Asymmetries in $H^* \to 4\ell$ *decays*

RADPyC 2023

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MOTIVATION

H* evidence at the LHC

nature physics

ARTICLES

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Check for updates

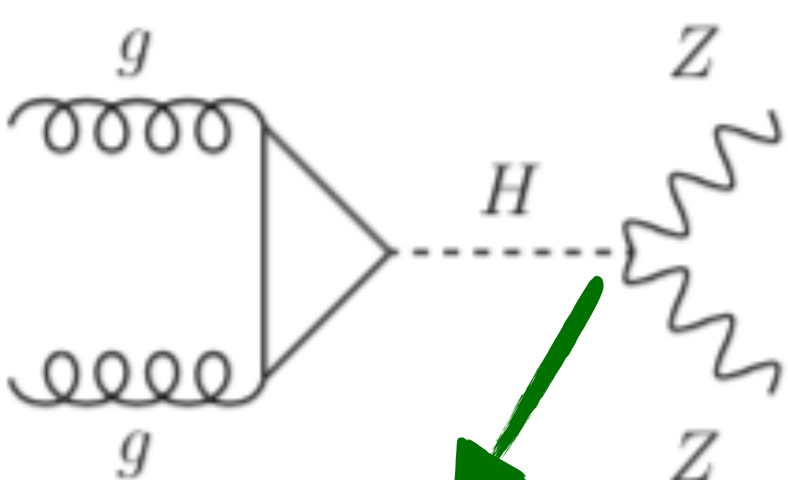
OPEN

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

The CMS Collaboration*✉

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**



$$m_H < 2m_Z$$

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

H* evidence at the LHC

Submitted to: Phys. Lett. B.

CERN-EP-2023-03
5th April 2023

Evidence of off-shell Higgs boson production from ZZ leptonic decay channels and constraints on its total width with the ATLAS detector

The ATLAS Collaboration

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**

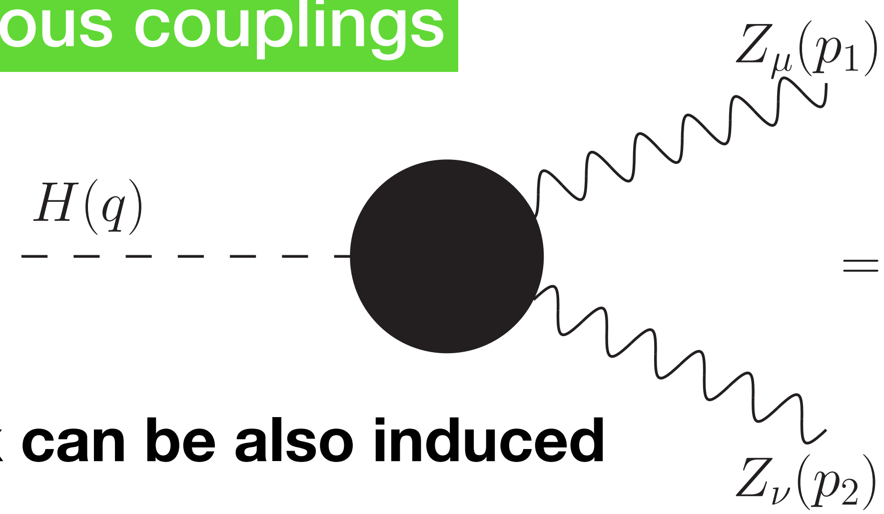
The obtained results are compatible with those from the CMS experiment. The evidence of off-shell Higgs boson production is now strongly established, with constraints placed on the relevant parameters.

$$m_H < 2m_Z$$

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

Anomalous couplings

Vertex functions



$$= i\frac{g}{c_W} m_Z \Gamma^{ZZH}_{\mu\nu}(p_1^2, p_2^2, q^2)$$

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:

$$h_1(q^2, p_1^2, p_2^2) = 1 + a_Z - \hat{b}_Z \frac{q^2 - p_1^2 - p_2^2}{m_Z^2} + \frac{\hat{c}_Z}{2} \frac{p_1^2 + p_2^2}{m_Z^2},$$

$$h_2(q^2, p_1^2, p_2^2) = \pm 2\hat{b}_Z,$$

$$h_3(q^2, p_1^2, p_2^2) = \pm 2\widetilde{b}_Z.$$

Bounds on the anomalous couplings:

Indirect bounds through effective ratios

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}	$\Gamma_H = \Gamma_H^{SM}$	$[-46, 107]$
	Γ_H unconstrained	$[-46, 110]$
f_{Λ_1}	$\Gamma_H = \Gamma_H^{SM}$	$[-11, 46]$
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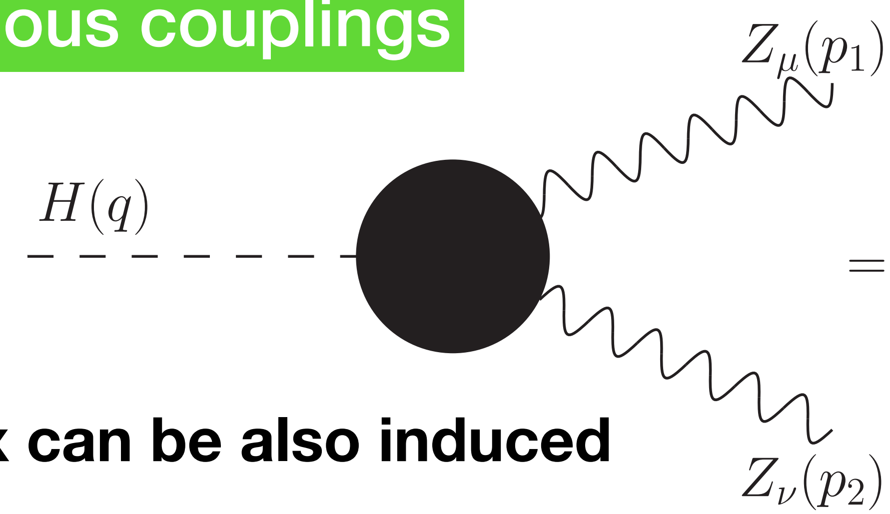
A. A. Tumasyan et al. (CMS), Measurement of the Higgs boson width and evidence of its off-shell contributions to ZZ production, Nature Phys. 18, 1329 (2022)

Anomalous couplings

Vertex functions



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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.

