# New Physics Prospects in Higgs Couplings

## RADPyC 2025

*A. I. Hernández-Juárez, R Gaitán*
*alan.hernandezjua@alumno.buap.mx*
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# The $H \to Z\gamma$ decay

PHYSICAL REVIEW LETTERS **132,** 021803 (2024)

Editors' Suggestion    Featured in Physics

## Evidence for the Higgs Boson Decay to a *Z* Boson and a Photon at the LHC

G. Aad *et al.*[*]
(ATLAS and CMS Collaborations)

(Received 8 September 2023; accepted 27 November 2023; published 11 January 2024)

The first evidence for the Higgs boson decay to a $Z$ boson and a photon is presented, with a statistical significance of 3.4 standard deviations. The result is derived from a combined analysis of the searches performed by the ATLAS and CMS Collaborations with proton-proton collision datasets collected at the CERN Large Hadron Collider (LHC) from 2015 to 2018. These correspond to integrated luminosities of around 140 $\mathrm{fb}^{-1}$ for each experiment, at a center-of-mass energy of 13 TeV. The measured signal yield is $2.2 \pm 0.7$ times the standard model prediction, and agrees with the theoretical expectation within 1.9 standard deviations.

DOI: 10.1103/PhysRevLett.132.021803

# The $H \to Z\gamma$ decay

The signal strength is defined as

$$\mu_i^{Z\gamma} = \frac{\sigma_i \mathscr{B}^{Z\gamma}}{(\sigma_i)_{\textbf{SM}} (\mathscr{B}^{Z\gamma})_{\textbf{SM}}} = 2.2 \pm 0.7,$$

- $\sigma_i$ is the cross-section of the Higgs production
- $\mathscr{B}^{Z\gamma}$ is the branching ratio of the $H \to Z\gamma$ decay

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Experimentally measured

SM prediction

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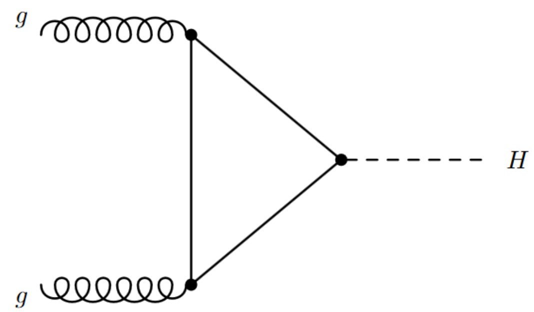
**Where is the new physics?**

- $\mathscr{B}^{Z\gamma}$ is the branching ratio of the $H \to Z\gamma$ decay

# The $H \to Z\gamma$ decay

The Higgs production is well measured and agrees with the SM production through a top quark loop in gluon fusion.

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Therefore, the new physics can only arise from the $H \to Z\gamma$ decay:

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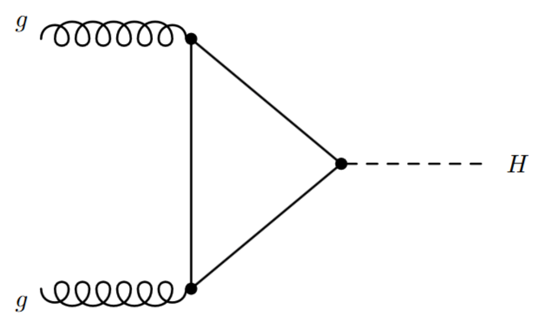


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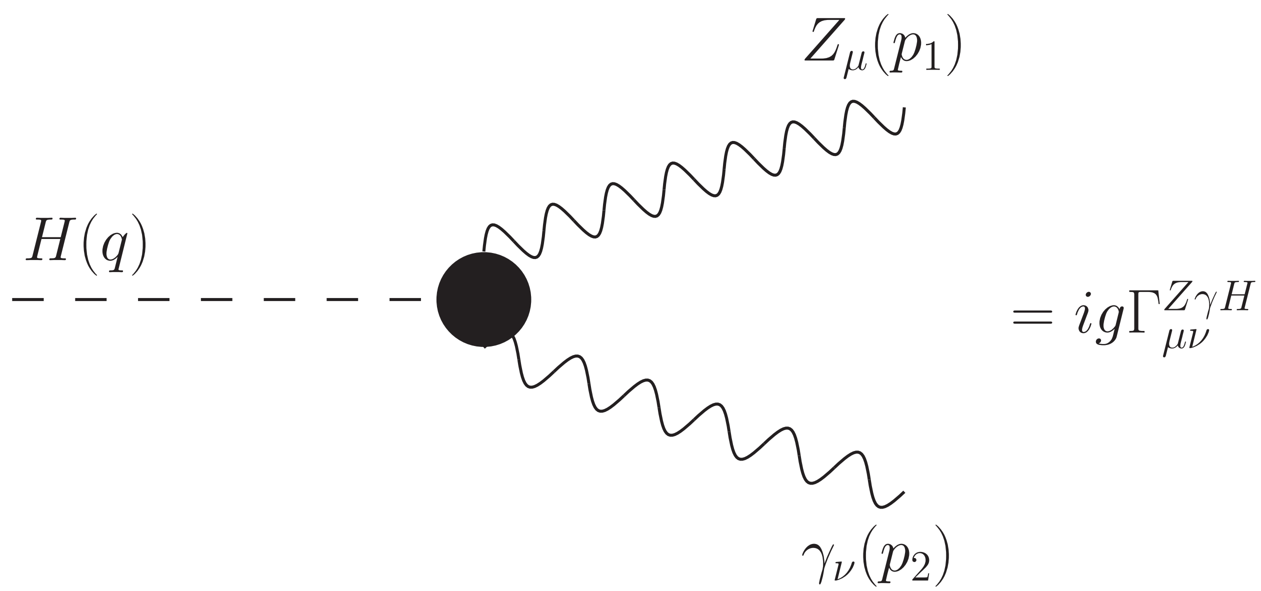
CP violation can also explain this excess!

A lot of models trying to explain this excess (THDM, MSSM, left-right models, new particles,…)

# The $H \to Z\gamma$ decay

The $H \to Z\gamma$ decay can be parametrized by the vertex function $\Gamma^{\mu\nu}_{Z\gamma H}$.




