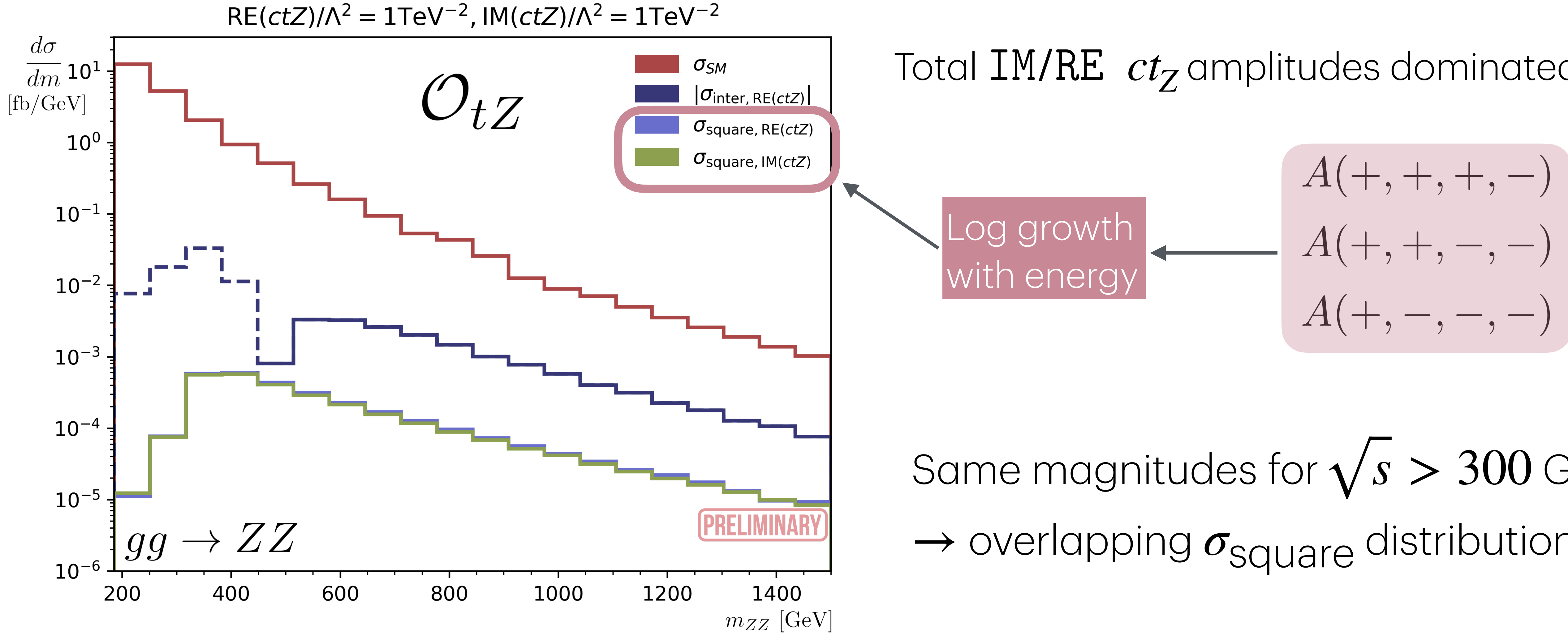
High energy behaviour of the helicity amplitudes

$\to$ $\mathtt{RE}c_{t\varphi}$ and $\mathtt{IM}c_{t\varphi}$ dominated by $(+,+,0,0)$

Growing amplitudes and tail effects

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





Total IM/RE ct_Z amplitudes dominated by:

Same magnitudes for $\sqrt{s} > 300$ GeV

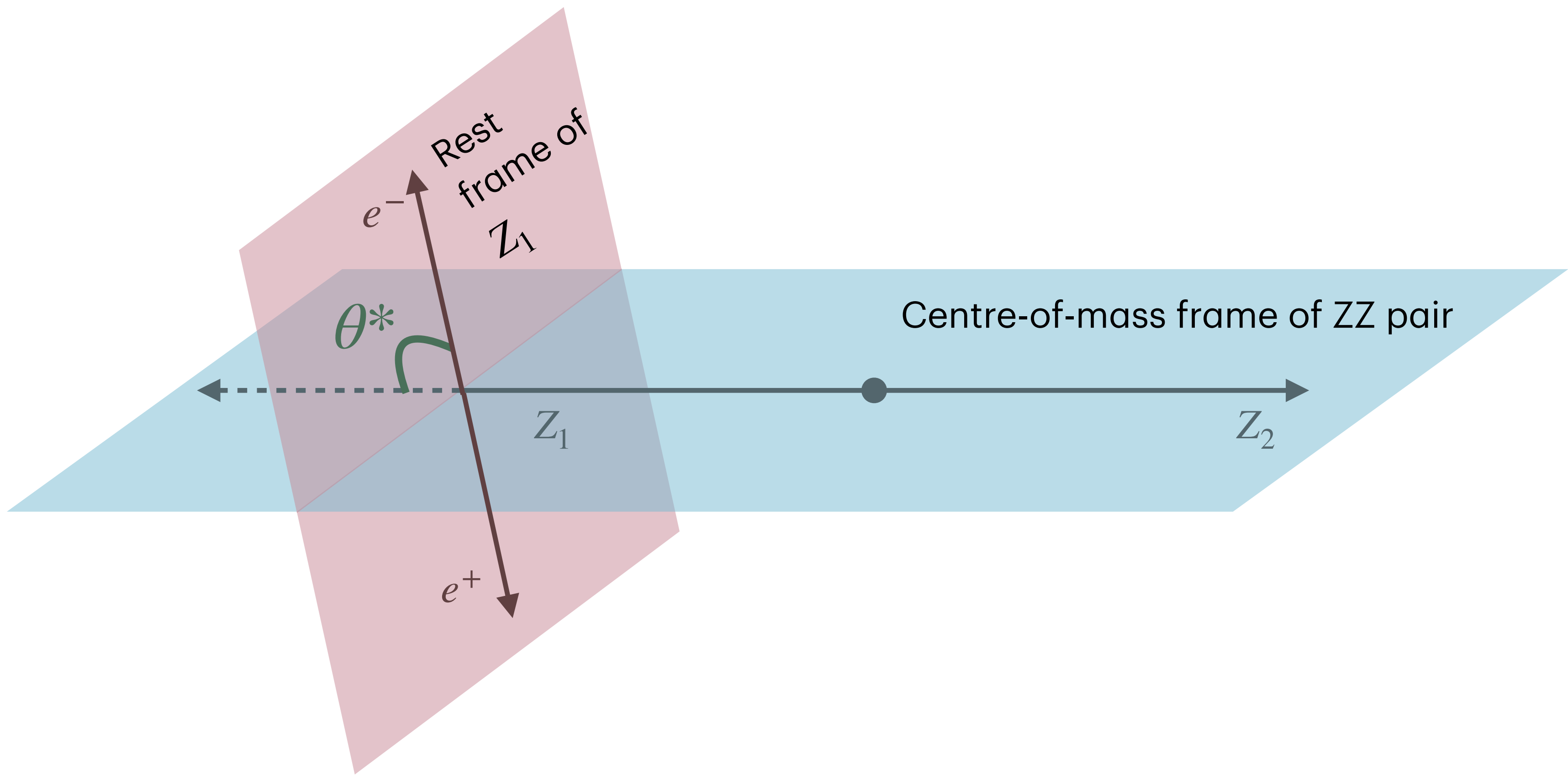
→ overlapping σ_{square} distributions

Distinguishing CP-odd contributions with angular observables

Consider $gg \to ZZ \to e^+e^-\mu^+\mu^-$

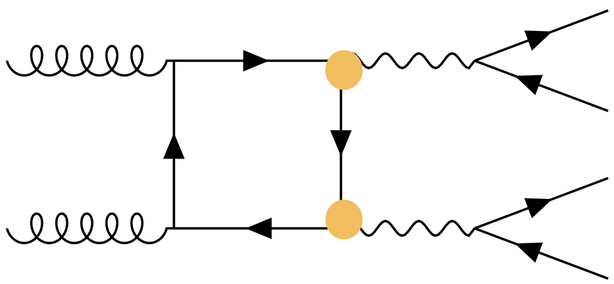
No kinematic cuts except on-shell Z bosons

θ^* : angle between Z boson momentum in ZZ pair centre-of-mass frame and momentum of e^- in Z rest frame