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Phys. 18, 1329 (2022)

Anomalous couplings

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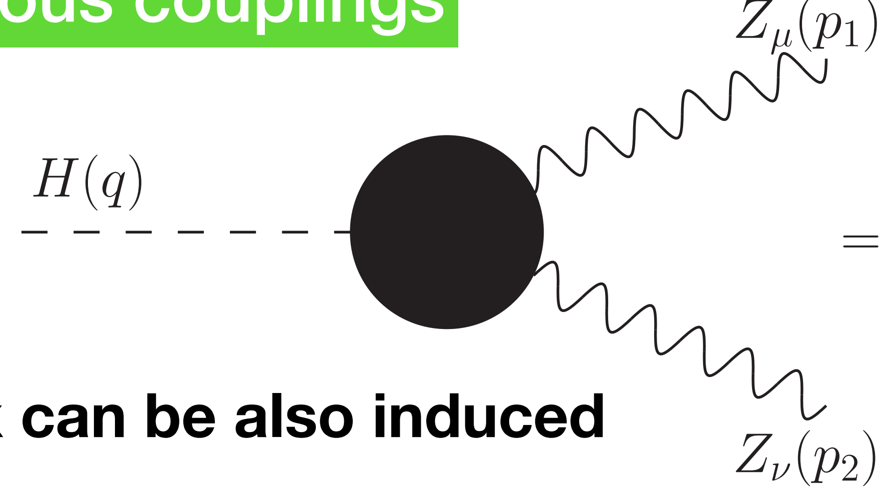

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CP-violating

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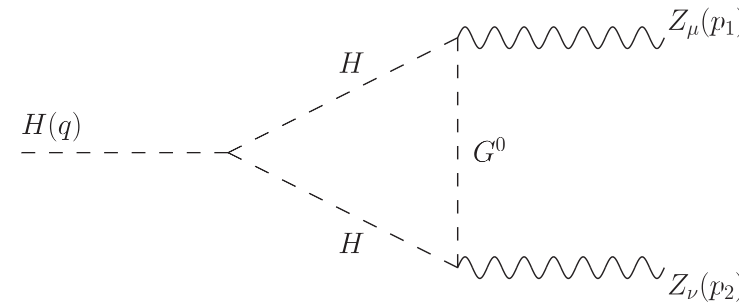
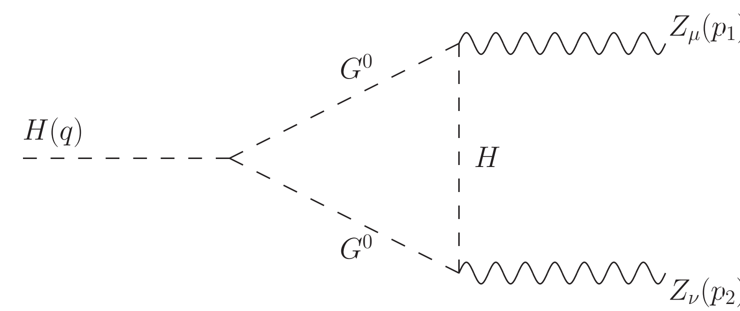
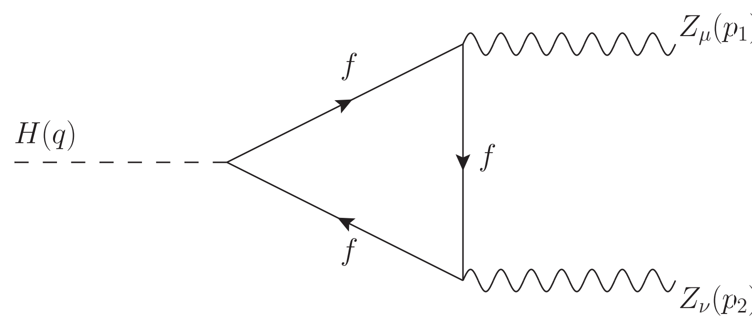
ONE LOOP CONTRIBUTIONS

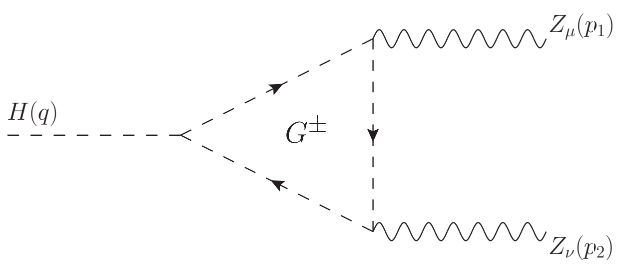
The anomalous couplings are induced at one loop level (or more)