The general form of the vertex function $\Gamma^{\mu\nu}_{Z\gamma H}$ is given as follows

$$\Gamma^{\mu\nu}_{Z\gamma H} = h_1^{Z\gamma} g^{\mu\nu} + \frac{1}{m_Z^2}\left\{ h_2^{Z\gamma} p_1^\nu p_2^\mu + h_3^{Z\gamma} \epsilon^{\mu\nu\alpha\beta} p_{1\alpha} p_{2\beta} \right\},$$

$$h_2^{Z\gamma} = \frac{2\ m_Z^2}{m_Z^2 - m_H^2} h_1^{Z\gamma}.$$

Complex
$\sim 10^{-1}$ in the SM

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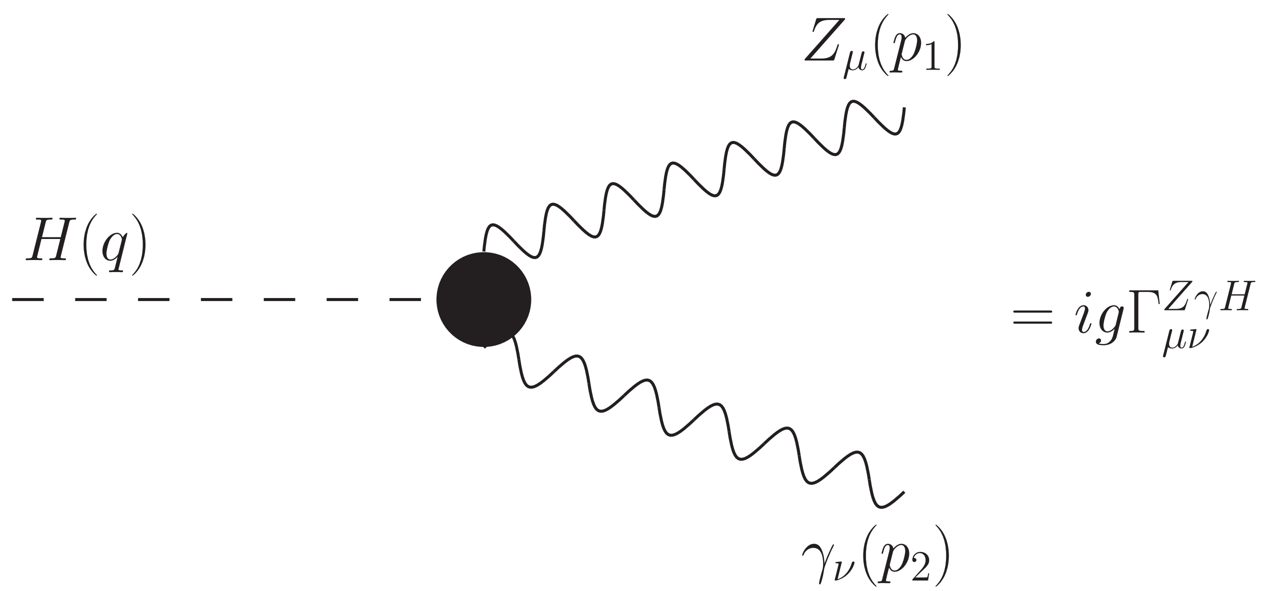


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Complex
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CP-violating and zero in the SM

# The $H \to Z\gamma$ decay

$$\Gamma(H \to Z\gamma) = g^2 \frac{m_H^2 - m_Z^2}{32\ \pi m_H^3 m_Z^4}\left(4\,|\,h_1^{Z\gamma}|^2 m_Z^4 + |\,h_3^{Z\gamma}|^2\left(m_H^2 - m_Z^2\right)^2\right)$$

$$= \Gamma^{\textbf{SM}}(H \to Z\gamma) + \delta\Gamma(H \to Z\gamma),$$

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Complex
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CP-violating and zero in the SM

# The $H \to Z\gamma$ decay

The signal strength $\mu^{Z\gamma}$ can be expressed as follows

$$\mu^{Z\gamma} \simeq \frac{\mathscr{B}^{\text{SM}}(H \to Z\gamma) + \delta\Gamma(H \to Z\gamma)/\Gamma_H}{\mathscr{B}^{\text{SM}}(H \to Z\gamma)},$$