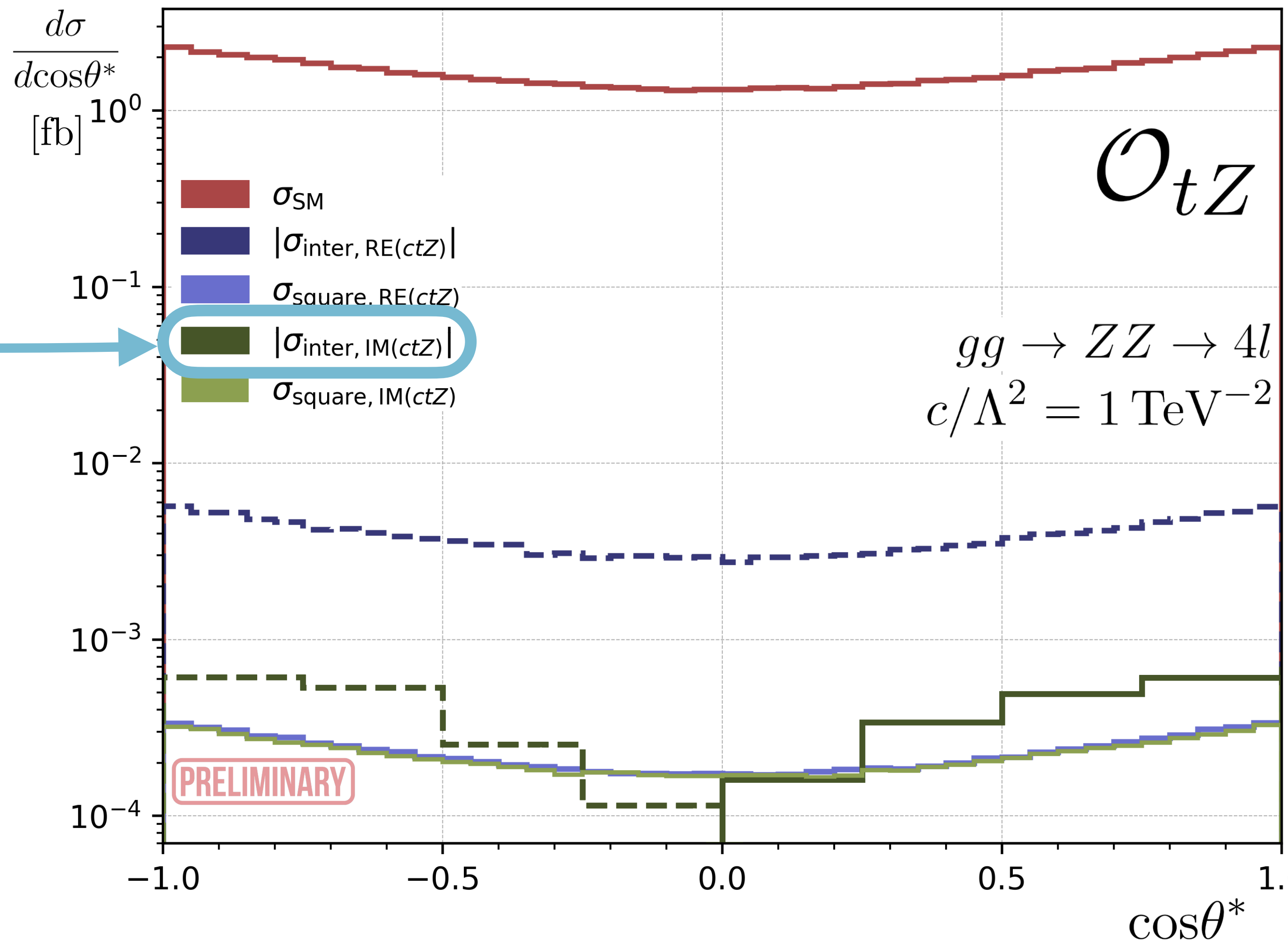


Distinguishing CP-odd contributions with angular observables

IMctZ interference is non-zero and odd around $\cos\theta^* = 0$



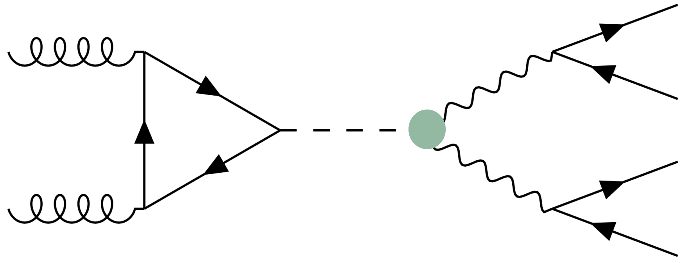
All other distributions are even around $\cos\theta^* = 0$