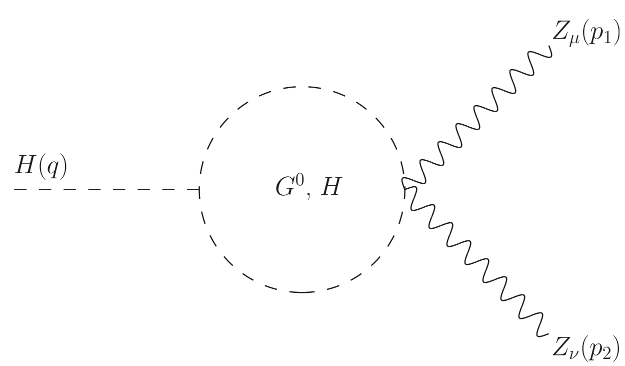


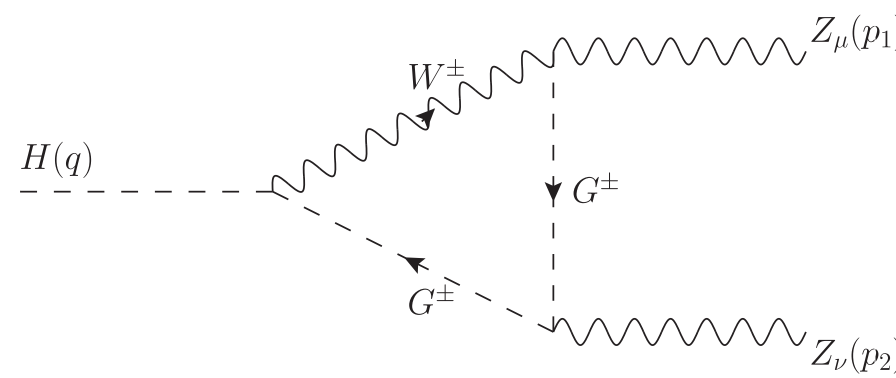
ZZH in the SM

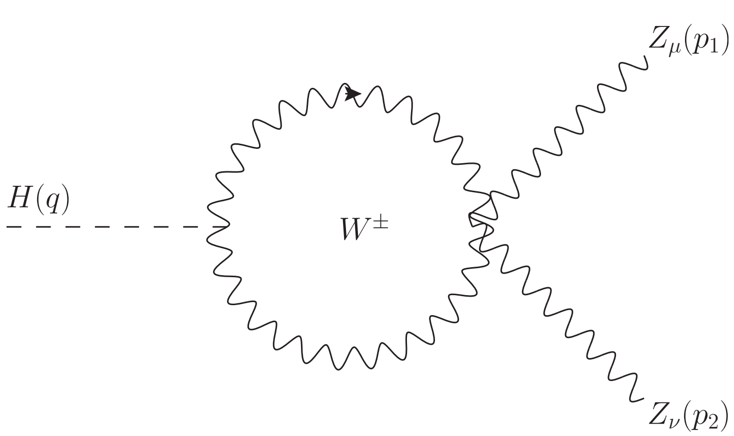


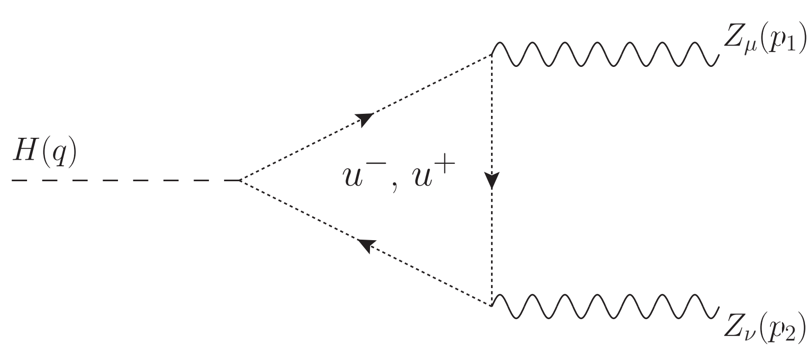


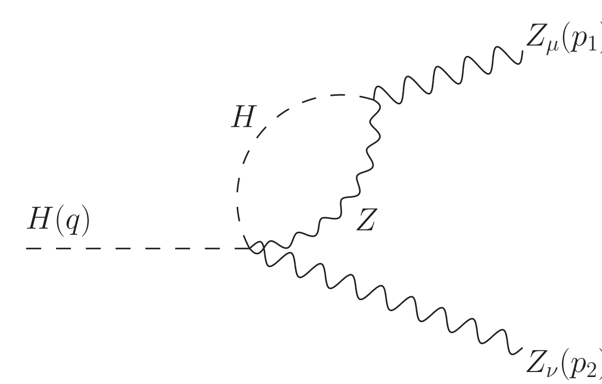










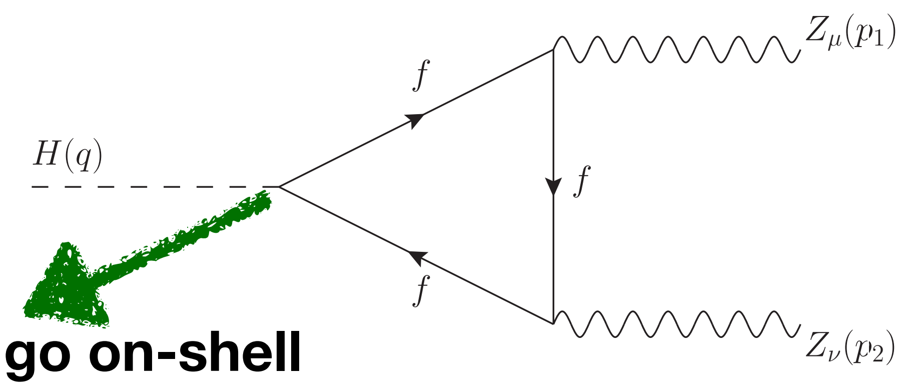


More diagrams.....