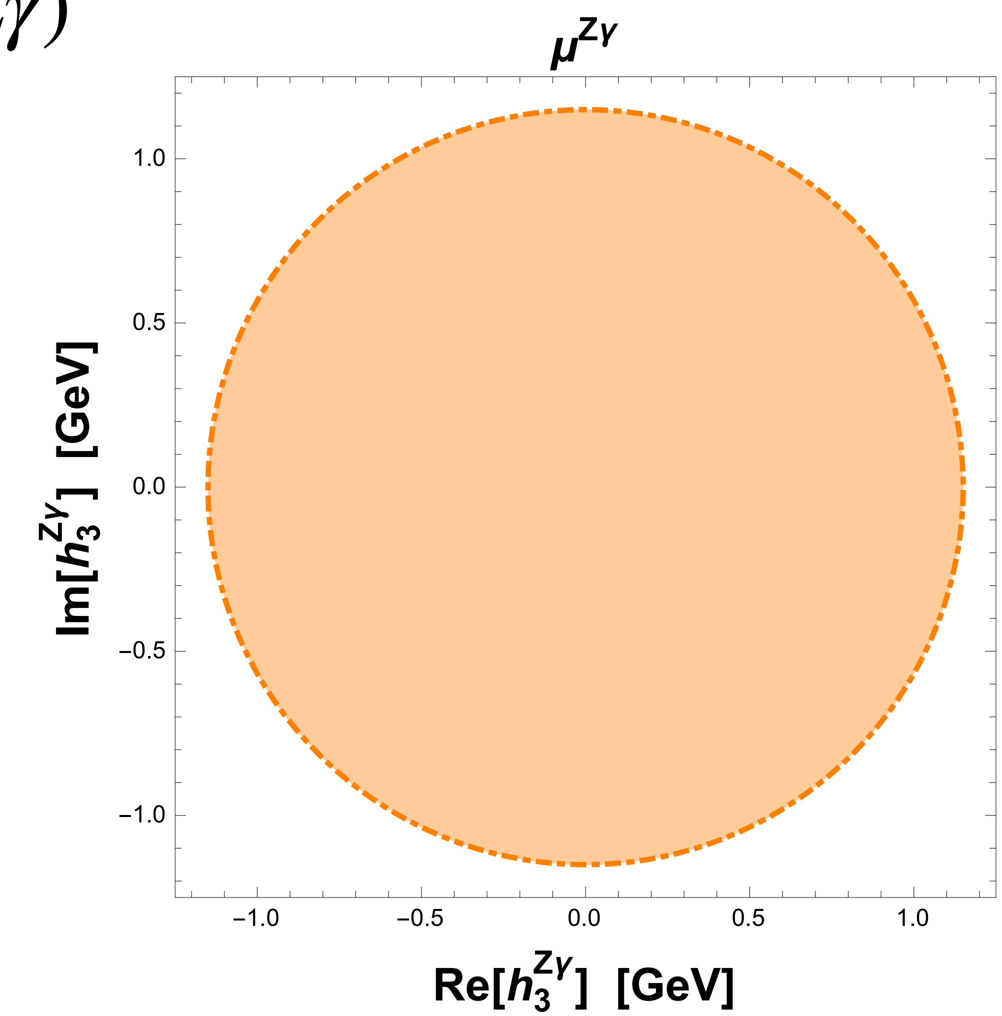
Where

$$\delta\Gamma(H \to Z\gamma) = g^2 \frac{\left(m_H^2 - m_Z^2\right)^3}{32\, \pi m_H^3 m_Z^4} |h_3^{Z\gamma}|^2 .$$

A. I. Hernández-Juárez, R. Gaitán and R. Martinez, H → Zγ decay and CP violation, Phys. Rev. D 111, 015001 (2025), arXiv:2405.03094 [hep-ph].

$\left|\text{Re}\left[h_3^{Z\gamma}\right]\right|, \left|\text{Im}\left[h_3^{Z\gamma}\right]\right| \lesssim 1.15$ **GeV** **at 95 % CL.**

First direct limit on $h_3^{Z\gamma}$ from experimental data



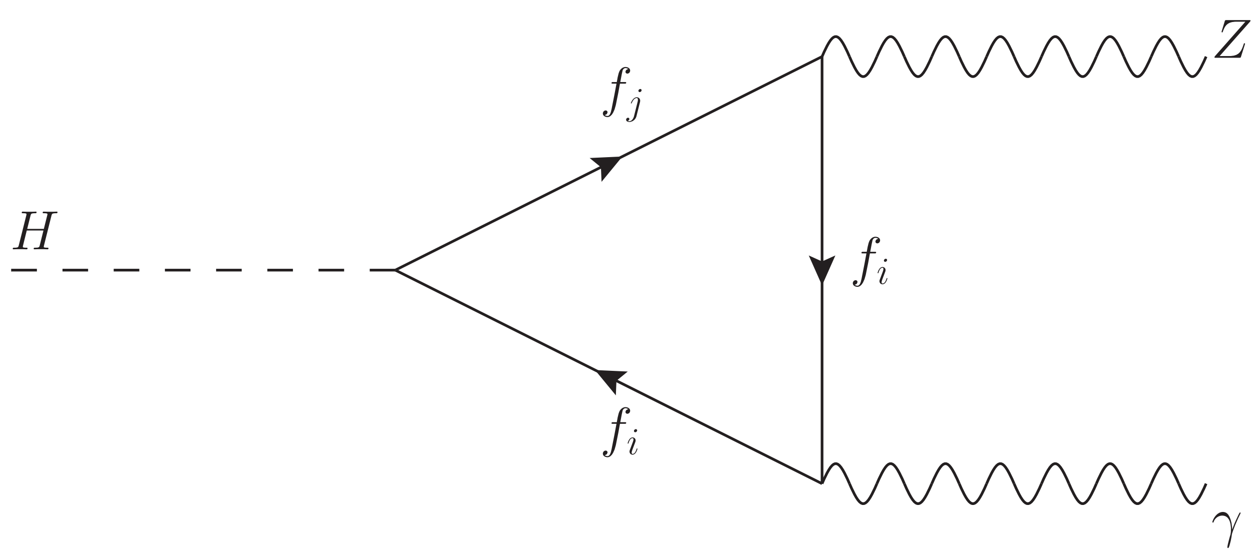
# The $H \to Z\gamma$ decay

Effective Lagrangian that induces FCNC of the Higgs and $Z$ boson:

$$\mathscr{L} = \frac{g}{c_W}\bar{f}_i\left(g_V^{ij} - g_A^{ij}\gamma^5\right)f_j Z^\mu + \frac{g}{2m_W}\bar{f}_i\left(g_S^{ij} + g_P^{ij}\gamma^5\right)f_j H,$$

$g_V^{ij}$, $g_A^{ij}$, $g_S^{ij}$ and $g_P^{ij}$ complex constants

A possible new physics contribution:




It does not contribute to the $H \to \gamma\gamma$ decay

# The $H \to Z\gamma$ decay

$$h_3^{Z\gamma} = \frac{g\ \mathcal{Q}\ e\ m_Z^2\ N_c}{4\pi^2 c_W m_W}\Bigg\{ m_j \mathbf{C}_0\left(0, m_H^2, m_Z^2, m_j^2, m_j^2, m_i^2\right)\left[-\mathrm{Im}\left\{g_A^{ij}\left(g_S^{ij}\right)^*\right\} + \mathrm{Im}\left\{g_V^{ij}\left(g_P^{ij}\right)^*\right\}\right]$$
$$+ m_i \mathbf{C}_0\left(0, m_H^2, m_Z^2, m_i^2, m_i^2, m_j^2\right)\left[\mathrm{Im}\left\{g_A^{ij}\left(g_S^{ij}\right)^*\right\} + \mathrm{Im}\left\{g_V^{ij}\left(g_P^{ij}\right)^*\right\}\right]\Bigg\}$$

