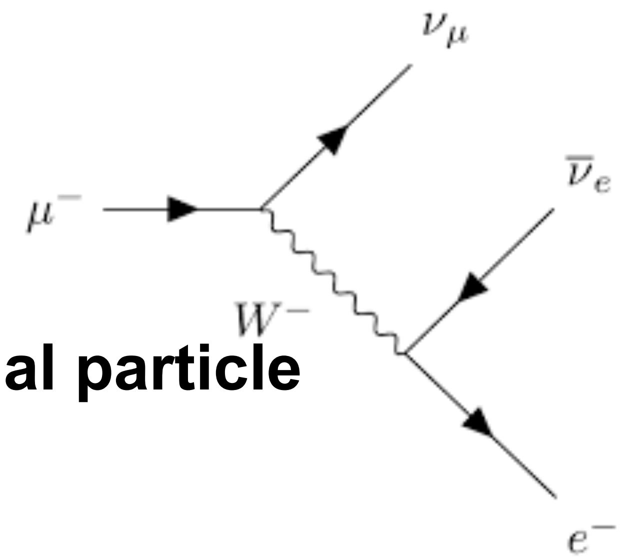
Off-shell couplings

XVIII Mexican Workshop on Particles and Fields

A. I. Hernández-Juárez, A. Fernández-Téllez, G. Tavares, A. Moyotl

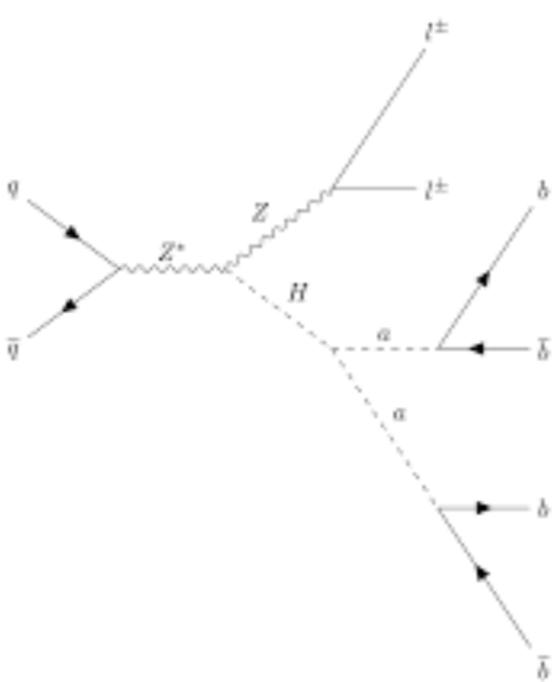
21-25 November 2022

BASICS



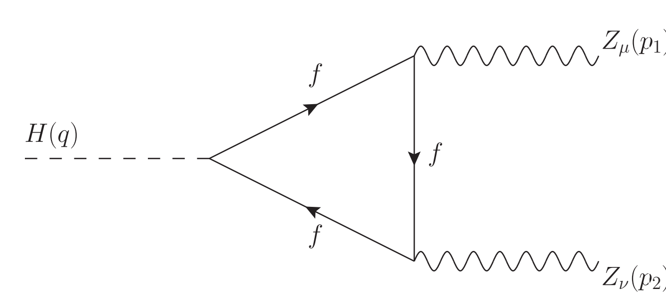
An off-shell coupling requires at least one external virtual particle

The virtual or off-shell particles are denoted by an asterisk: $Z^*, H^*, W^{\pm *}, \ldots$



In this talk we only considere couplings with off-shell bosons

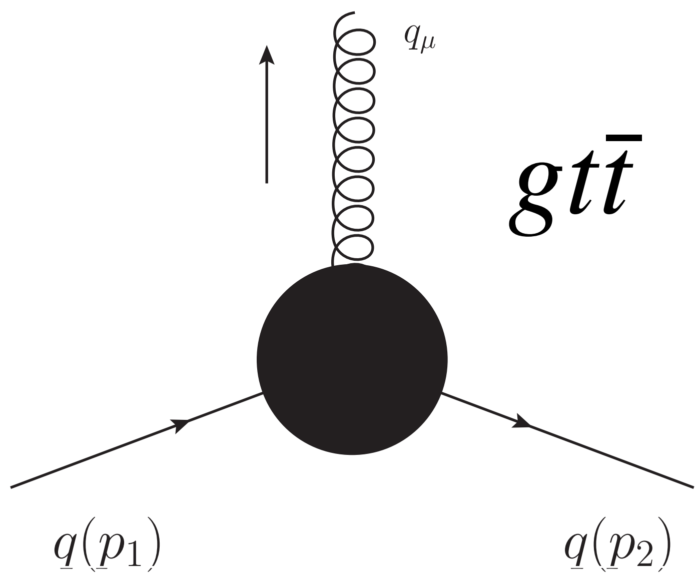
q **is the 4-momentum of the off-shell boson**



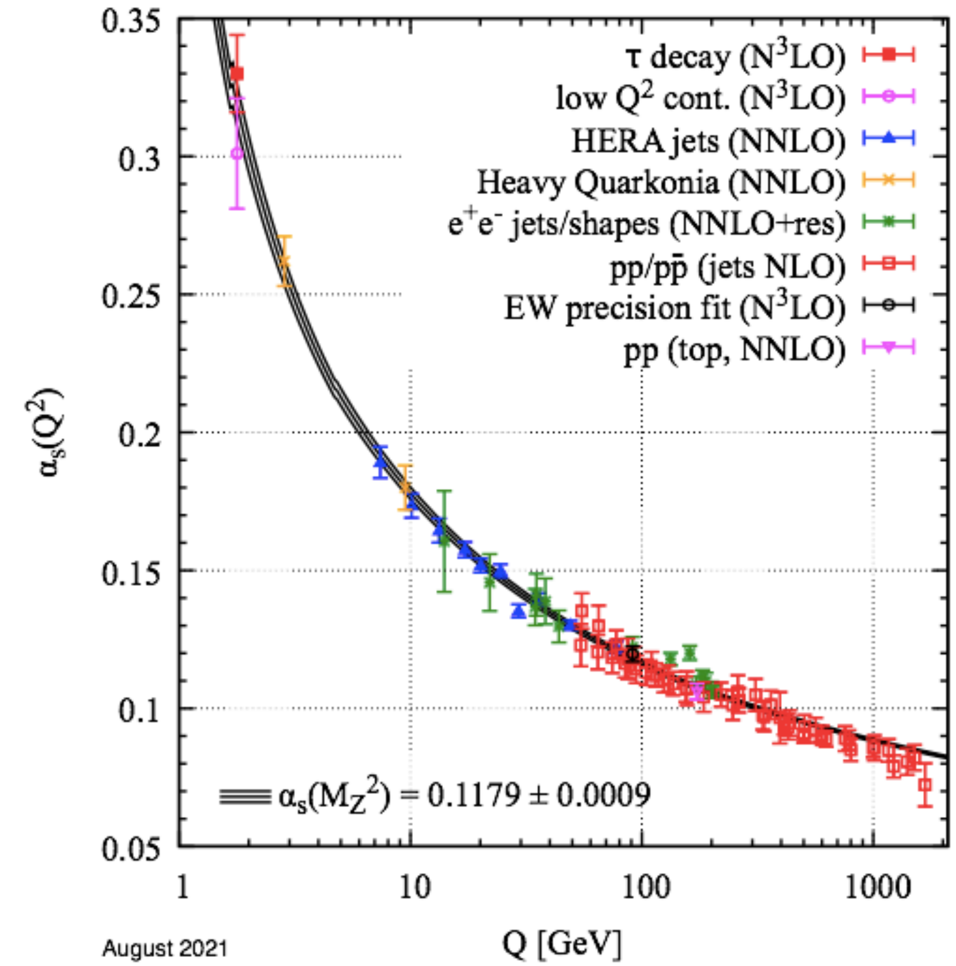
MOTIVATION

Off-shell couplings have been of great interest in recent years

Top quark anomalous couplings



Chromomagnetic dipole moment (CMDM)



At $q^2 = 0$ the CMDM is not well defined as the QCD at this energy is not perturbative → **For an on-shell gluon a non-finite CMDM is found**

I.D. Choudhury, A. Lahiri, Mod. Phys. Lett. A 30(23), 1550113 (2015).

MOTIVATION

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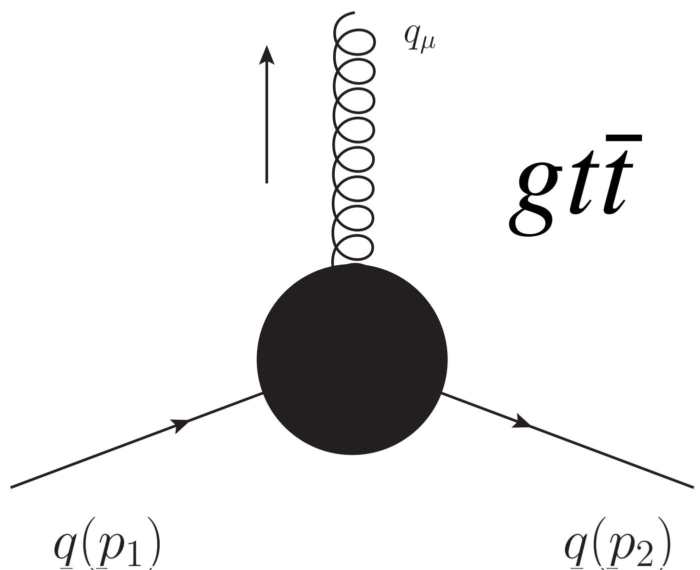

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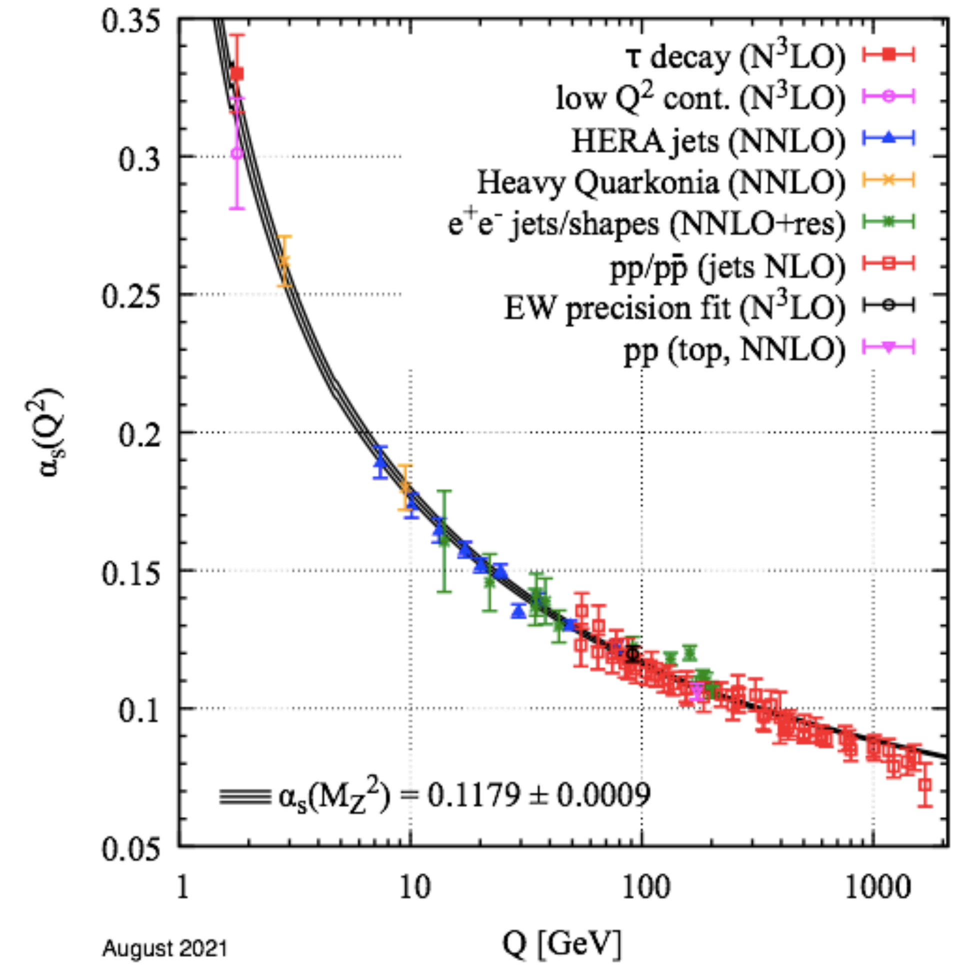


For an off-shell gluon the CMDM is finite

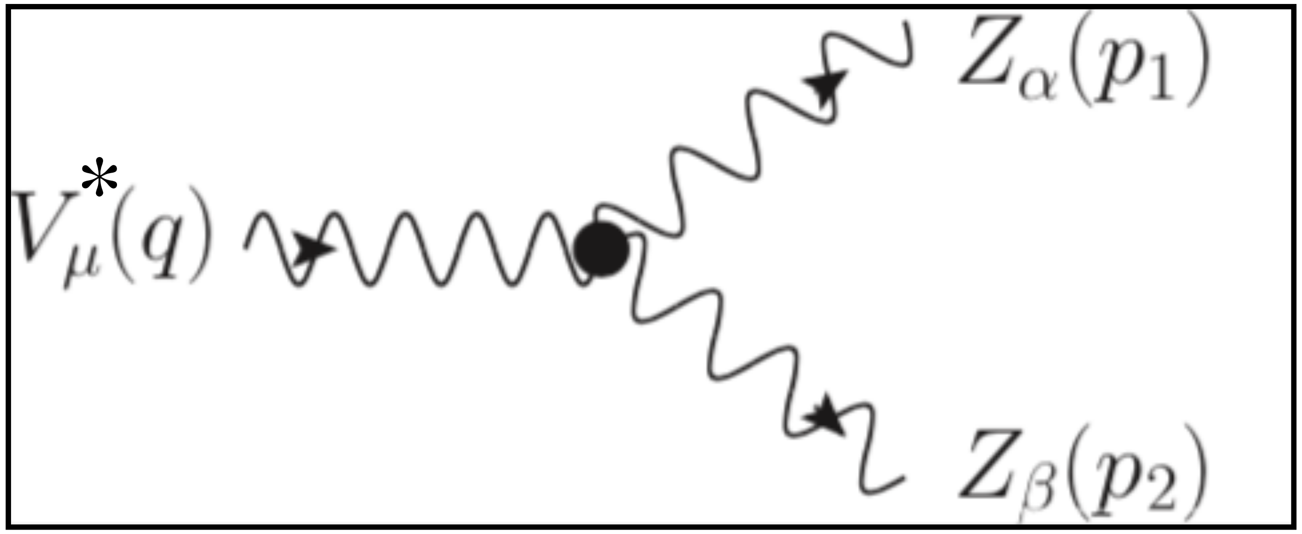
A. I. Hernández-Juárez, A. Moyotl, and G. Tavares-Velasco. New estimate of the chromomagnetic dipole moment of quarks in the standard model. Eur. Phys. J. Plus, 136(2): 262, 2021.