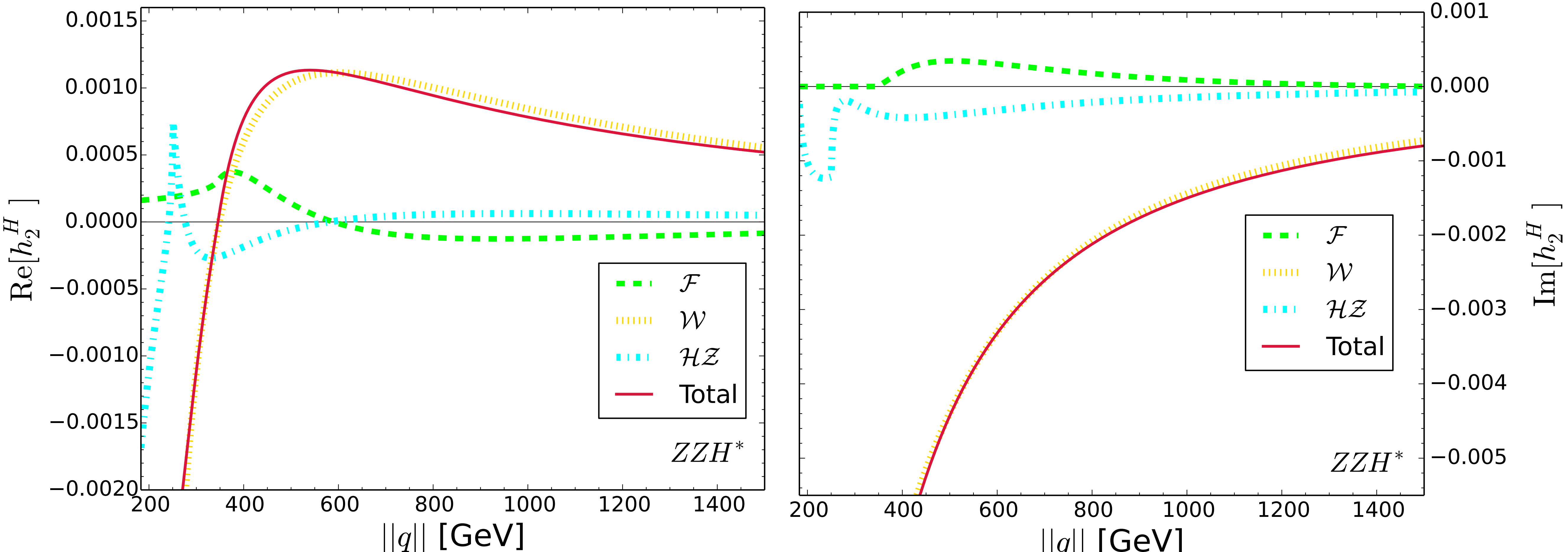
ONE LOOP CONTRIBUTIONS

ZZH^* in the SM

A. I. Hernández-Juárez, G. Tavares-Velasco, and A. Fernández-Téllez,, arXiv:2301.13127. Accepted for publication in PRD.



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



One-loop contributions to the real (left plot) and absorptive (right plot) parts of the form factor h_2^H as functions of the Higgs boson transfer momentum $||q||$: fermion ($\mathscr{F}$), W gauge boson ($\mathscr{W}$), $H-Z$ bosons ($\mathscr{H}\mathscr{Z}$) and total contributions.

ONE LOOP CONTRIBUTIONS

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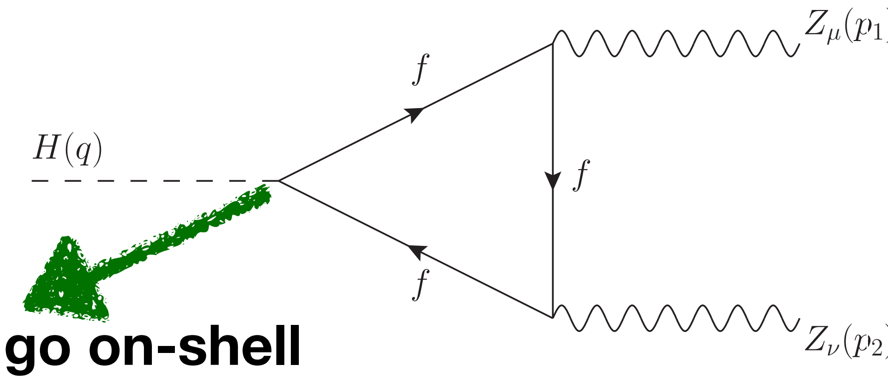

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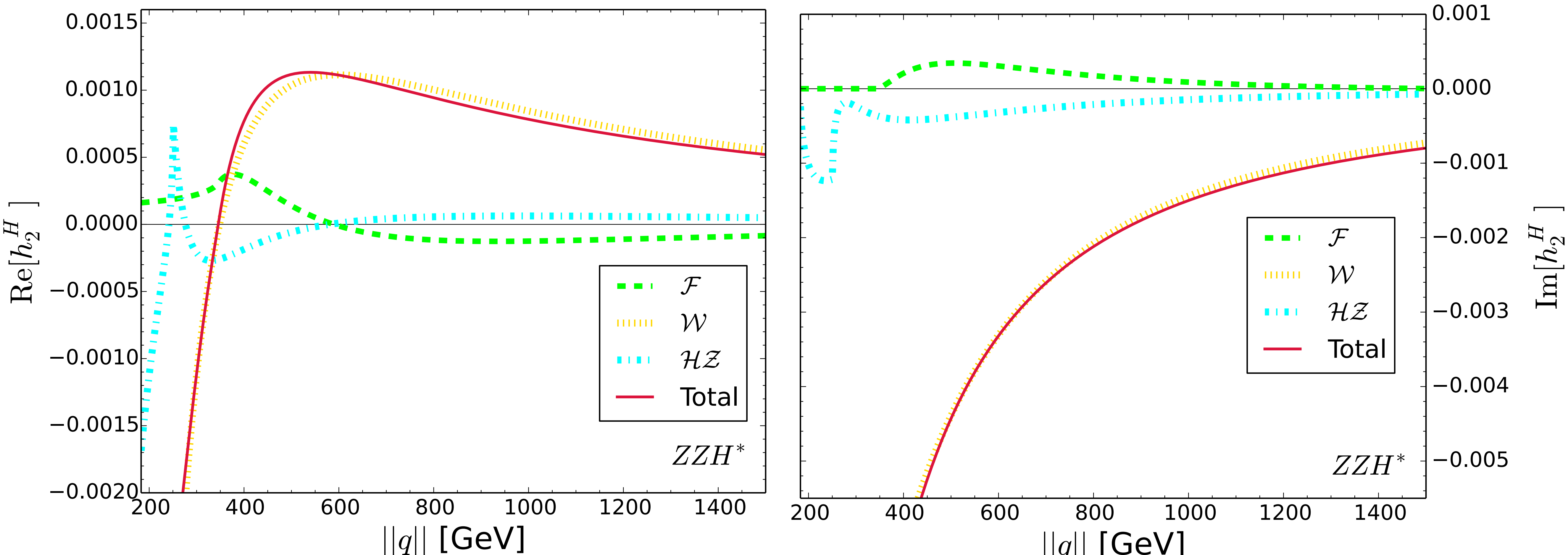

One-loop con[…]actor h_2^H as functions of the Higgs b[…]sons ($\mathscr{H}\mathscr{Z}$) and total contributions

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

BOUNDS ON ANOMALOUS COUPLINGS

A. I. Hernández-Juárez, G. Tavares-Velasco, and A. Fernández-Téllez,, arXiv:2301.13127. Accepted for publication in PRD.

Allowed intervals of the real and absorptive parts of the CP-violating form factor of the H^*ZZ coupling for a few values of the transfer momentum:

$\|\|q\|\|$	$\mathrm{Re}[a_3^{ZZ}]$	$\mathrm{Re}[\tilde{b}_Z]$	$\mathrm{Re}[\tilde{c}_{zz}]$	$\mathrm{Im}[a_3^{ZZ}]$	$\mathrm{Im}[\tilde{b}_Z]$	$\mathrm{Im}[\tilde{c}_{zz}]$
190	$[-0.024, 0.009]$	$[-0.0045, 0.012]$	$[-0.033, 0.088]$	$[-0.026, 0.01]$	$[-0.005, 0.013]$	$[-0.037, 0.096]$
285	$[-0.0029, 0.0011]$	$[-0.00055, 0.0014]$	$[-0.004, 0.01]$	$[-0.018, 0.0069]$	$[-0.0034, 0.009]$	$[-0.025, 0.066]$
400	$[-0.00053, 0.0014]$	$[-0.0007, 0.00026]$	$[-0.0051, 0.0019]$	$[-0.012, 0.0044]$	$[-0.0022, 0.006]$	$[-0.016, 0.044]$
800	$[-0.00069, 0.0018]$	$[-0.0009, 0.00034]$	$[-0.0066, 0.0025]$	$[-0.0039, 0.0015]$	$[-0.00075, 0.0019]$	$[-0.0055, 0.014]$
1500	$[-0.00036, 0.00095]$	$[-0.00047, 0.00018]$	$[-0.0034, 0.0013]$	$[-0.0015, 0.00057]$	$[-0.00028, 0.00075]$	$[-0.002, 0.0055]$

$\|\|q\|\|$	$\mathrm{Re}[k_1^{ZZ}]$ $(\mathrm{Re}[\hat{c}_Z])$	$\mathrm{Re}[c_{z\Box}]$	$\mathrm{Im}[k_1^{ZZ}]$ $(\mathrm{Im}[\hat{c}_Z])$	$\mathrm{Im}[c_{z\Box}]$
190	$[-0.0024, 0.0046]$	$[-0.0058, 0.011]$	$[-0.0026, 0.005]$	$[-0.0063, 0.012]$
285	$[-0.00028, 0.00055]$	$[-0.00068, 0.0013]$	$[-0.0018, 0.0035]$	$[-0.0043, 0.0085]$
400	$[-0.00027, 0.00014]$	$[-0.00065, 0.00034]$	$[-0.0012, 0.0023]$	$[-0.0029, 0.0055]$
800	$[-0.00034, 0.00017]$	$[-0.00082, 0.00041]$	$[-0.00038, 0.00075]$	$[-0.00092, 0.0018]$
1500	$[-0.00019, 0.0001]$	$[-0.00046, 0.00024]$	$[-0.00015, 0.00029]$	$[-0.00036, 0.0007]$

IMAGINARY CONTRIBUTIONS

We study the process:

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

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

We considere the anomalous couplings as complex

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

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Asymmetry

$$\mathscr{A}_{LR} = \frac{\Gamma_{H^* \to Z_L Z_L} - \Gamma_{H^* \to Z_R Z_R}}{\Gamma_{H^* \to Z_L Z_L} + \Gamma_{H^* \to Z_R Z_R}}$$

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$$\mathscr{A}_{LR} = \frac{4m_Z^2\|q\|\sqrt{q^2-4m_Z^2}\left(\mathrm{Re}\left[h_1^H\right]\mathrm{Im}\left[h_3^H\right]-\mathrm{Re}\left[h_3^H\right]\mathrm{Im}\left[h_1^H\right]\right)}{q^2\left(q^2-4m_Z^2\right)\left(\mathrm{Re}\left[h_3^H\right]^2+\mathrm{Im}\left[h_3^H\right]^2\right)+4m_Z^4\left(\mathrm{Im}\left[h_1^H\right]^2+\mathrm{Re}\left[h_1^H\right]^2\right)}$$

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Asymmetry

CP-violation

$$\mathscr{A}_{LR} = \frac{4m_Z^2\|q\|\sqrt{q^2-4m_Z^2}\left(\mathrm{Re}\left[h_1^H\right]\mathrm{Im}\left[h_3^H\right] - \mathrm{Re}\left[h_3^H\right]\mathrm{Im}\left[h_1^H\right]\right)}{q^2\left(q^2-4m_Z^2\right)\left(\mathrm{Re}\left[h_3^H\right]^2+\mathrm{Im}\left[h_3^H\right]^2\right)+4m_Z^4\left(\mathrm{Im}\left[h_1^H\right]^2+\mathrm{Re}\left[h_1^H\right]^2\right)}$$

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Imaginary parts

IMAGINARY CONTRIBUTIONS

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

To induce a non-zero asymmetry 2 elements are required

1. **CP-violation**
2. **Complex anomalous couplings**

Asymmetry **CP-violation**

$$\mathscr{A}_{LR} = \frac{4m_Z^2 \|q\| \sqrt{q^2 - 4m_Z^2} \left(\mathrm{Re}\left[h_1^H\right] \mathrm{Im}\left[h_3^H\right] - \mathrm{Re}\left[h_3^H\right] \mathrm{Im}\left[h_1^H\right] \right)}{q^2 \left(q^2 - 4m_Z^2\right) \left(\mathrm{Re}\left[h_3^H\right]^2 + \mathrm{Im}\left[h_3^H\right]^2 \right) + 4m_Z^4 \left(\mathrm{Im}\left[h_1^H\right]^2 + \mathrm{Re}\left[h_1^H\right]^2 \right)}$$

Imaginary parts

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$\mathscr{A}_{LR} = 0$ **at tree-level the SM**