Calculated for the first time also

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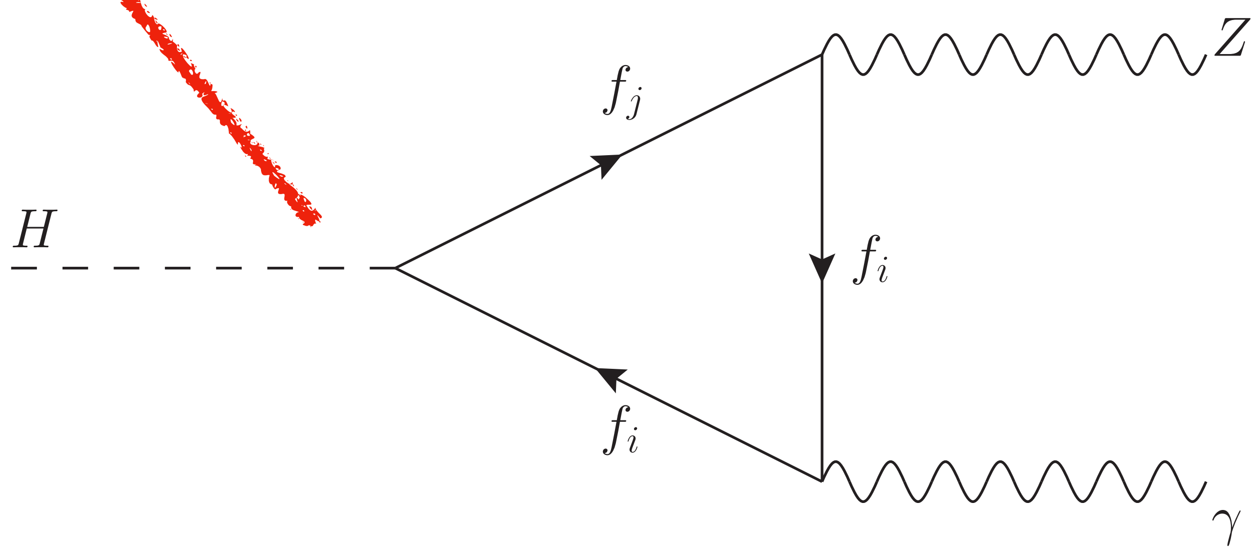


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**Limits on top quark FCNC couplings:**

$|g_{V,A}^{tc}| < 0.0095, \quad |g_{S,P}^{tc}| \lesssim 0.25$ **GeV**

- We estimate that for FCNC of the top quark $h_3^{Z\gamma} \approx 10^{-5}$, too small to explain the $\mu^{Z\gamma}$ excess.

- Contributions from new quarks are also possible and close to the bounds on $h_3^{Z\gamma}$.

# The $HZZ$ vertex

nature physics

ARTICLES

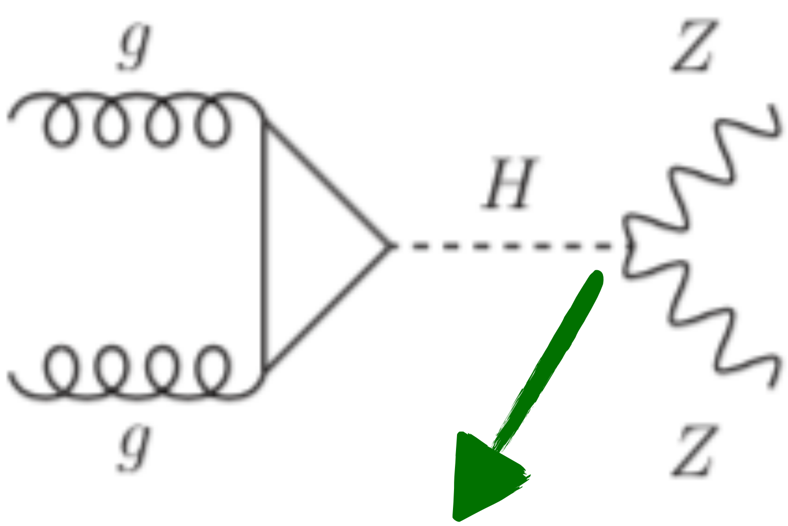
https://doi.org/10.1038/s41567-022-01682-0

Check for updates

OPEN

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

The CMS Collaboration*✉




$$m_H < 2m_Z$$

ATLAS EXPERIMENT

Submitted to: Phys. Lett. B.

CERN

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

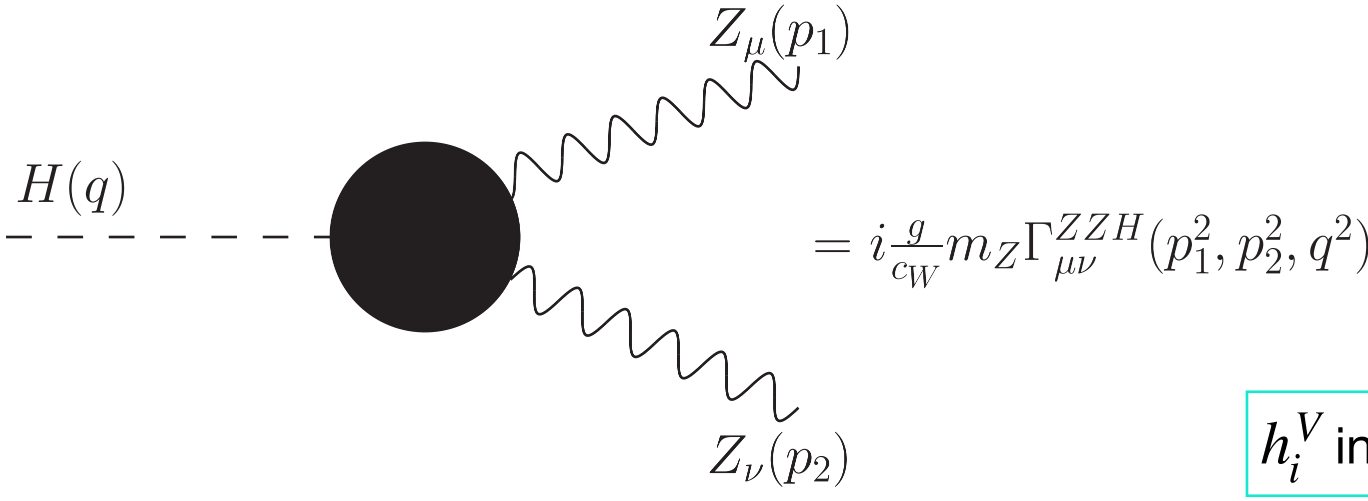
$$\Gamma_H = 3.2^{+2.4}_{-1.7} \text{ MeV}$$