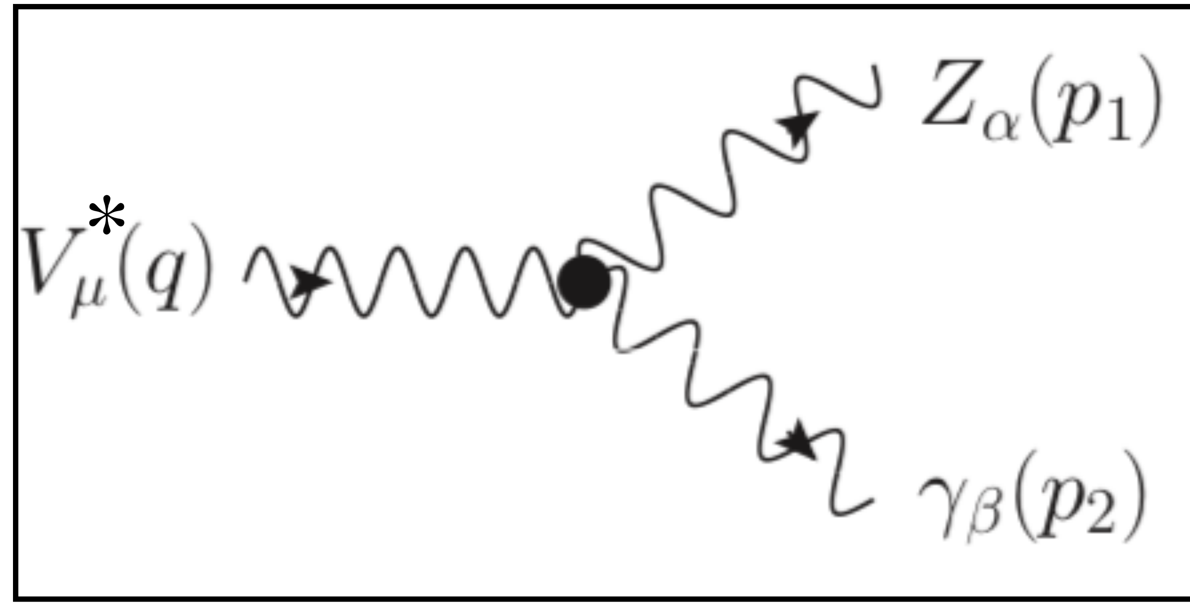
J. I. Aranda, T. Cisneros-Pérez, J. Montaño, B. Quezadas-Vivian, F. Ramírez-Zavaleta, and E. S. Tututi, Revisiting the top quark chromomagnetic dipole moment in the SM, Eur. Phys. J. Plus 136, 164 (2021).

MOTIVATION

Trilinear neutral gauge boson couplings (TNGBCs)

They do not exist at tree level in the SM





$$V = Z, \gamma$$

For an off-shell V boson the vertex function is:

$$\Gamma^{\mu\alpha\beta}(q^2) \sim \frac{q^2 - m_V^2}{m_Z^2}$$

G.J. Gounaris, J. Layssac, F.M. Renard, Phys. Rev. D62, 073013 (2000).

V **on shell** $\Rightarrow q^2 = m_V^2$

TNGBCs require at least one off-shell boson to exist

MOTIVATION

H* evidence at the LHC

nature physics

ARTICLES

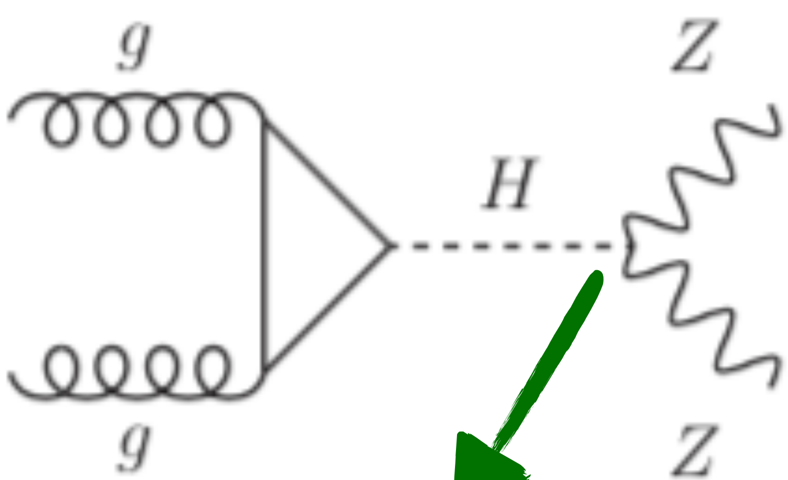
https://doi.org/10.1038/s41567-022-01682-0

Check for updates

OPEN

Measurement of the Higgs boson width and evidence of its off-shell contributions to ZZ production

The CMS Collaboration*✉



$m_H < 2m_Z$

The Higgs boson must to be off-shell to produce two on-shell Z bosons

Evidence for off-shell Higgs boson production in the final state with two Z bosons decaying into 4 charged leptons has been reported for the FIRST TIME

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

Anomalous couplings

Vertex functions

The vertex function for the anomalous $gt\bar{t}$ can be written as

$$\Gamma^{\mu} = i\sigma_{\mu\nu}q^{\nu}\left(\frac{a_q}{2m_q} + id_q\gamma^5\right),$$

Whereas for the TNGBCs:

Similar for the $Z\gamma V^*$ case

$$\Gamma^{\alpha\beta\mu}_{ZZV*}\left(p_1, p_2, q\right) = \frac{i(q^2 - m_V^2)}{m_Z^2}\left[f_4^V\left(q^{\alpha}g^{\mu\beta} + q^{\beta}g^{\mu\alpha}\right) - f_5^V\epsilon^{\mu\alpha\beta\rho}\left(p_1 - p_2\right)_{\rho}\right],$$

Anomalous couplings for the ZZH vertex can be also induced

$$\Gamma^{ZZH}_{\mu\nu} = h_1^V g_{\mu\nu} + \frac{h_2^V}{m_Z^2}p_{1\nu}p_{2\mu} + \frac{h_3^V}{m_Z^2}\epsilon_{\mu\nu\alpha\beta}p_1^{\alpha}p_2^{\beta},$$

→ **Two cases** → **H off-shell** / **Z off-shell**

h_i^V in terms of the anomalous couplings

Anomalous couplings

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For off-shell couplings the anomalous couplings are functions of q^2, where q is the 4-momentum of the off-shell boson.

hell

hell

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→ **Two cases**
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f_4^V

CP violation

Anomalous couplings for the ZZH vertex can be also induced

$\frac{h_3^V}{m_Z^2}$

Two cases

H off-shell

Z off-shell

h_i^V in terms of the anomalous couplings

Limits on off-shell couplings at the LHC

CMDM and CEDM:

$$\hat{\mu}_t = -0.024^{+0.013}_{-0.009}(\textbf{stat})^{+0.016}_{0.011}(\textbf{syst}) \quad \textbf{and} \quad |\hat{d}_t| < 0.03$$

A. M. Sirunyan et al. (CMS), JHEP 06, 146 (2020), 1912.09540.

TNGBCs:

$$-0.00066 < f_4^Z < 0.0006,$$
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ZZH COUPLING

Parameter in units $\times 10^{-5}$	Scenario	Observed at 95% CL
f_{a2}	$\Gamma_H = \Gamma_H^{SM}$	$[-32{,}514]$
	Γ_H unconstrained	$[-38{,}503]$
f_{a3}	$\Gamma_H = \Gamma_H^{SM}$	$[-46{,}107]$
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Indirect bounds through effective ratios

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ZZH **COUPLING**

Real observables

		Observed at 95% CL
[illegible]	[illegible]	$[-32, 514]$
[illegible]	[illegible]ned	$[-38, 503]$
f_{a3}	$\Gamma_H = \Gamma_H^{SM}$	$[-46, 107]$
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Indirect bounds through effective ratios

We must to calculate off-shell observables

On-shell Green functions → gauge invariant and gauge independent

ONE LOOP CONTRIBUTIONS

We must to compute off-shell observables

On-shell
Green functions → gauge invariant
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ONE LOOP CONTRIBUTIONS

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Off-shell Green functions → Not necessarily gauge invariant and gauge independent

ONE LOOP CONTRIBUTIONS

We must to compute off-shell obs

On-shell Green functions

Off-shell Green functions → Not necessarily gauge invariant and gauge independent

ONE LOOP CONTRIBUTIONS

We must to find a way to obtain well-behaved observables

An approach to obtain well-behaved off-shell Green functions out of which valid observable quantities can be extracted

Pinch technique ⟷ Background field method

Feynman-´t Hooft gauge $(\xi_Q = 1)$

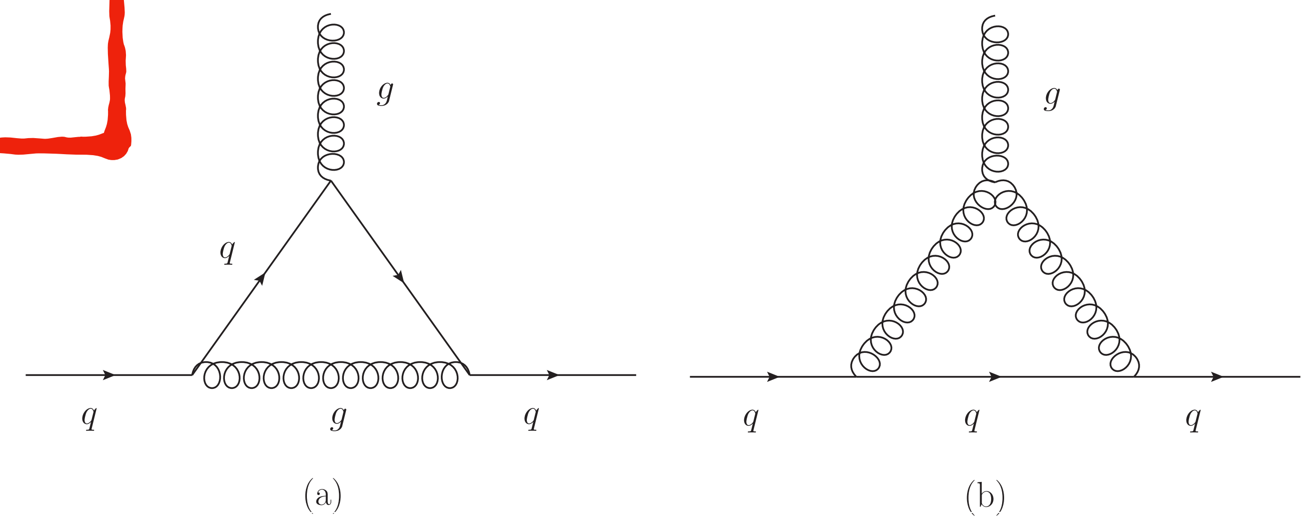
Diagrammatic method that combines self-energy, vertex and box diagrams related to a physical process to remove any gauge dependent term

ONE LOOP CONTRIBUTIONS

The anomalous couplings are induced at one loop level (or more)