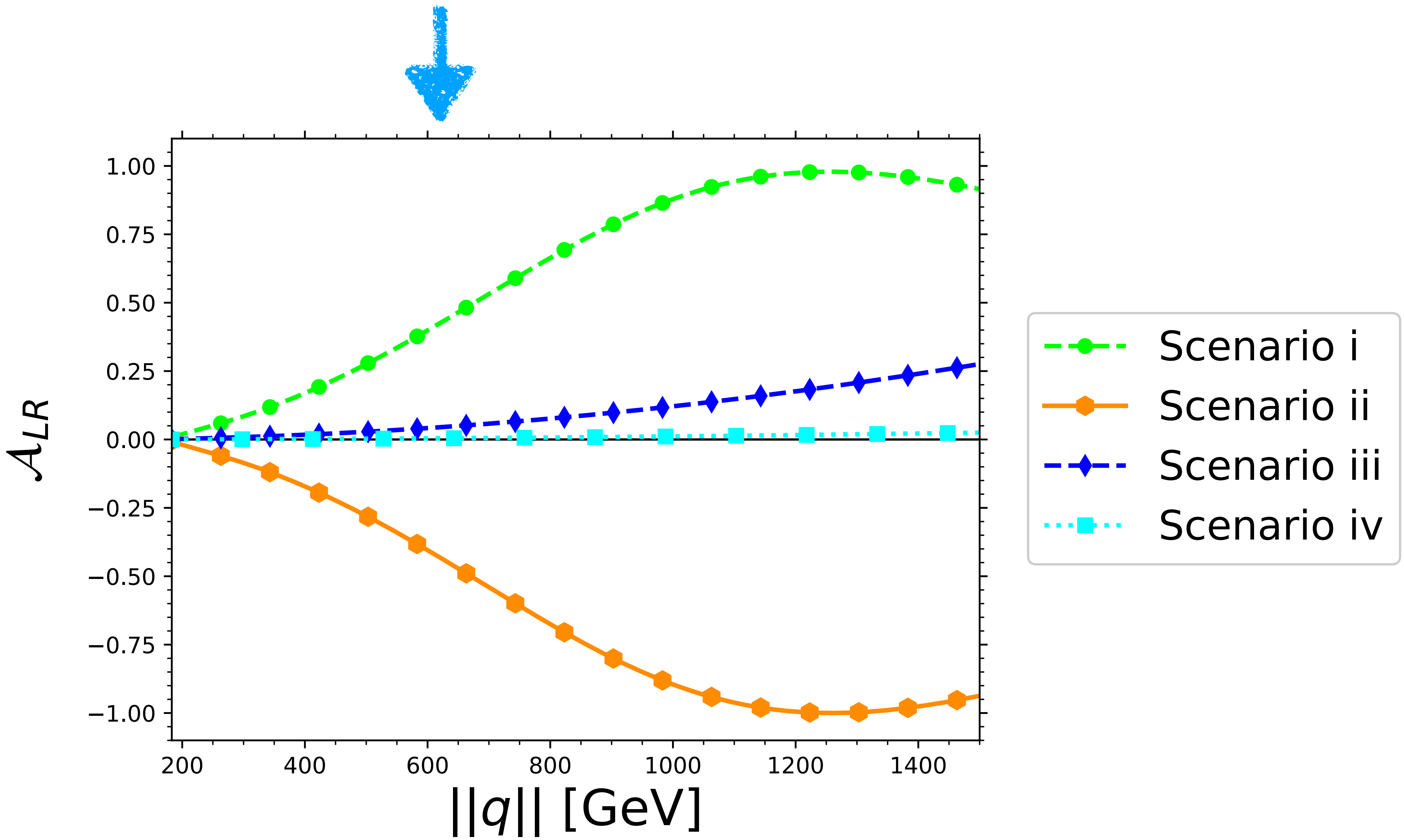
A. Soni and R. M. Xu, Probing CP violation via Higgs decays to four leptons, Phys. Rev. D 48, 5259 (1993).

The CP-violating form factor h_3^H is supposed to be induced at three-loop level in the SM, with a value of the order of 10^{-11}.

$$\mathscr{A}_{LR}^{SM} \approx 10^{-8} - 10^{-9}.$$

IMAGINARY CONTRIBUTIONS

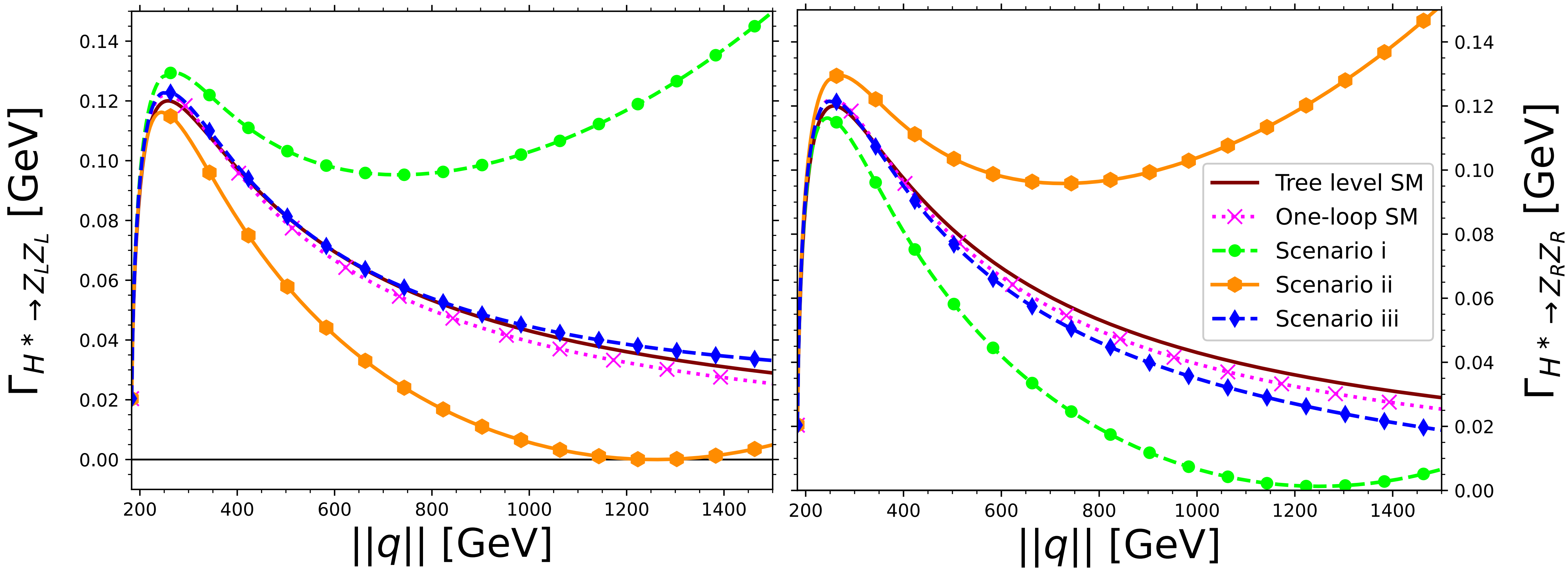
$$\mathscr{A}_{LR} = \frac{4m_Z^2\|q\|\sqrt{q^2 - 4m_Z^2}\left(\mathrm{Re}\left[h_1^H\right]\mathrm{Im}\left[h_3^H\right] - \mathrm{Re}\left[h_3^H\right]\mathrm{Im}\left[h_1^H\right]\right)}{q^2\left(q^2 - 4m_Z^2\right)\left(\mathrm{Re}\left[h_3^H\right]^2 + \mathrm{Im}\left[h_3^H\right]^2\right) + 4m_Z^4\left(\mathrm{Im}\left[h_1^H\right]^2 + \mathrm{Re}\left[h_1^H\right]^2\right)}$$