The $H \to ZZ^*$ well measured at the LHC

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

# The $HZZ$ vertex

Anomalous couplings for the $ZZH$ vertex can be induced




Similar for the $HW^\pm W^\mp$ case

$h_i^V$ in terms of the anomalous couplings

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

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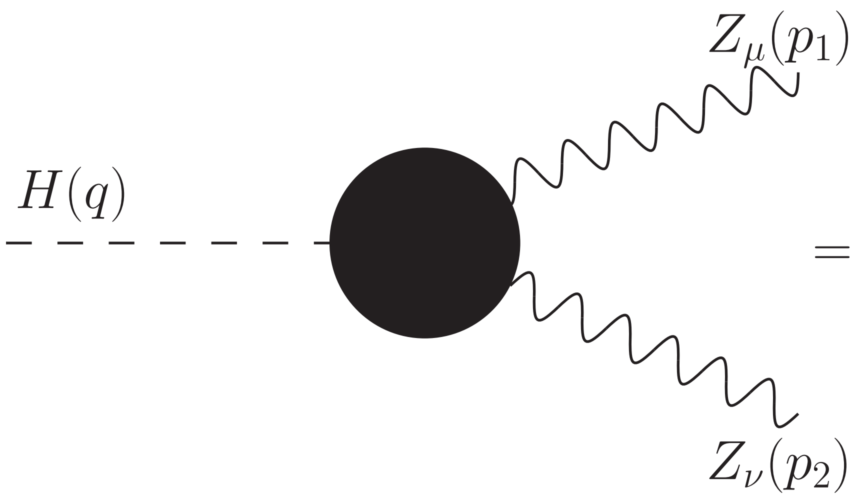


$$= i\frac{g}{c_W} m_Z \Gamma^{ZZH}_{\mu\nu}(p_1^2, p_2^2, q^2)$$

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CP-conserving

CP-violating

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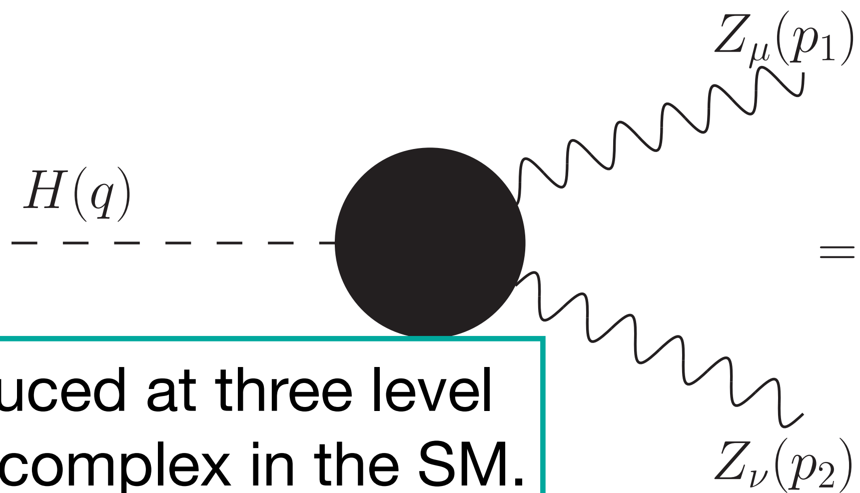


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$h_i^V$ in terms of the anomalous couplings

Induced at three level and complex in the SM.

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Induced at one-loop level and complex in the SM.

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$h_3^V \sim 10^{-11}$

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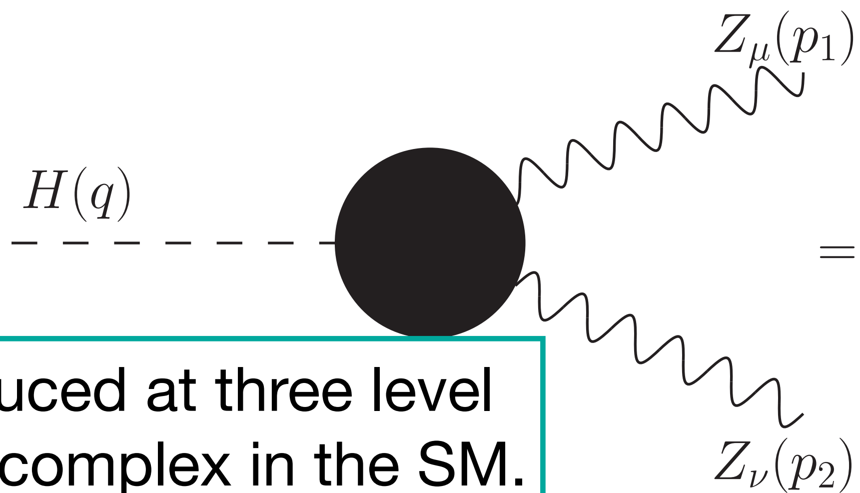


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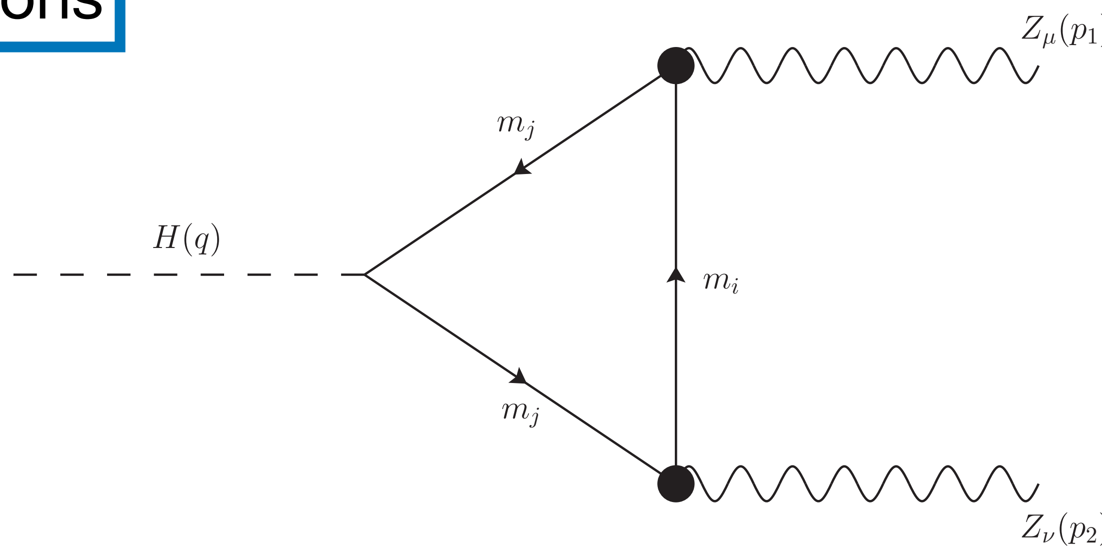
Possibilities of new physics!