CMDM in the SM

QCD



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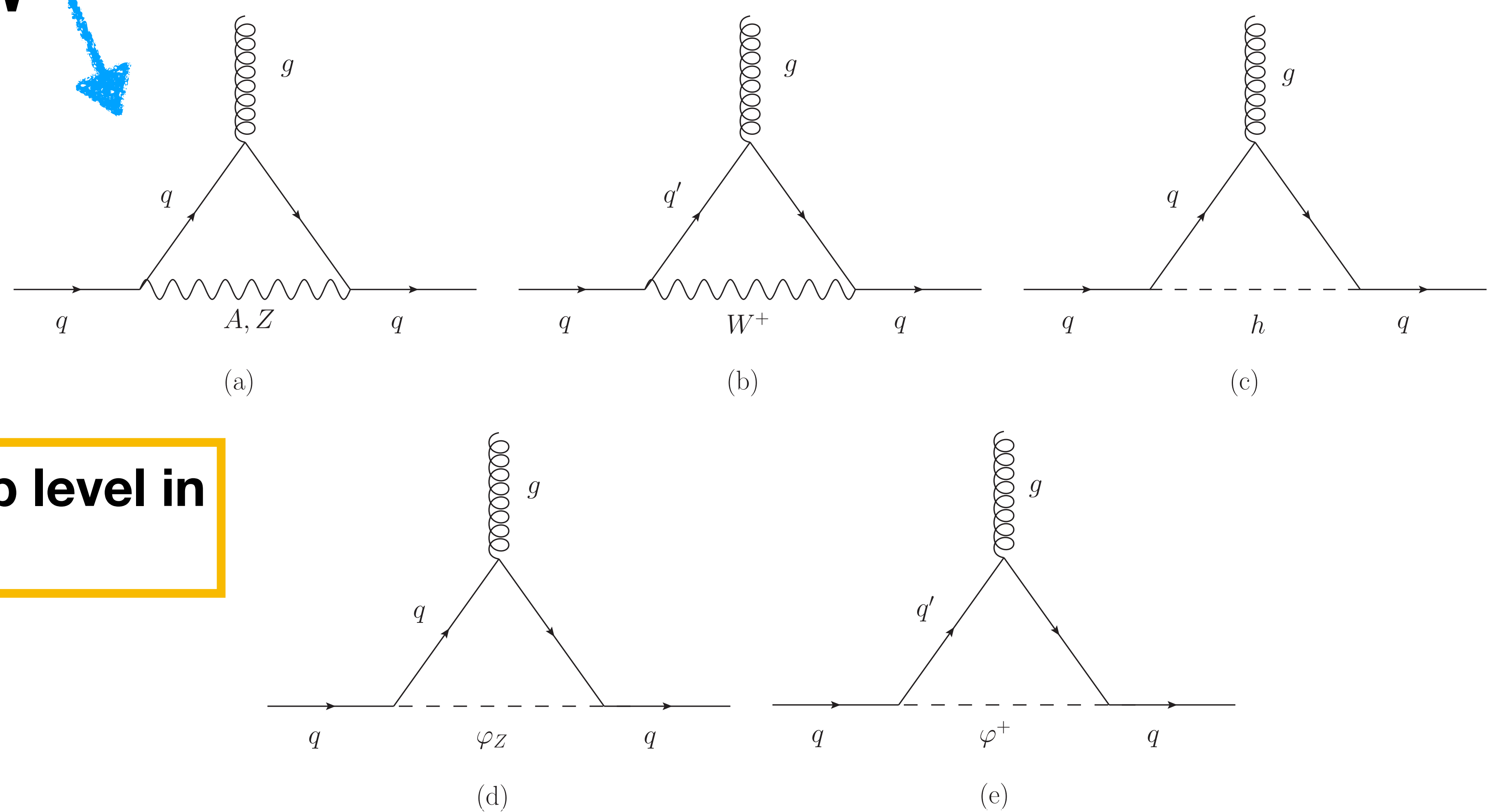

CEDM at three loop level in the SM

ONE LOOP CONTRIBUTIONS

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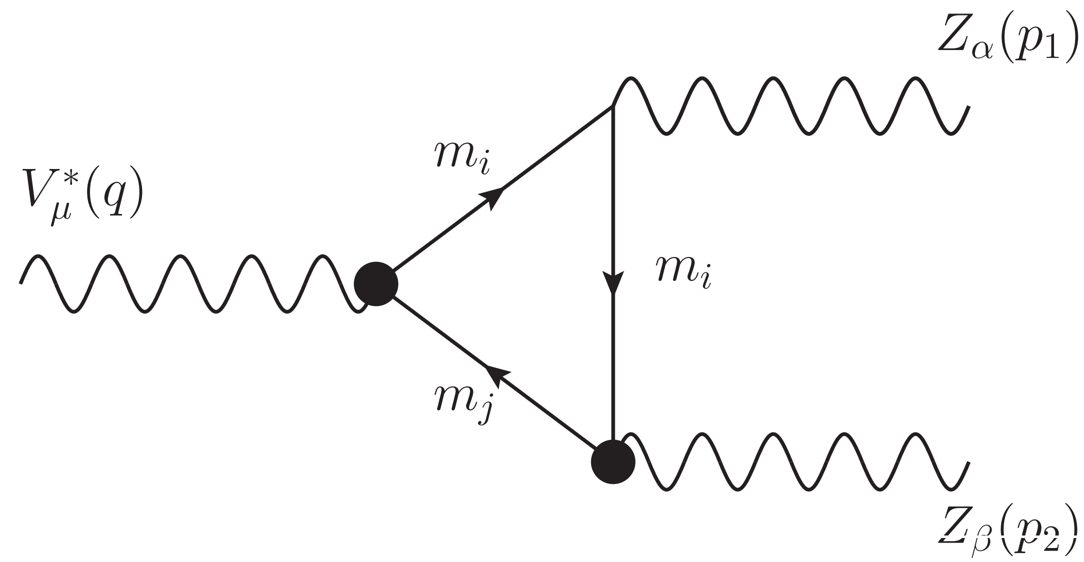
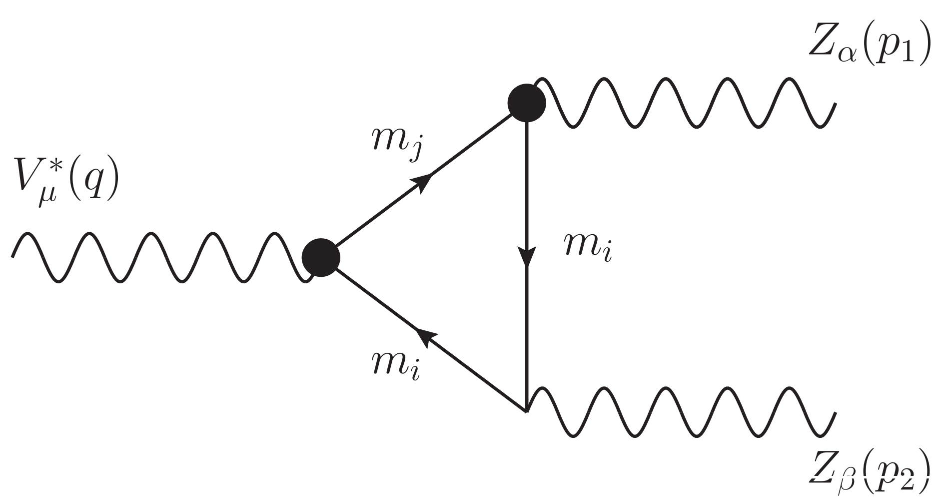
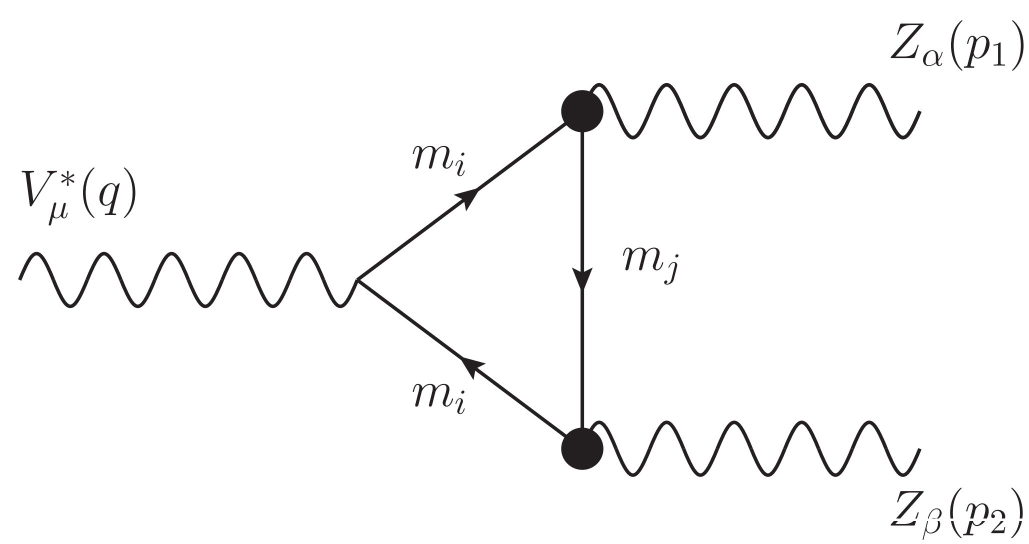


TNGBCs





In the SM, they can only exist at one loop level

ONE LOOP CONTRIBUTIONS

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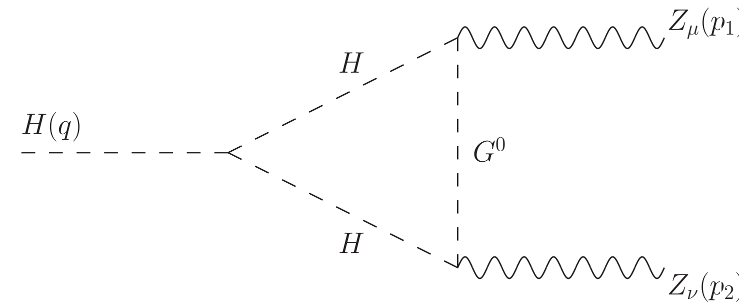
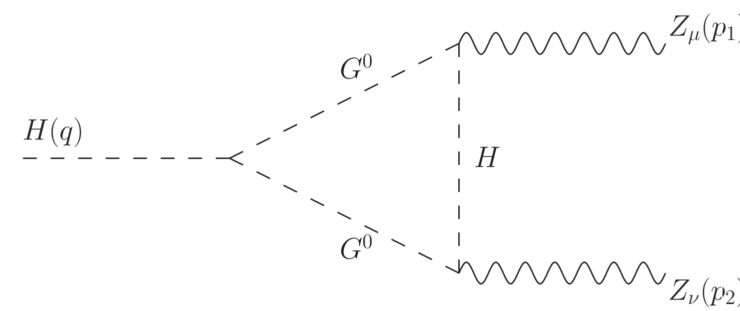
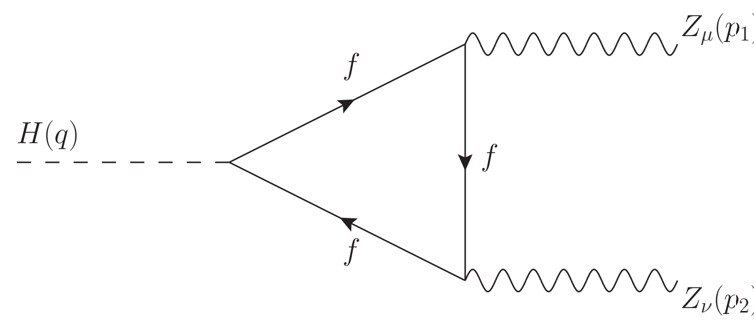
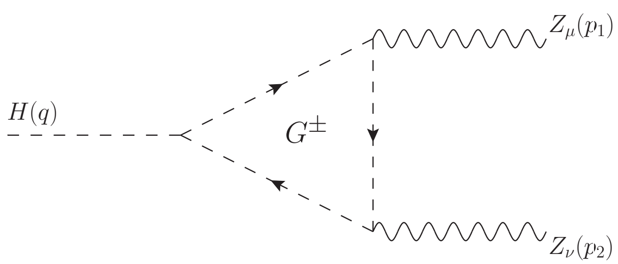
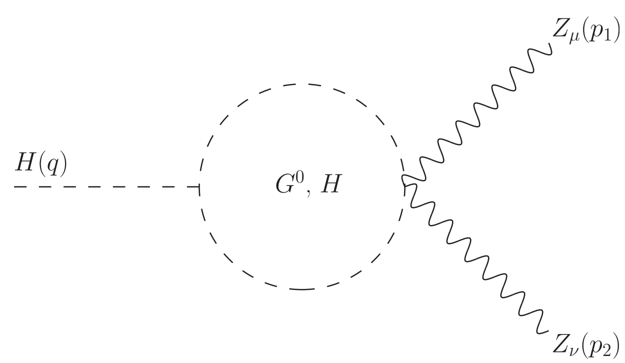
ZZH in the SM