$\mathscr{A}_{LR}$ asymmetry as a function of the transfer momentum of the Higgs boson $\|q\|$.

IMAGINARY CONTRIBUTIONS

$$\Gamma_{H^* \to Z_L Z_L}, \Gamma_{H^* \to Z_R Z_R}$$

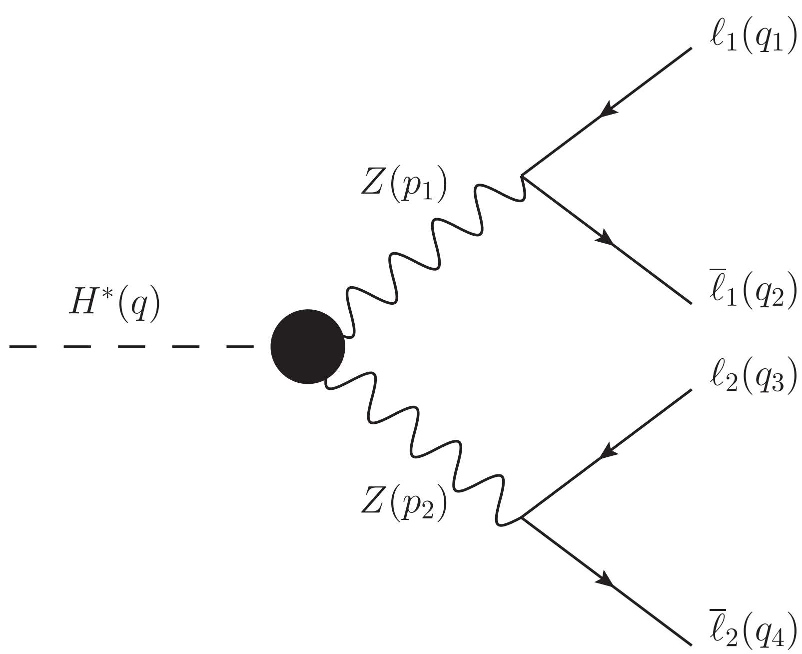


Partial decay widths of the processes $H^* \to Z_L Z_L / Z_R Z_R$ as functions of the Higgs boson transfer momentum $\|q\|$.

IMAGINARY CONTRIBUTIONS

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

We expect to observe $\mathscr{A}_{LR}$ effects in the $4l$ final state.



The same space phase to the discussed in previously (see C.S. Kim and Juan Márquez talks)

$$\frac{d\Gamma_{H^* \to ZZ \to 2\ell_1 2\ell_2}}{ds_1 ds_2 d\theta_1 d\theta_2 d\phi} \to \frac{d\Gamma_{H^* \to ZZ \to 2\ell_1 2\ell_2}}{dM_{4\ell}}$$

IMAGINARY CONTRIBUTIONS

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

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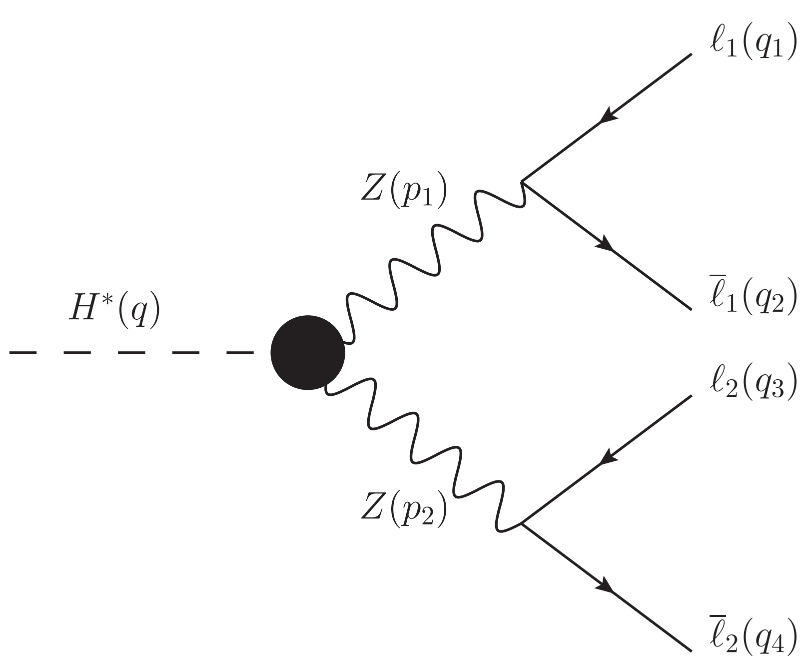