# $HZZ$ vertex function

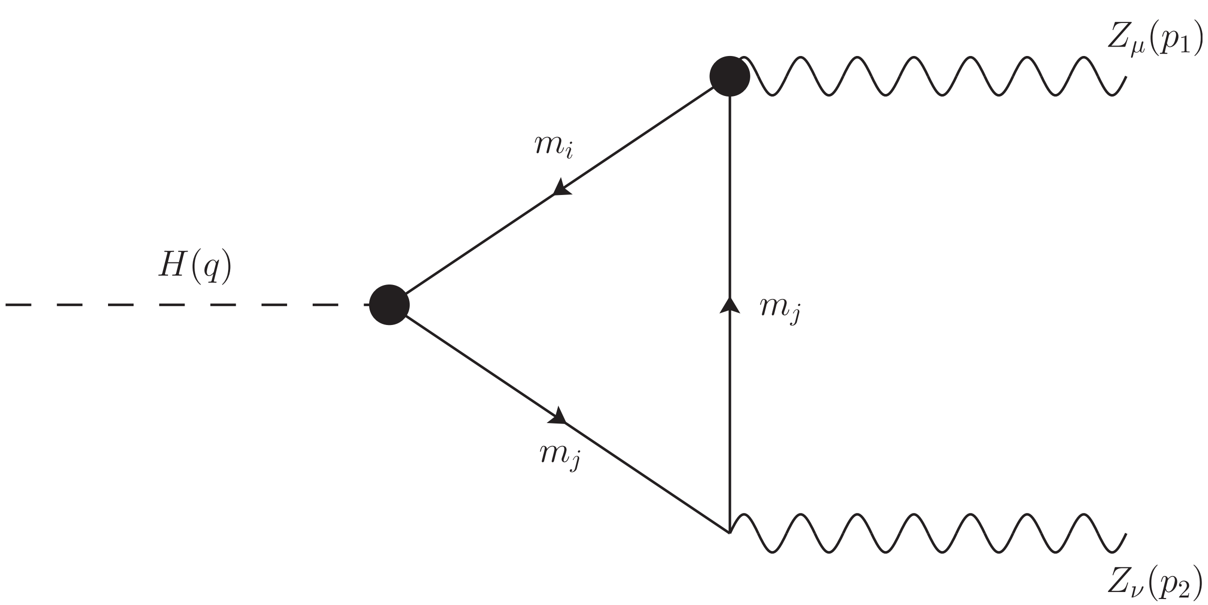
Again FCNC of $Z$ and $H$ bosons: $$\mathscr{L} = \frac{g}{c_W}\bar{f}_i\left(g_V^{ij} - g_A^{ij}\gamma^5\right)f_j Z^\mu + \frac{g}{2m_W}\bar{f}_i\left(g_S^{ij} + g_P^{ij}\gamma^5\right)f_j H,$$

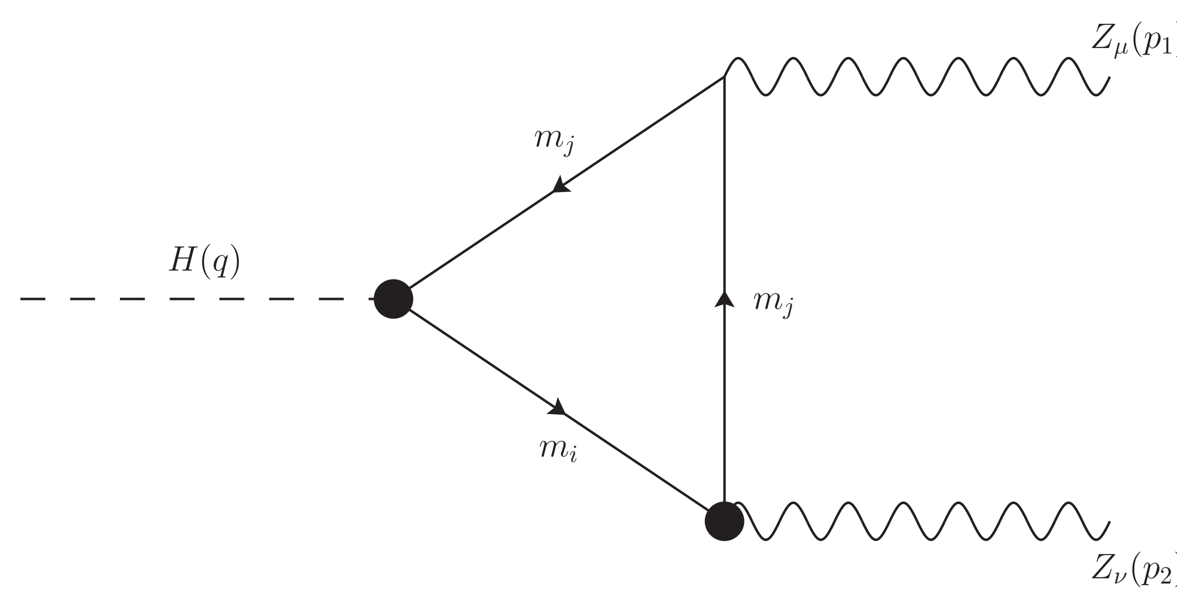
Two different contributions

Type I:




Type II:



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**Two different contributions**