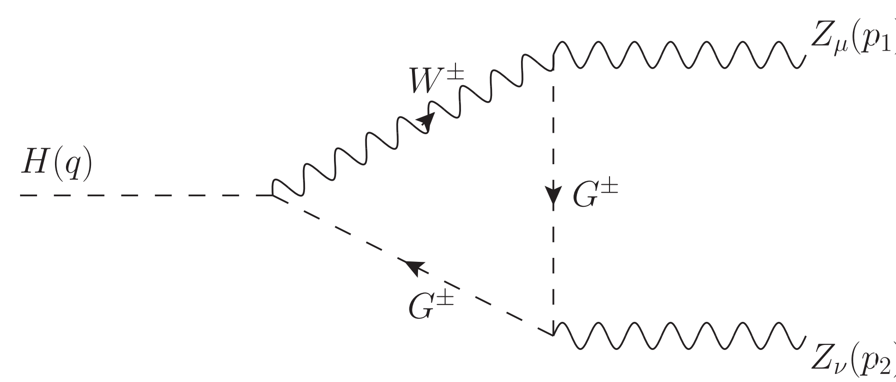


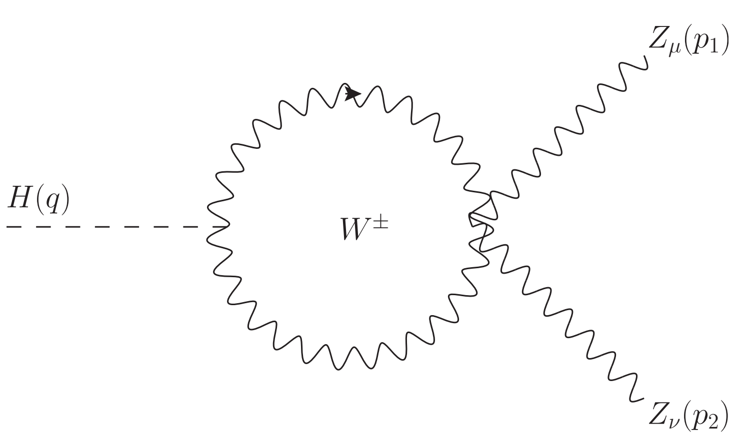


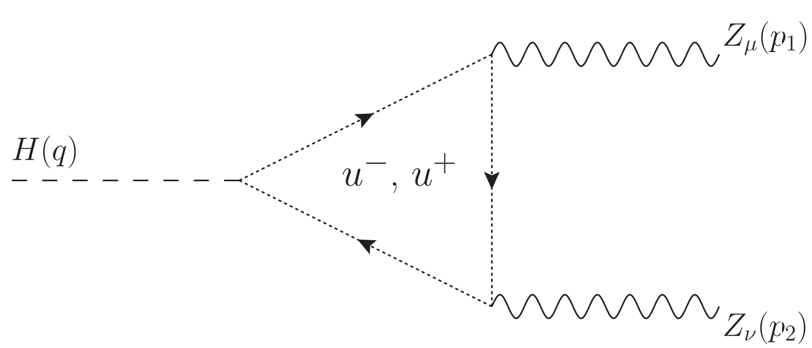


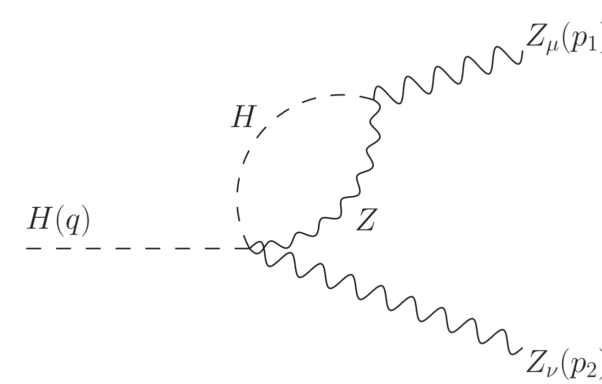












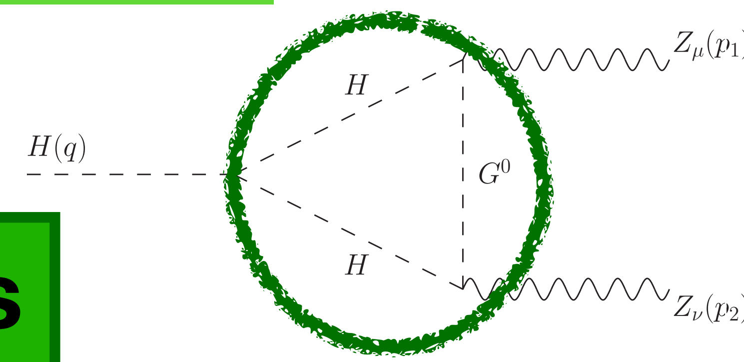
More diagrams.....

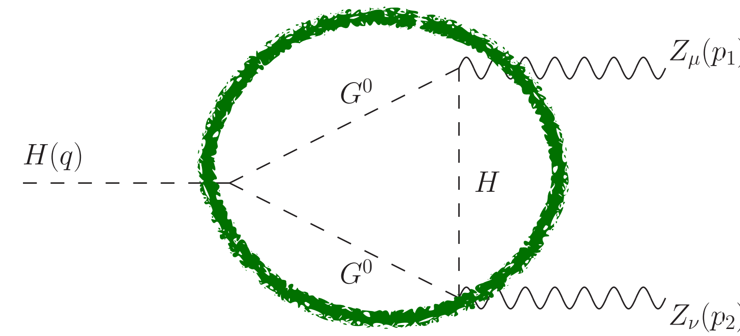
ONE LOOP CONTRIBUTIONS

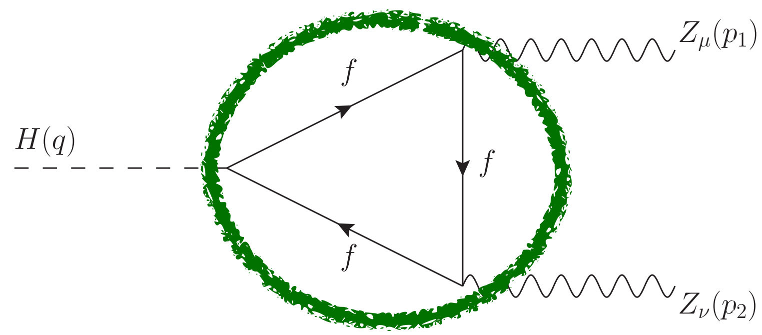
The anomalous couplings are

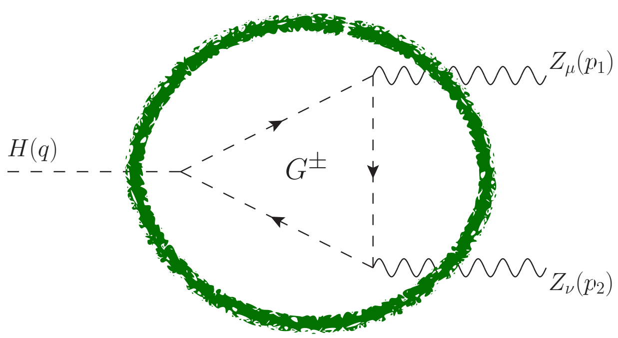
The particles in the loops are virtual

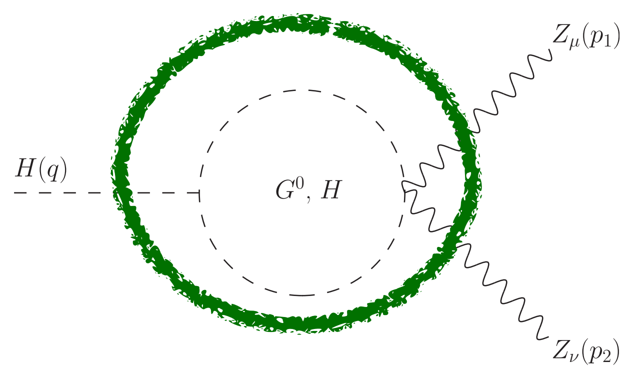
ZZH in the SM

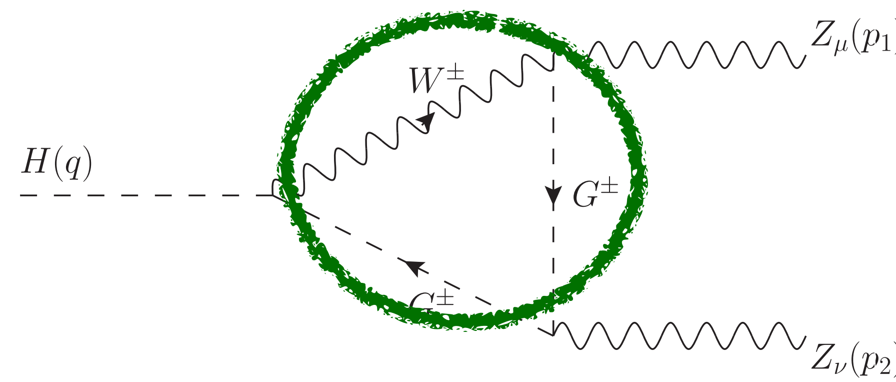


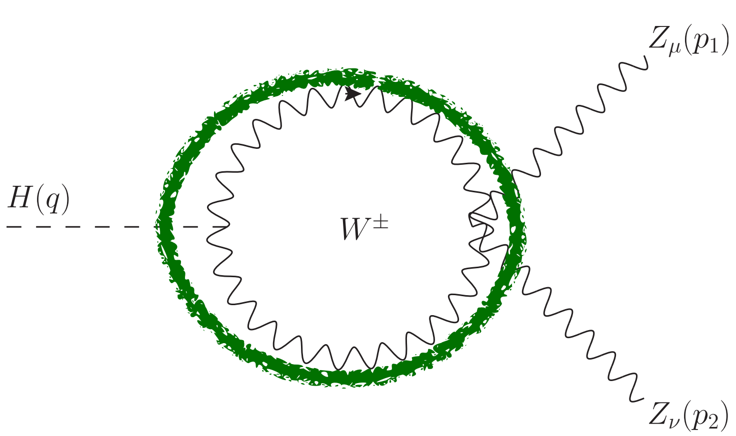


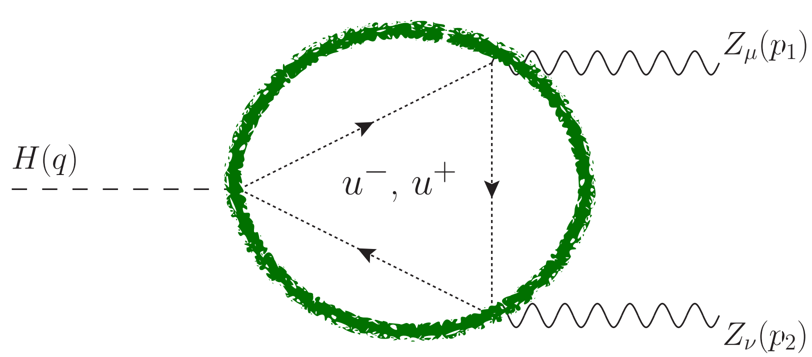


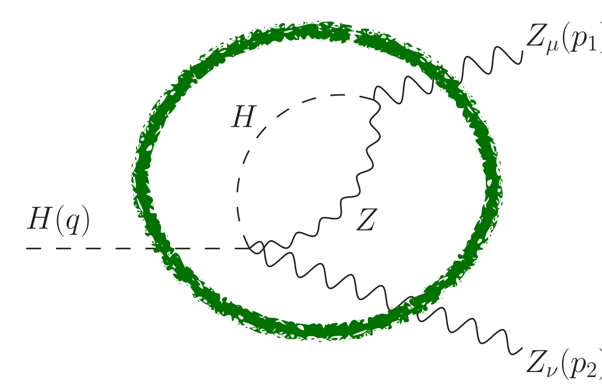












More diagrams…..

The Optical Theorem

Peskin and Schroeder. An introduction to QFT. 1995

The Optical Theorem for Feynman Diagrams

Let us now investigate how this identity for the imaginary part of an S-matrix element arises in the Feynman diagram expansion. It is easily checked (in QED, for example) that each diagram contributing to an S-matrix element $\mathcal{M}$ is purely real unless some denominators vanish, so that the $i\epsilon$ prescription for treating the poles becomes relevant. A Feynman diagram thus yields an imaginary part for $\mathcal{M}$ only when the virtual particles in the diagram go on-shell. We will now show how to isolate and compute this imaginary part.