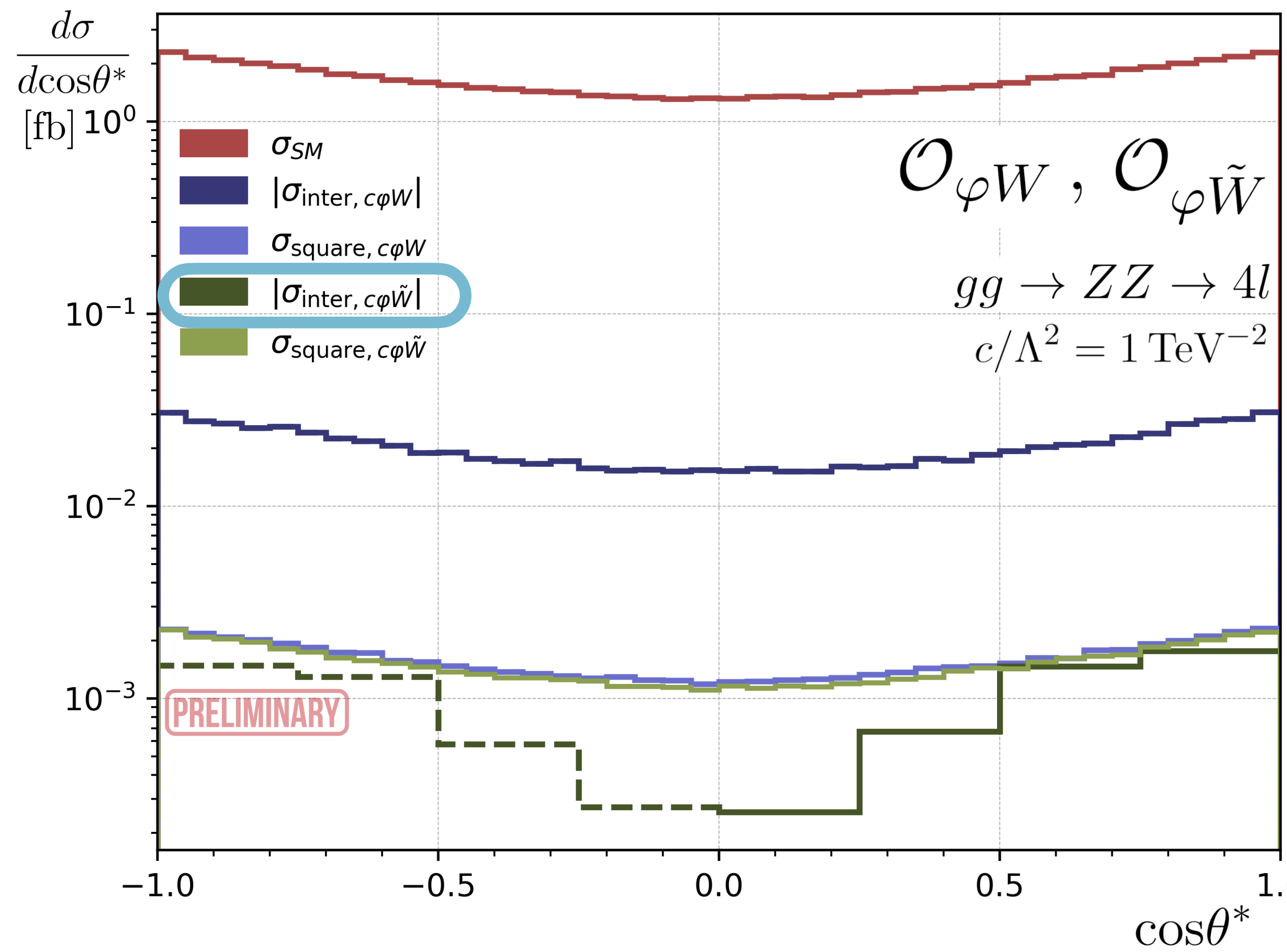


Dashed line = negative interference

Distinguishing CP-odd contributions with angular observables

Same behaviour for bosonic operators that enter in the tree part, for eg. $\mathcal{O}_{\varphi W}$ and $\mathcal{O}_{\varphi \tilde{W}}$





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Conclusion

- 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 Madgraph ($\rightarrow$ calculation of rational terms and UV counterterms)
- In $gg \rightarrow ZZ \rightarrow 4l$ angular observables distinguish between CP-even and CP-odd contributions

➡ More is under study, stay tuned!

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➡ More is under study, stay tuned!

Thank you !

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-loop 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

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

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