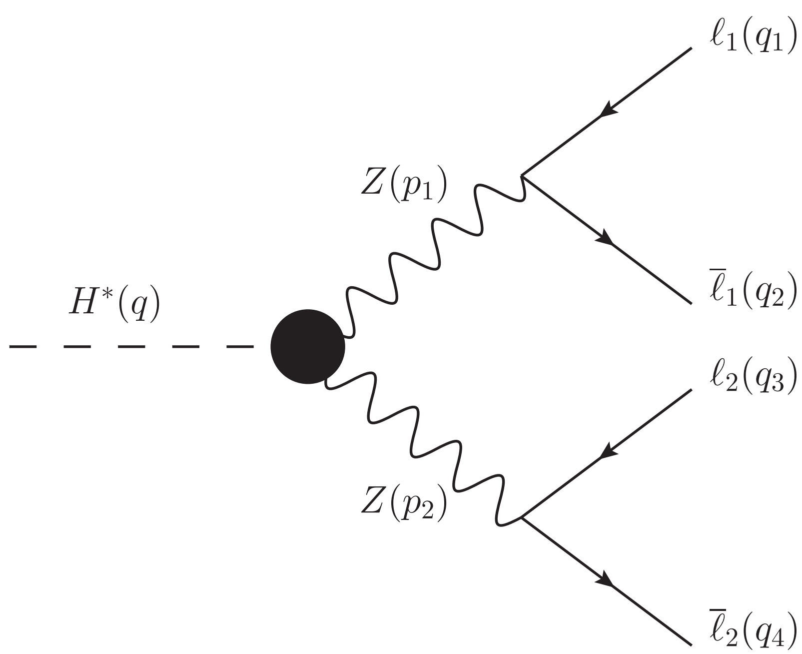
We observe new physics effects in

$$\mathscr{A}_{LR} = \frac{\Gamma_{H^* \to Z_L Z_L \to 2\ell_1 2\ell_2} - \Gamma_{H^* \to Z_R Z_R \to 2\ell_1 2\ell_2}}{\Gamma_{H^* \to Z_L Z_L \to 2\ell_1 2\ell_2} + \Gamma_{H^* \to Z_R Z_R \to 2\ell_1 2\ell_2}}$$

IMAGINARY CONTRIBUTIONS

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

We expect to observe $\mathscr{A}_{LR}$ effects in the $4l$ final states.



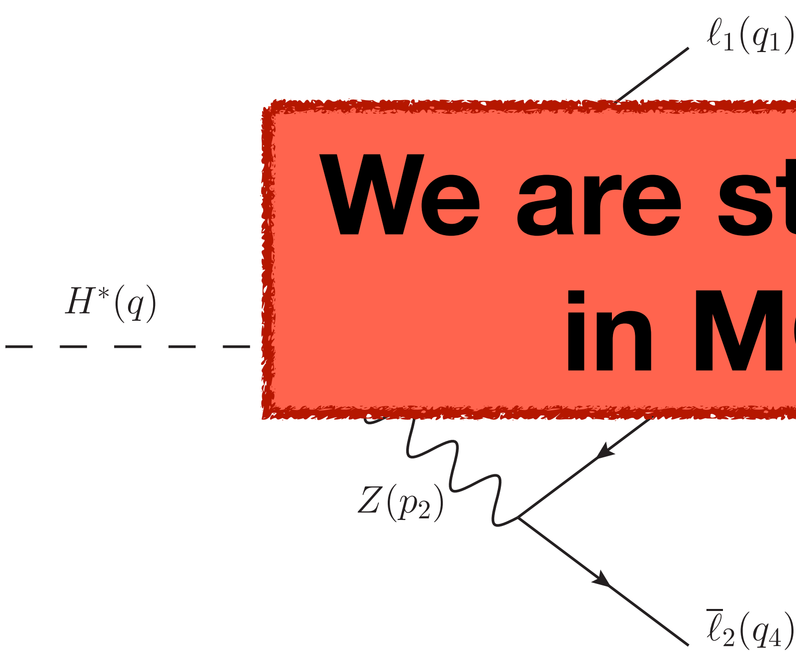
We observe new physics effects in

$$\frac{d\Gamma_{H^* \to Z_{L/R} Z_{L/R} \to 2\ell_1 2\ell_2}}{dM_{4\ell}}$$

IMAGINARY CONTRIBUTIONS

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

We expect to observe $\mathscr{A}_{LR}$ effects in the $4l$ final states.



$dM_{4\ell}$

We are still validating our results in MC event generators

Summary

- Complex anomalous couplings can be obtained from off-shell couplings.
- The imaginary parts may be relevant in some process, which are not well-understood.
- Polarizations of gauge bosons are sensitive to the imaginary part and also to CP-violation.
- New physics effects can be tested at the LHC through 4 leptons production.

¡Gracias!

Backup

ONE LOOP CONTRIBUTIONS

We must to compute off-shell observables

On-shell Green functions	→	gauge invariant and gauge independent
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

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

Feynman-´t Hooft gauge

$(\xi_Q = 1)$

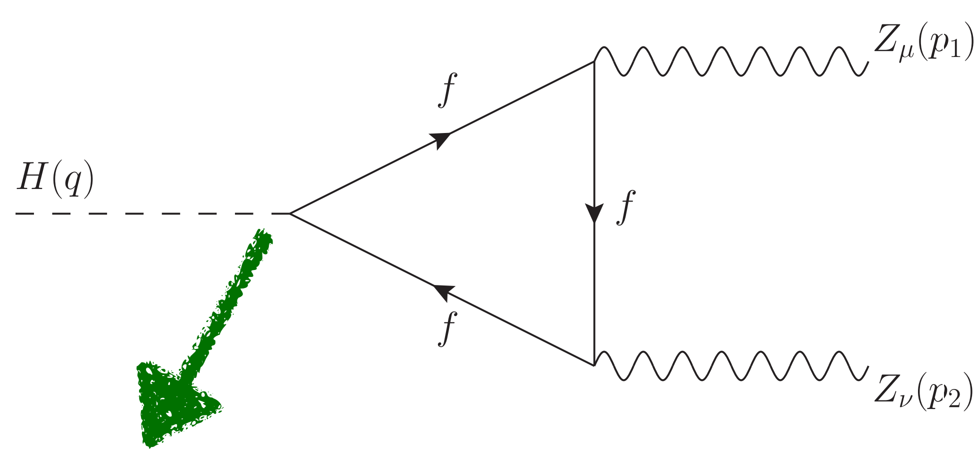
ONE LOOP CONTRIBUTIONS

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.



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