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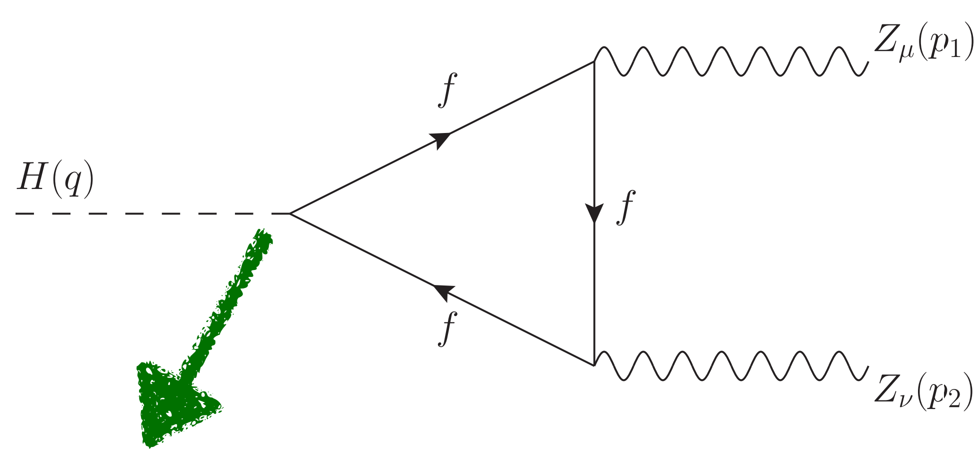

For $q \geq 2m_f$ the two fermions go on-shell

ONE LOOP CONTRIBUTIONS

Thus, the anomalous couplings may be complex

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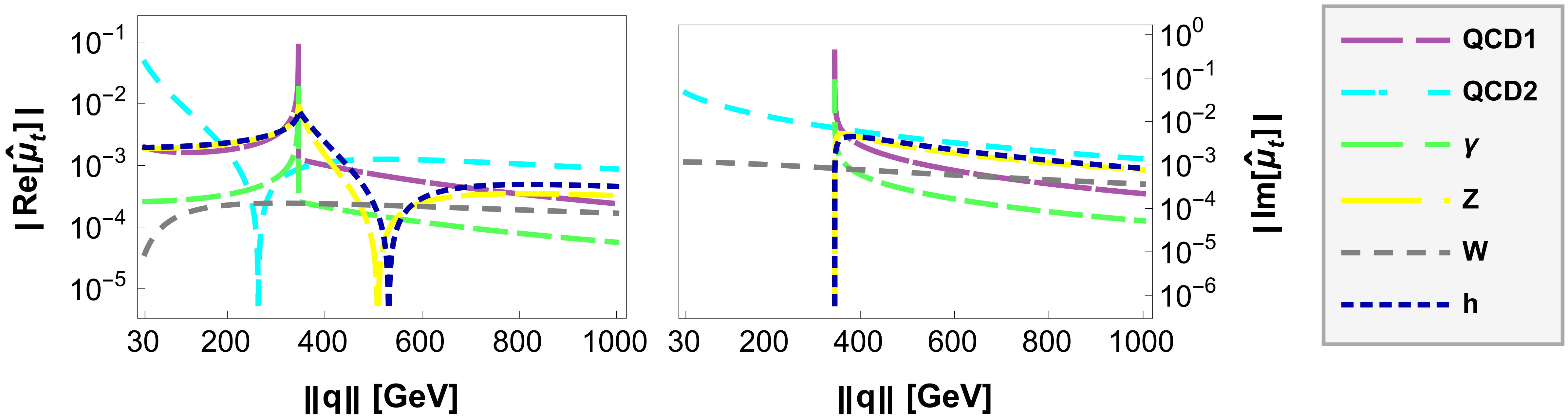
The imaginary parts are not studied at the LHC

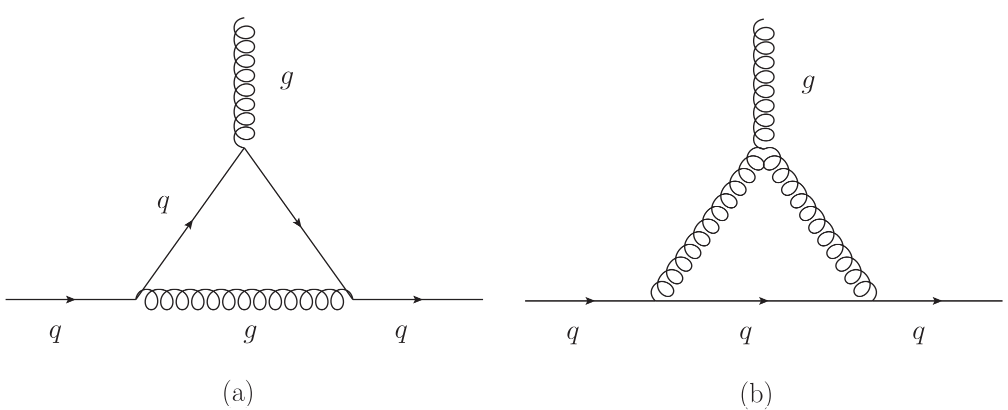
through effective ratios

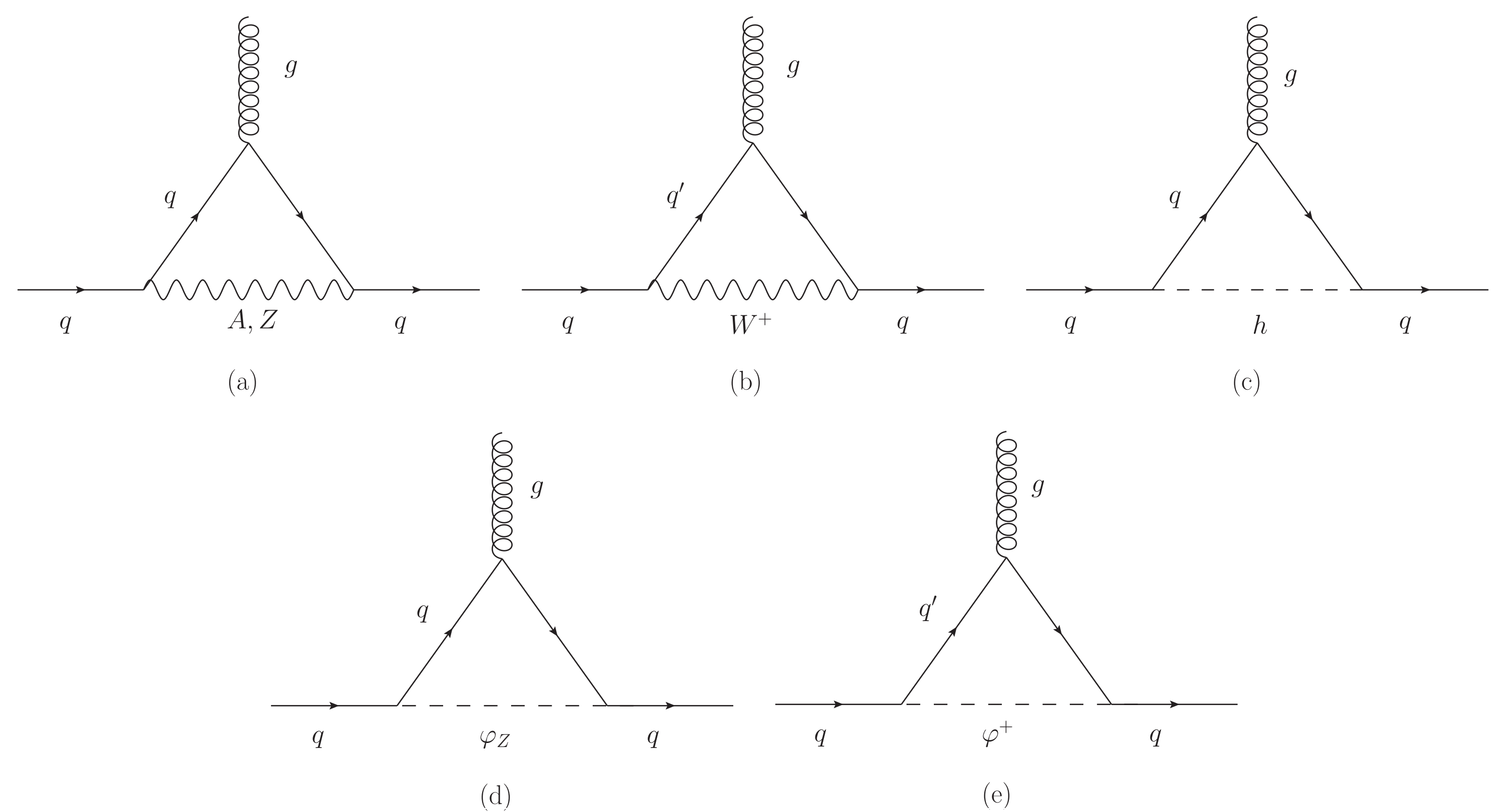
ONE LOOP CONTRIBUTIONS

Top quark CMDM in the SM numerical results

A. I. Hernández-Juárez, A. Moyotl, and G. Tavares-Velasco. New estimate of the chromagnetic dipole moment of quarks in the standard model. Eur. Phys. J. Plus, 136(2):262, 2021.

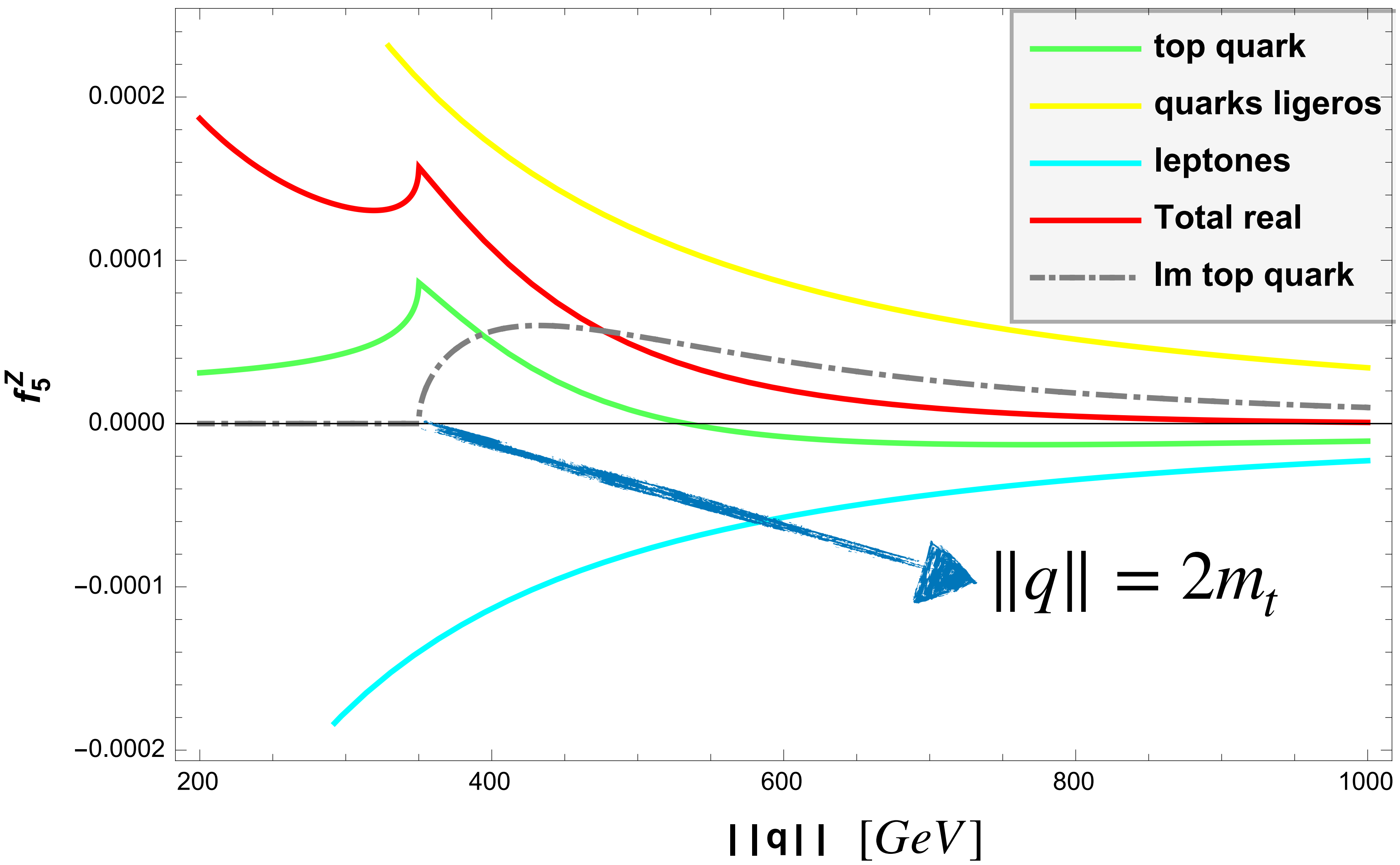






ONE LOOP CONTRIBUTIONS

TNGBCs: ZZZ^* in the SM



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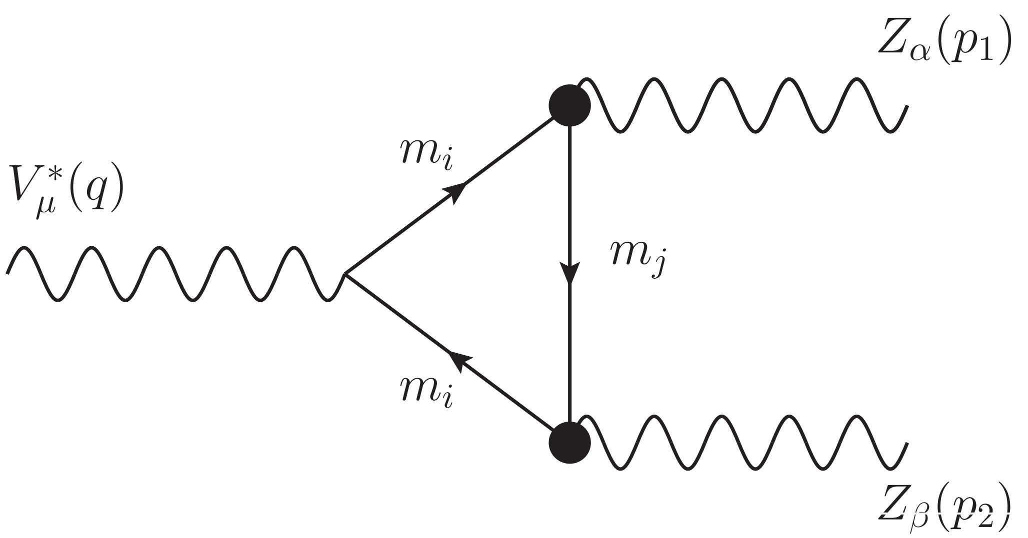
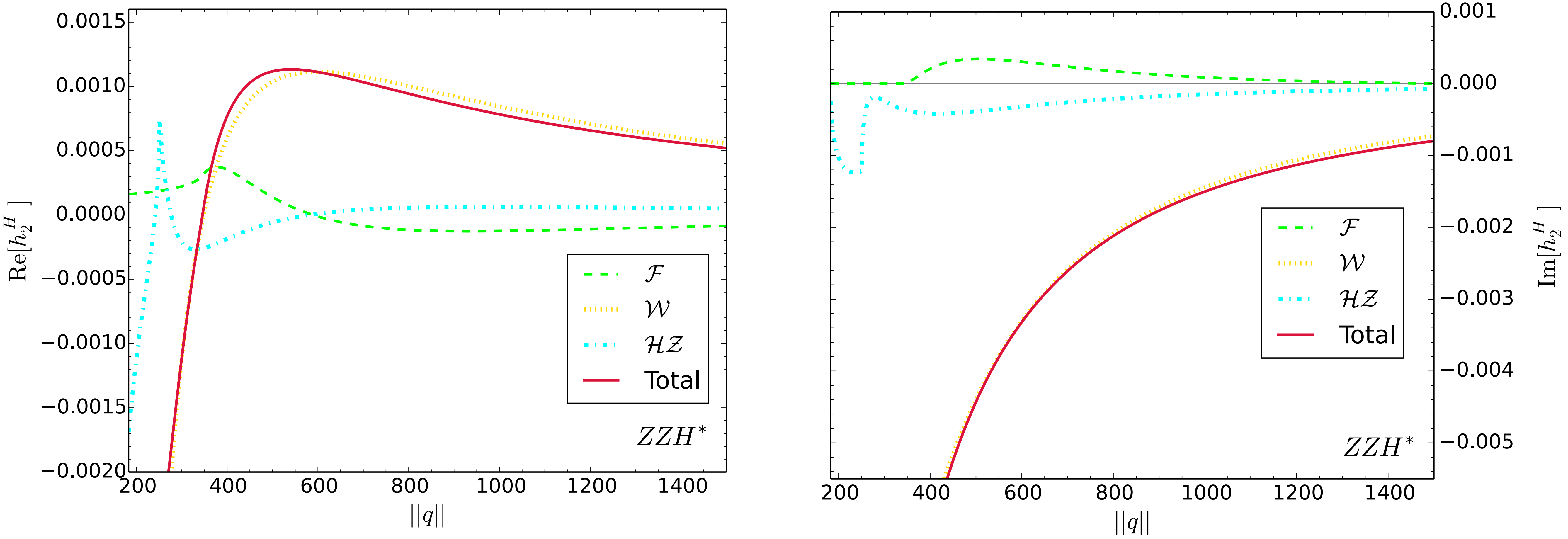


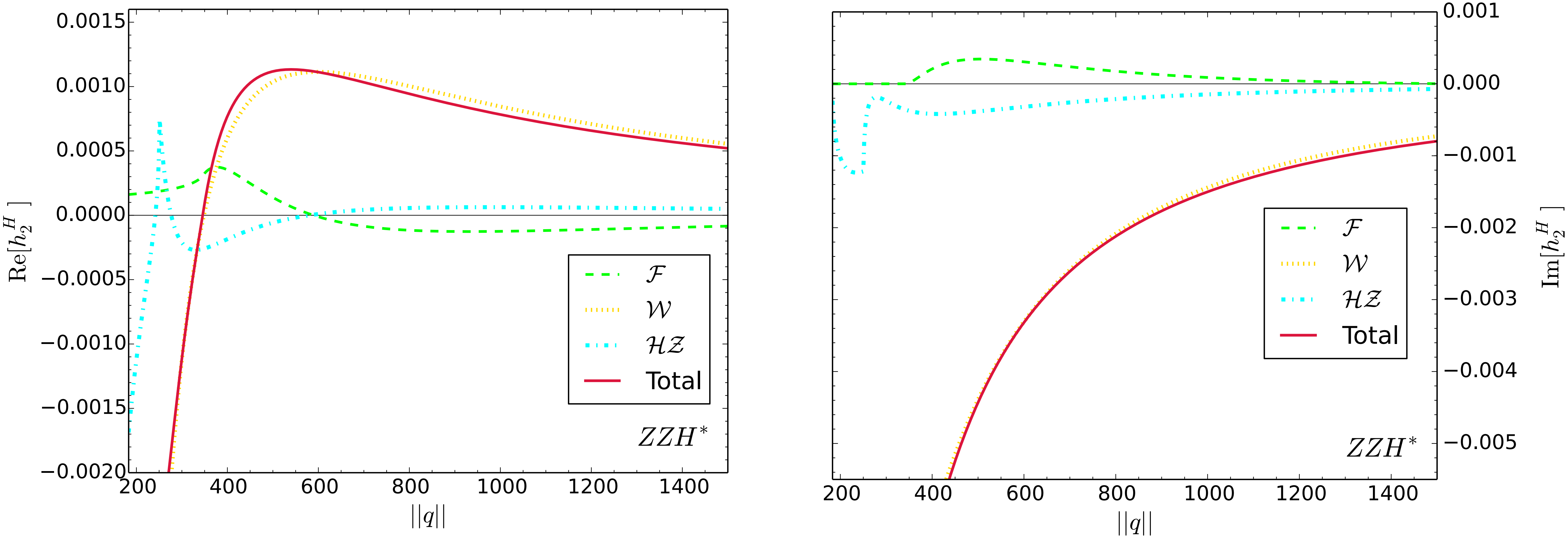
ONE LOOP CONTRIBUTIONS

ZZH^* in the SM



ONE LOOP CONTRIBUTIONS

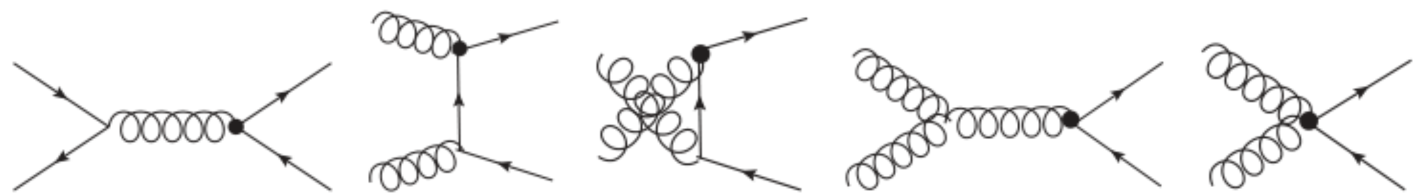
ZZH^* **in the SM**



In general, the imaginary part are of the same order of the real part

IMAGINARY CONTRIBUTIONS

The imaginary parts may be relevant and their implications not fully understand



(a) (b) (c) (d) (e)

$\sigma_{p\bar{p}\to t\bar{t}}$ **considering only real CMDM and CEDM:**

$$\frac{d\hat{\sigma}_{q\bar{q}}}{d\hat{t}} = \frac{\pi\alpha_s^2}{\hat{s}^2}\frac{8}{9}\left(\frac{1}{2} - v + z + 2\hat{\mu}'_t + (\hat{\mu}'^2_t - \hat{d}'^2_t) + (\hat{\mu}'^2_t + \hat{d}'^2_t)\frac{v}{z}\right) ,$$

$$\frac{d\hat{\sigma}_{GG}}{d\hat{t}} = \frac{\pi\alpha_s^2}{\hat{s}^2}\frac{1}{12}\Big[\left(\frac{4}{v} - 9\right)\left(\frac{1}{2} - v + 2z(1 - \frac{z}{v}) + 2\hat{\mu}'_t(1 + \hat{\mu}'_t)\right)$$
$$+ (\hat{\mu}'^2_t + \hat{d}'^2_t)\left(\frac{7}{z}(1 + 2\hat{\mu}'_t) + \frac{1}{2v}(1 - 5\hat{\mu}'_t)\right) + (\hat{\mu}'^2_t + \hat{d}'^2_t)^2\left(-\frac{1}{z} + \frac{1}{v} + \frac{4v}{z^2}\right)\Big] .$$

- P. Haberl, O. Nachtmann, and A. Wilch, Phys. Rev. D 53, 4875 (1996), hep-ph/9505409.

IMAGINARY CONTRIBUTIONS

Complex CMDM and CEDM: $\hat{\mu}_t = \mathrm{Re}[\hat{\mu}_t] + i\mathrm{Im}[\hat{\mu}_t], \quad \hat{d}_t = \mathrm{Re}[\hat{d}_t] + i\mathrm{Im}[\hat{d}_t]$

$$\frac{d\hat{\sigma}_{q\bar{q}}}{d\hat{t}} = \frac{\pi\alpha_s^2}{\hat{s}^2}\frac{8}{9}\Big[\frac{1}{2} - v + z + 2\mathrm{Re}[\hat{\mu}_t] + \Big(\mathrm{Re}[\hat{\mu}_t]^2 + \mathrm{Im}[\hat{\mu}_t]^2 - \mathrm{Re}[\hat{d}_t]^2 - \mathrm{Im}[\hat{d}_t]^2\Big) + \Big(\mathrm{Re}[\hat{\mu}_t]^2 + \mathrm{Im}[\hat{\mu}_t]^2 + \mathrm{Re}[\hat{d}_t]^2 + \mathrm{Im}[\hat{d}_t]^2\Big)\frac{v}{z}\Big],$$

$$\begin{aligned}\frac{d\hat{\sigma}_{gg}}{d\hat{t}} =& \frac{\pi\alpha_s^2}{\hat{s}^2}\frac{1}{12}\Big[\Big(\frac{4}{v} - 9\Big)\Big(\frac{1}{2} - v - 2z\big(1 - \frac{z}{v}\big) + 2\ \mathrm{Re}[\hat{\mu}_t]\Big) + \frac{1}{512vz}\Big\{v\Big(55\ \mathrm{Re}[\hat{d}_t]^2 + \mathrm{Re}[\hat{\mu}_t]^2(55 - 144z)\Big)\\
&+ z\Big(4\ \mathrm{Re}[\hat{d}_t]^2 + 70\ \mathrm{Re}[\hat{\mu}_t]^2\Big) + \frac{1}{vz}\Big\{ - 16v^3\Big(4\Big(\mathrm{Re}[\hat{\mu}_t]^2\mathrm{Im}[\hat{d}_t]^2 - 4\ \ \mathrm{Re}[\hat{\mu}_t]\ \mathrm{Im}[\hat{\mu}_t]\ \mathrm{Re}[\hat{d}_t]\ \mathrm{Im}[\hat{d}_t]\\
&+ \mathrm{Im}[\hat{\mu}_t]^2\ \mathrm{Re}[\hat{d}_t]^2\Big) + 9z\Big(\mathrm{Im}[\hat{\mu}_t]^2 + \mathrm{Im}[\hat{d}_t]^2\Big)\Big) + v^2z\Big(- 512\ \mathrm{Re}[\hat{\mu}_t]\ \mathrm{Im}[\hat{\mu}_t]\ \mathrm{Re}[\hat{d}_t]\ \mathrm{Im}[\hat{d}_t]\\
&+ \mathrm{Im}[\hat{d}_t]^2\Big(16\ \mathrm{Re}[\hat{\mu}_t]\Big(15\ \mathrm{Re}[\hat{\mu}_t] + 7\Big) + 288z + 63\Big) + 3\ \mathrm{Im}[\hat{\mu}_t]\Big(80\ \mathrm{Re}[\hat{d}_t] + 48z + 21\Big)\Big)\\
&- 2vz^2\Big(92\ \mathrm{Im}[\hat{\mu}_t]\ \mathrm{Re}[\hat{d}_t]\ \mathrm{Im}[\hat{d}_t] + \Big(1 - 8\ \mathrm{Re}[\hat{d}_t]^2\Big)\mathrm{Im}[\hat{\mu}_t]^2 + 2\ \mathrm{Im}[\hat{d}_t]^2\Big(- \mathrm{Re}[\hat{\mu}_t]\Big(4\ \mathrm{Re}[\hat{\mu}_t] + 41\Big)\\
&+ 72z + 17\Big)\Big) + 128\ \mathrm{Im}[\hat{d}_t]z^3\Big\}\Big\} + \mathrm{Re}[\hat{\mu}_t]\Big\{\mathrm{Re}[\hat{\mu}_t]^2 + \mathrm{Im}[\hat{\mu}_t]^2 + \mathrm{Re}[\hat{d}_t]\Big\}\Big\{\frac{14}{z} - \frac{5}{2v}\Big\}\\
&+ \Big\{\Big(\mathrm{Re}[\hat{\mu}_t]^2 + \mathrm{Im}[\hat{\mu}_t]^2\Big)^2 + 2\Big(\mathrm{Re}[\hat{\mu}_t]^2\ \mathrm{Re}[\hat{d}_t]^2 + \mathrm{Im}[\hat{\mu}_t]^2\ \mathrm{Im}[\hat{d}_t]^2\Big) + \Big(\mathrm{Re}[\hat{d}_t]^2 + \mathrm{Im}[\hat{d}_t]^2\Big)^2\Big\}\\
&\times\Big(- \frac{1}{z} + \frac{1}{v} + \frac{4v}{z^2}\Big)\Big],\end{aligned}$$

IMAGINARY CONTRIBUTIONS

Complex CMDM and CEDM: $\hat{\mu}_t = \mathrm{Re}\big[\hat{\mu}_t\big] + i\mathrm{Im}\big[\hat{\mu}_t\big], \quad \hat{d}_t = \mathrm{Re}\big[\hat{d}_t\big] + i\mathrm{Im}\big[\hat{d}_t\big],$

$$\frac{d\hat{\sigma}_{q\bar{q}}}{d\hat{t}} = \frac{\pi\alpha_s^2}{\hat{s}^2}\frac{8}{9}\Bigg[\frac{1}{2} - v + z + 2\mathrm{Re}\big[\hat{\mu}_t\big] + \Bigg(\mathrm{Re}\big[\hat{\mu}_t\big]^2 + \mathrm{Im}\big[\hat{\mu}_t\big]^2 - \mathrm{Re}\big[\hat{d}_t\big]^2$$

$$\ldots\big]^2\Bigg)\frac{v}{z}\Bigg],$$

More terms appear when the anomalous couplings are considered as complex explicitly

$$\begin{aligned}
\frac{d\hat{\sigma}_{gg}}{d\hat{t}} =& \frac{\pi\alpha_s^2}{\hat{s}^2}\frac{1}{12}\Bigg[\Big(\frac{4}{v} - 9\Big)\Big(\frac{1}{2} - v - 2z\big(1 - \frac{z}{v}\big) + 2\,\mathrm{Re}\big[\hat{\mu}_t\big]\Big) + \frac{1}{512vz}\Big\{v\Big(55\,\mathrm{Re}\big[\hat{d}_t\big]^2 + \mathrm{Re}\big[\hat{\mu}_t\big]^2(55 - 144z)\Big)\\
&+ z\Big(4\,\mathrm{Re}\big[\hat{d}_t\big]^2 + 70\,\mathrm{Re}\big[\hat{\mu}_t\big]^2\Big) + \frac{1}{vz}\Big\{ - 16v^3\Big(4\Big(\mathrm{Re}\big[\hat{\mu}_t\big]^2\mathrm{Im}\big[\hat{d}_t\big]^2 - 4\,\mathrm{Re}\big[\hat{\mu}_t\big]\,\mathrm{Im}\big[\hat{\mu}_t\big]\,\mathrm{Re}\big[\hat{d}_t\big]\,\mathrm{Im}\big[\hat{d}_t\big]\\
&+ \mathrm{Im}\big[\hat{\mu}_t\big]^2\,\mathrm{Re}\big[\hat{d}_t\big]^2\Big) + 9z\Big(\mathrm{Im}\big[\hat{\mu}_t\big]^2 + \mathrm{Im}\big[\hat{d}_t\big]^2\Big)\Big) + v^2z\Big(- 512\,\mathrm{Re}\big[\hat{\mu}_t\big]\,\mathrm{Im}\big[\hat{\mu}_t\big]\,\mathrm{Re}\big[\hat{d}_t\big]\,\mathrm{Im}\big[\hat{d}_t\big]\\
&+ \mathrm{Im}\big[\hat{d}_t\big]^2\Big(16\,\mathrm{Re}\big[\hat{\mu}_t\big]\Big(15\,\mathrm{Re}\big[\hat{\mu}_t\big] + 7\Big) + 288z + 63\Big) + 3\,\mathrm{Im}\big[\hat{\mu}_t\big]\Big(80\,\mathrm{Re}\big[\hat{d}_t\big] + 48z + 21\Big)\Big)\\
&- 2vz^2\Big(92\,\mathrm{Im}\big[\hat{\mu}_t\big]\,\mathrm{Re}\big[\hat{d}_t\big]\,\mathrm{Im}\big[\hat{d}_t\big] + \Big(1 - 8\,\mathrm{Re}\big[\hat{d}_t\big]^2\Big)\mathrm{Im}\big[\hat{\mu}_t\big]^2 + 2\,\mathrm{Im}\big[\hat{d}_t\big]^2\Big(- \mathrm{Re}\big[\hat{\mu}_t\big]\Big(4\,\mathrm{Re}\big[\hat{\mu}_t\big] + 41\Big)\\
&+ 72z + 17\Big)\Big) + 128\,\mathrm{Im}\big[\hat{d}_t\big]z^3\Big\}\Big\} + \mathrm{Re}\big[\hat{\mu}_t\big]\Big\{\mathrm{Re}\big[\hat{\mu}_t\big]^2 + \mathrm{Im}\big[\hat{\mu}_t\big]^2 + \mathrm{Re}\big[\hat{d}_t\big]\Big\}\Big\{\frac{14}{z} - \frac{5}{2v}\Big\}\\
&+ \Big\{\Big(\mathrm{Re}\big[\hat{\mu}_t\big]^2 + \mathrm{Im}\big[\hat{\mu}_t\big]^2\Big)^2 + 2\Big(\mathrm{Re}\big[\hat{\mu}_t\big]^2\,\mathrm{Re}\big[\hat{d}_t\big]^2 + \mathrm{Im}\big[\hat{\mu}_t\big]^2\,\mathrm{Im}\big[\hat{d}_t\big]^2\Big) + \Big(\mathrm{Re}\big[\hat{d}_t\big]^2 + \mathrm{Im}\big[\hat{d}_t\big]^2\Big)^2\Big\}\\
&\times\Big(- \frac{1}{z} + \frac{1}{v} + \frac{4v}{z^2}\Big)\Bigg],
\end{aligned}$$

IMAGINARY CONTRIBUTIONS

Complex CMDM and CEDM: $\hat{\mu}_t = \mathrm{Re}[\hat{\mu}_t] + i\mathrm{Im}[\hat{\mu}_t], \quad \hat{d}_t = \mathrm{Re}[\hat{d}_t] + i\mathrm{Im}[\hat{d}_t]$

$$\frac{d\hat{\sigma}_{q\bar{q}}}{d\hat{t}} = \frac{\pi\alpha_s^2}{\hat{s}^2}\frac{8}{9}\Big[\frac{1}{2} - v + z + 2\mathrm{Re}[\hat{\mu}_t] + \Big(\mathrm{Re}[\hat{\mu}_t]^2 + \mathrm{Im}[\hat{\mu}_t]^2 - \mathrm{Re}[\hat{d}_t]^2$$

$$\ldots]^2\Big)\frac{v}{z}\Big],$$

More terms appear when the anomalous couplings are considered as complex explicitly

$$\frac{d\hat{\sigma}_{gg}}{d\hat{t}} = \frac{\pi\alpha_s^2}{\hat{s}^2}\frac{1}{12}\Big[\Big(\frac{4}{v} - 9\Big)\Big(\frac{1}{2} - v - 2z(1 - \frac{z}{v}) + 2\ \mathrm{Re}[\hat{\mu}_t]\Big) + \frac{1}{512vz}\Big\{v\Big(55\ \mathrm{Re}[\hat{d}_t]^2 + \mathrm{Re}[\hat{\mu}_t]^2(55 - 144z)\Big)$$

$$+ z\Big(4\ \mathrm{Re}[\hat{d}_t]^2 + 70\ \mathrm{Re}[\hat{\mu}_t]^2\Big) + \frac{1}{vz}\Big\{ - 16v^3\Big(4\Big(\mathrm{Re}[\hat{\mu}_t]^2\mathrm{Im}[\hat{d}_t]^2 - 4\ \ \mathrm{Re}[\hat{\mu}_t]\ \mathrm{Im}[\hat{\mu}_t]\ \mathrm{Re}[\hat{d}_t]\ \mathrm{Im}[\hat{d}_t]$$

$$\ldots [\hat{d}_t]$$

Effects of the imaginary parts may have been neglected in classical calculations

$$- 2vz^2\Big(92\ \mathrm{Im}[\hat{\mu}_t]\ \mathrm{Re}[\hat{d}_t]\ \mathrm{Im}[\hat{d}_t] + \Big(1 - 8\ \mathrm{Re}[\hat{d}_t]^2\Big)\mathrm{Im}[\hat{\mu}_t]^2 + 2\ \mathrm{Im}[\hat{d}_t]^2\Big(- \mathrm{Re}[\hat{\mu}_t]\Big(4\ \mathrm{Re}[\hat{\mu}_t] + 41$$

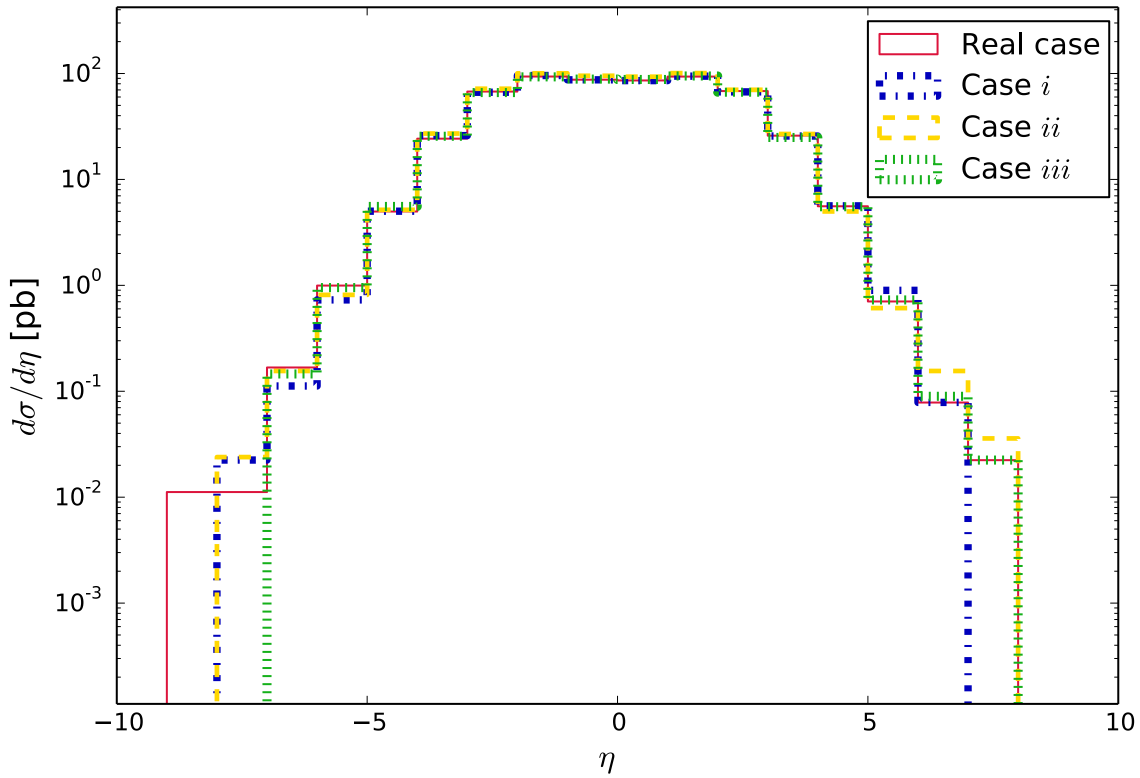
$$+ 72z + 17\Big)\Big) + 128\ \mathrm{Im}[\hat{d}_t]z^3\Big\}\Big\} + \mathrm{Re}[\hat{\mu}_t]\Big\{\mathrm{Re}[\hat{\mu}_t]^2 + \mathrm{Im}[\hat{\mu}_t]^2 + \mathrm{Re}[\hat{d}_t]\Big\}\Big\{\frac{14}{z} - \frac{5}{2v}\Big\}$$

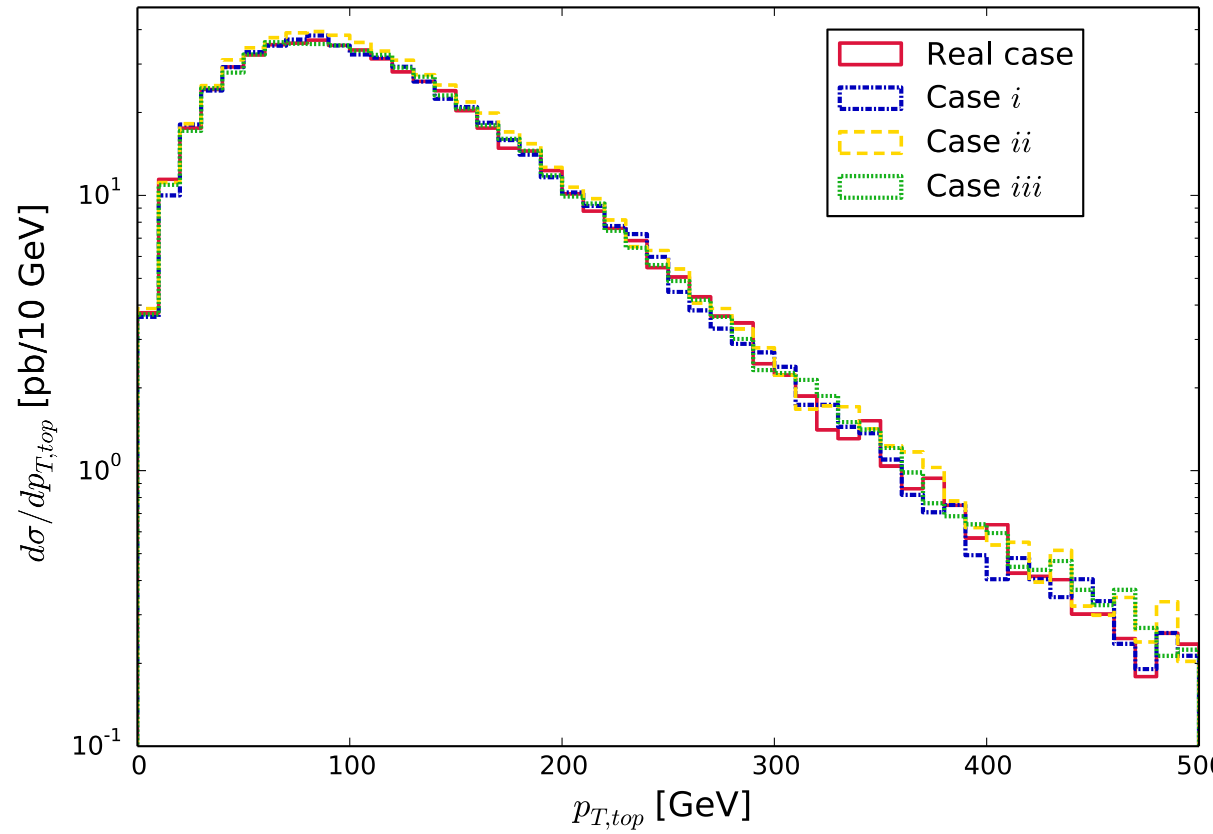
$$+ \Big\{\Big(\mathrm{Re}[\hat{\mu}_t]^2 + \mathrm{Im}[\hat{\mu}_t]^2\Big)^2 + 2\Big(\mathrm{Re}[\hat{\mu}_t]^2\ \mathrm{Re}[\hat{d}_t]^2 + \mathrm{Im}[\hat{\mu}_t]^2\ \mathrm{Im}[\hat{d}_t]^2\Big) + \Big(\mathrm{Re}[\hat{d}_t]^2 + \mathrm{Im}[\hat{d}_t]^2\Big)^2\Big\}$$

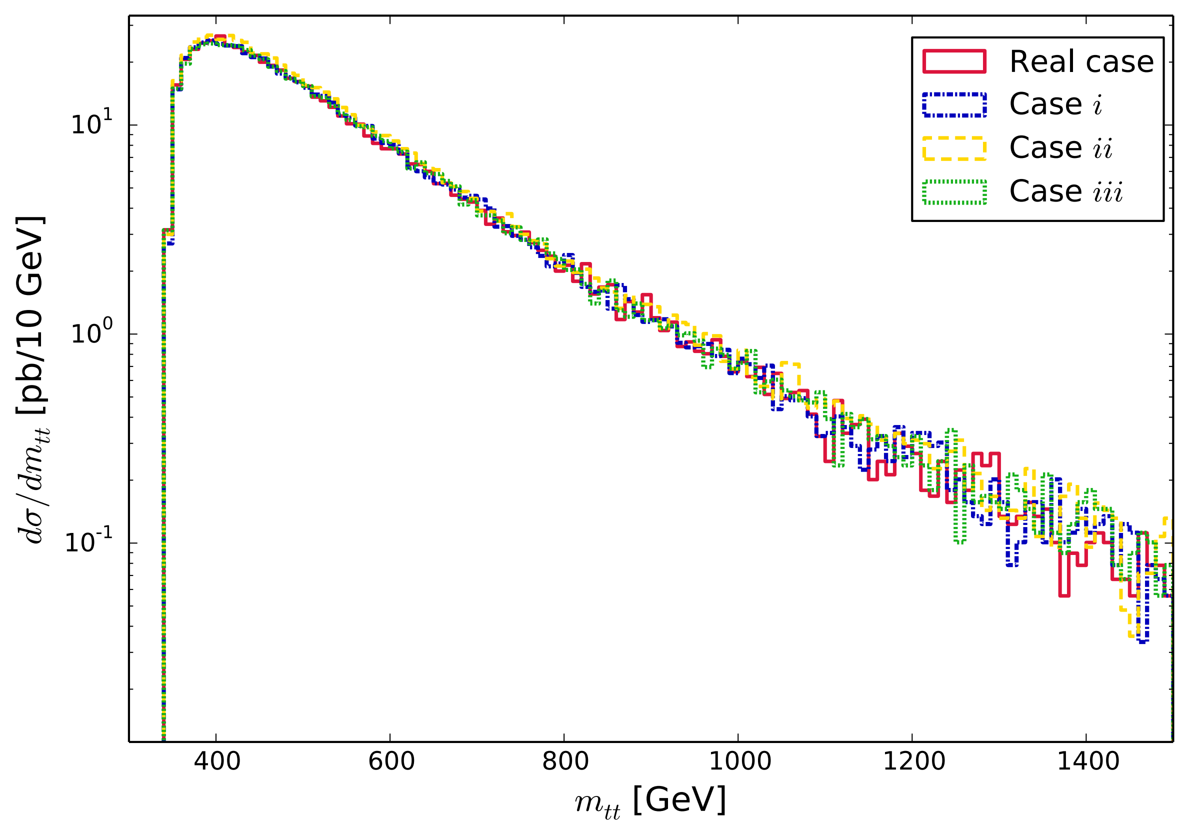
$$\times\Big(- \frac{1}{z} + \frac{1}{v} + \frac{4v}{z^2}\Big)\Big],$$

IMAGINARY CONTRIBUTIONS

The effects of the imaginary parts of the top quark CMDM and CEDM are not visible in $\sigma_{p\bar{p}\rightarrow t\bar{t}}$







A. I. Hernández-Juárez, A. Moyotl, and G. Tavares-Velasco. Bounds on the absorptive parts of the chromomagnetic and chromoelectric dipole moments of the top quark from LHC data. Eur. Phys. J. Plus, 137:925, 2022.

IMAGINARY CONTRIBUTIONS

Off-shell particles in “decays”

$$gg \to H^* \to ZZ \to 4l$$

Complex mass scheme:

$$\frac{1}{q^2 - m_H^2 - i m_H \Gamma_H} \longrightarrow \frac{1}{q^2 - \mu_H^2 - i \mu_H \gamma_H}$$

μ_H is an input parameter similar to the on-shell mass and γ_H can be the on-shell total width

$$q\bar{q} \to Z^* \to ZH$$

For off-shell gauge bosons an extra polarization must be considered

IMAGINARY CONTRIBUTIONS

We study the process:

$$gg \to H^* \to ZZ \to 4l$$

IMAGINARY CONTRIBUTIONS

We study the process:

$$gg \to H^* \to ZZ \to 4l$$

$$\Gamma_{H^* \to ZZ}$$

IMAGINARY CONTRIBUTIONS

We study the process:

$$gg \rightarrow H^* \rightarrow ZZ \rightarrow 4l$$

$$\Gamma_{H^* \rightarrow ZZ}$$

We considere the anomalous couplings as complex

$$h_i^V = \mathrm{Re}[h_i^V] + i\mathrm{Im}[h_i^V]$$

IMAGINARY CONTRIBUTIONS

We study the process:

$$gg \to H^* \to ZZ \to 4l$$

$$\Gamma_{H^* \to ZZ}$$

We considere the anomalous couplings as complex

$$h_i^V = \mathrm{Re}[h_i^V] + i\mathrm{Im}[h_i^V]$$

We do not find relevant deviations from the case with only real anomalous couplings

IMAGINARY CONTRIBUTIONS

We study the process:

$$gg \to H^* \to ZZ \to 4l$$

$$\Gamma_{H^* \to Z_+ Z_+} + \Gamma_{H^* \to Z_- Z_-} + \Gamma_{H^* \to Z_0 Z_0}$$

IMAGINARY CONTRIBUTIONS

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$$h_i^V = \mathrm{Re}[h_i^V] + i\mathrm{Im}[h_i^V]$$

The $\Gamma_{HZ_{\pm,0}Z_{\pm,0}}$ increases 4%-30% for different energies of q if we include the imaginary parts

IMAGINARY CONTRIBUTIONS

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The $\Gamma_{HZ_{\pm,0}Z_{\pm,0}}$ increases 4%-30% for different energies of q if we include the imaginary parts

The imaginary parts seem to be relevant

IMAGINARY CONTRIBUTIONS

$$\Gamma^{ZZH}_{\mu\nu} = h_1^V g_{\mu\nu} + \frac{h_2^V}{m_Z^2} p_{1\nu} p_{2\mu} + \frac{h_3^V}{m_Z^2} \epsilon_{\mu\nu\alpha\beta} p_1^\alpha p_2^\beta,$$

We considere the anomalous couplings as complex

$$h_i^V = \mathrm{Re}[h_i^V] + i\mathrm{Im}[h_i^V]$$

IMAGINARY CONTRIBUTIONS

$$\Gamma_{\mu\nu}^{ZZH} = h_1^V g_{\mu\nu} + \frac{h_2^V}{m_Z^2} p_{1\nu} p_{2\mu} + \frac{h_3^V}{m_Z^2} \epsilon_{\mu\nu\alpha\beta} p_1^\alpha p_2^\beta,$$

We considere the anomalous couplings as complex

$$h_i^V = \mathrm{Re}[h_i^V] + i\mathrm{Im}[h_i^V]$$

Asymmetry

$$\mathrm{A}_{+-} = \frac{\Gamma_{H^* \to Z_+ Z_+} - \Gamma_{H^* \to Z_- Z_-}}{\Gamma_{H^* \to Z_+ Z_+} + \Gamma_{H^* \to Z_- Z_-}}$$

IMAGINARY CONTRIBUTIONS

$$\Gamma^{ZZH}_{\mu\nu} = h_1^V g_{\mu\nu} + \frac{h_2^V}{m_Z^2} p_{1\nu} p_{2\mu} + \frac{h_3^V}{m_Z^2} \epsilon_{\mu\nu\alpha\beta} p_1^\alpha p_2^\beta,$$

We considere the anomalous couplings as complex

$$h_i^V = \mathrm{Re}[h_i^V] + i\mathrm{Im}[h_i^V]$$

Asymmetry

$$\mathrm{A}_{+-} \sim \mathrm{Re}[h_1^H]\mathrm{Im}[h_3^H] - \mathrm{Re}[h_3^H]\mathrm{Im}[h_1^H]$$

IMAGINARY CONTRIBUTIONS

$$\Gamma^{ZZH}_{\mu\nu} = h_1^V g_{\mu\nu} + \frac{h_2^V}{m_Z^2} p_{1\nu} p_{2\mu} + \frac{h_3^V}{m_Z^2} \epsilon_{\mu\nu\alpha\beta} p_1^\alpha p_2^\beta,$$

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$$\mathrm{A}_{+-} \sim \mathrm{Re}[h_1^H]\mathrm{Im}[h_3^H] - \mathrm{Re}[h_3^H]\mathrm{Im}[h_1^H] \longrightarrow \mathrm{A}_{+-} = 0$$ **in the SM**

IMAGINARY CONTRIBUTIONS

$$\Gamma^{ZZH}_{\mu\nu} = h_1^V g_{\mu\nu} + \frac{h_2^V}{m_Z^2} p_{1\nu} p_{2\mu} + \frac{h_3^V}{m_Z^2} \epsilon_{\mu\nu\alpha\beta} p_1^\alpha p_2^\beta,$$

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CP-violation

IMAGINARY CONTRIBUTIONS

$$\Gamma^{ZZH}_{\mu\nu} = h_1^V g_{\mu\nu} + \frac{h_2^V}{m_Z^2} p_{1\nu} p_{2\mu} + \frac{h_3^V}{m_Z^2} \epsilon_{\mu\nu\alpha\beta} p_1^\alpha p_2^\beta,$$

We considere the anomalous couplings as complex

$$h_i^V = \mathrm{Re}[h_i^V] + i\mathrm{Im}[h_i^V]$$

Asymmetry

Complex form

$$\mathrm{A}_{+-} \sim \mathrm{Re}[h_1^H]\mathrm{Im}[h_3^H] - \mathrm{Re}[h_3^H]\mathrm{Im}[h_1^H] \longrightarrow \mathrm{A}_{+-} = 0$$ **in the SM**

CP-violation

IMAGINARY CONTRIBUTIONS

$$\Gamma^{ZZH}_{\mu\nu} = h_1^V g_{\mu\nu} + \frac{h_2^V}{m_Z^2} p_{1\nu} p_{2\mu} + \frac{h_3^V}{m_Z^2} \epsilon_{\mu\nu\alpha\beta} p_1^\alpha p_2^\beta,$$

We considere the anomalous couplings as complex

$$h_i^V = \mathrm{Re}[h_i^V] + i\mathrm{Im}[h_i^V]$$

Asymmetry

Complex form

$$\mathrm{A}_{+-} \sim \mathrm{Re}[h_1^H]\mathrm{Im}[h_3^H] - \mathrm{Re}[h_3^H]\mathrm{Im}[h_1^H] \longrightarrow \mathrm{A}_{+-} = 0 \text{ in the SM}$$

CP-violation

To obtain $\mathrm{A}_{+-} \neq 0$ it is necessary CP-violation and complex anomalous couplings

$$gg \to H^* \to ZZ \to 4l$$

Summary

- Complex anomalous couplings can be obtained from off-shell couplings.
- The imaginary parts may be relevant in some process and may be not well-understood.
- Polarizations of gauge bosons may be sensitive to the imaginary part and also to CP-violation.
- There are any processes where the imaginary parts have not been studied: $e^-e^+ \to Z^*(\gamma^*) \to ZZ \to 4l$

¡Gracias!