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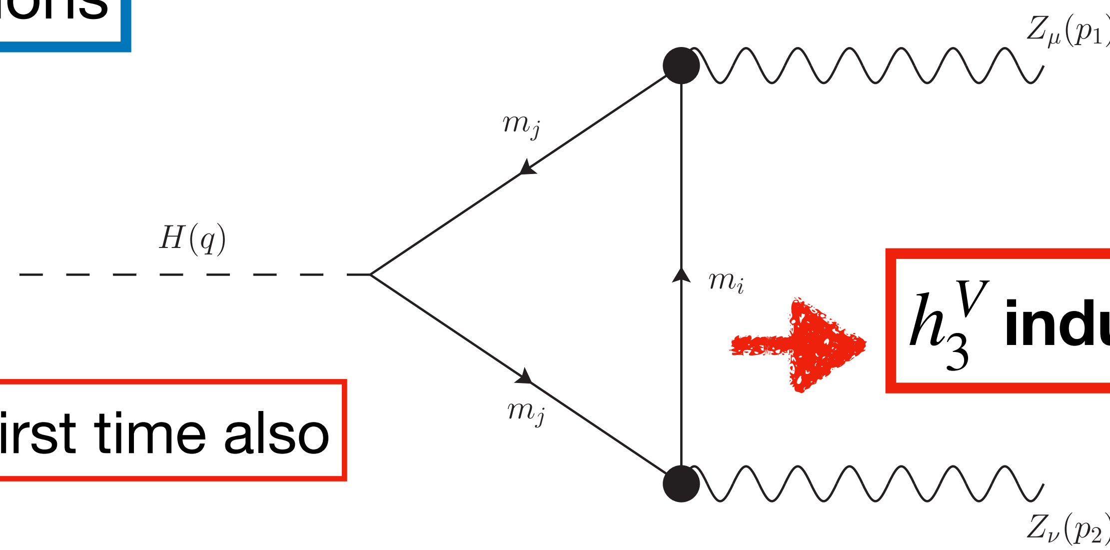
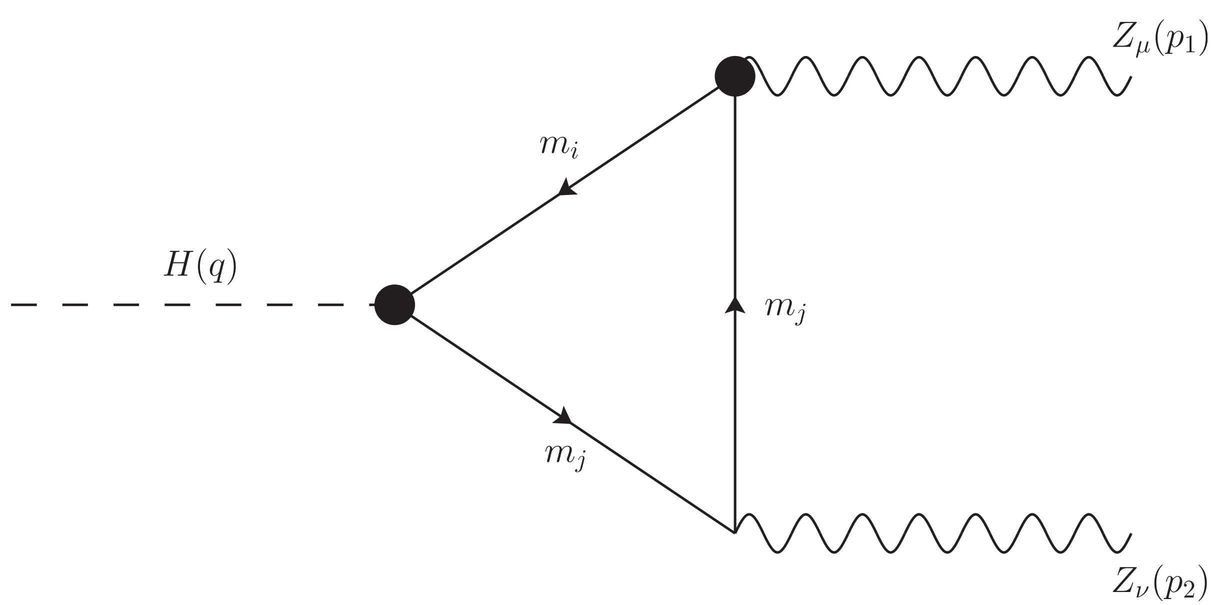
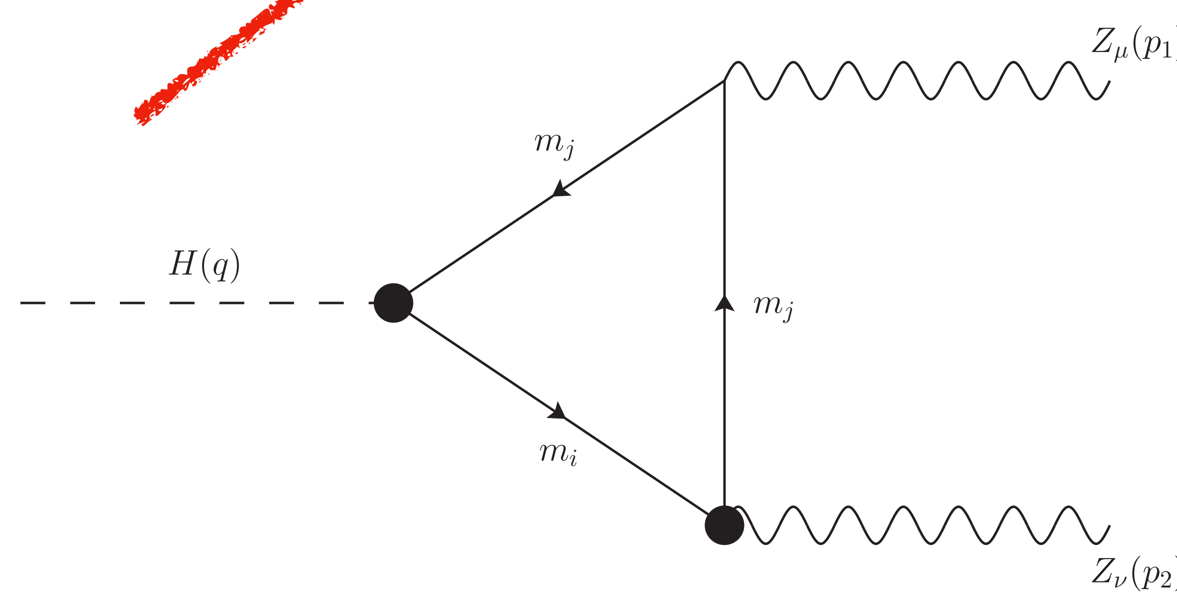



**$h_3^V$ induced at the one-loop level**

Calculated for the first time also

Type II:



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Two different contributions

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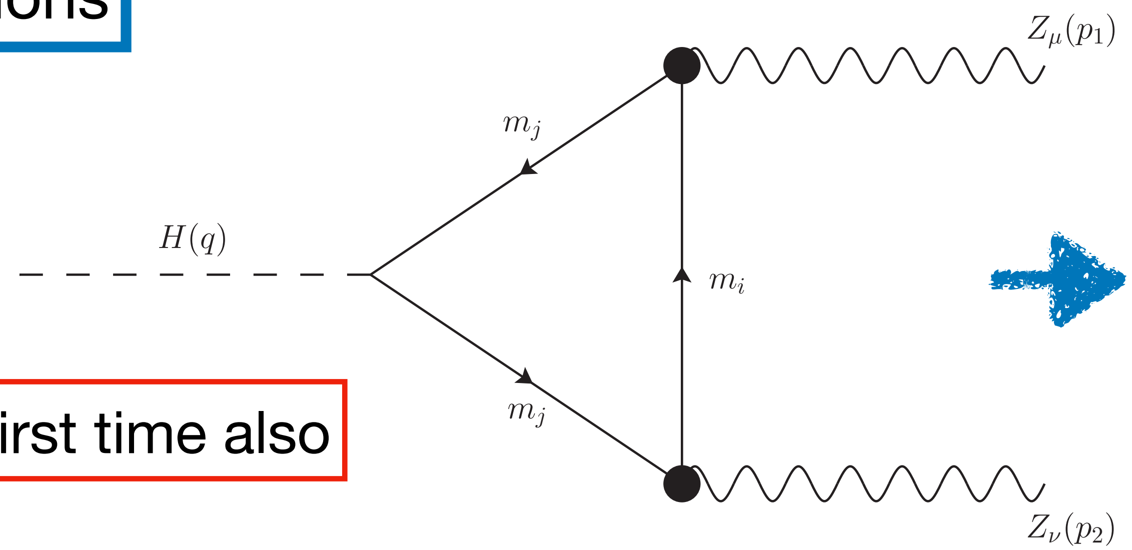
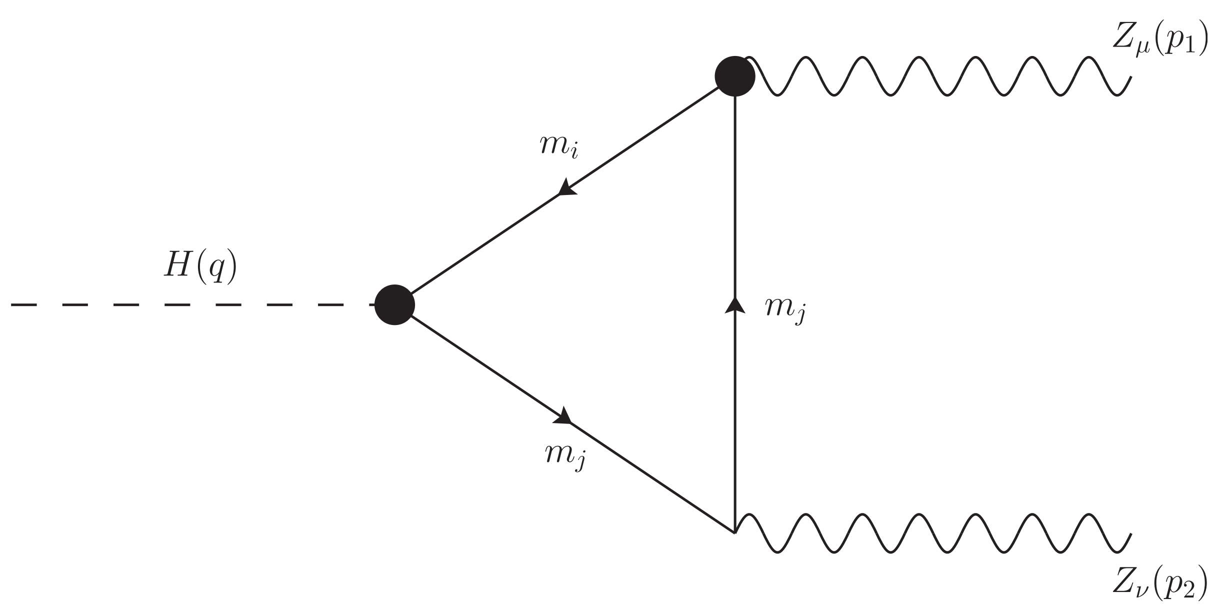


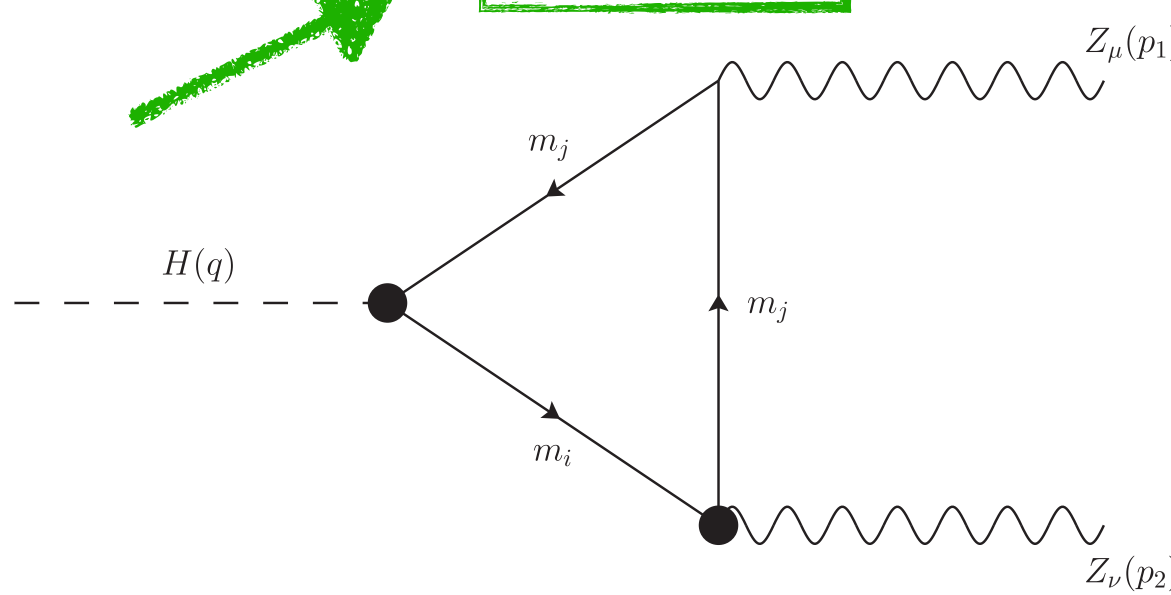

$h_3^V \sim 10^{-8}$

Calculated for the first time also

$h_3^V \sim 10^{-7}$

Type II:



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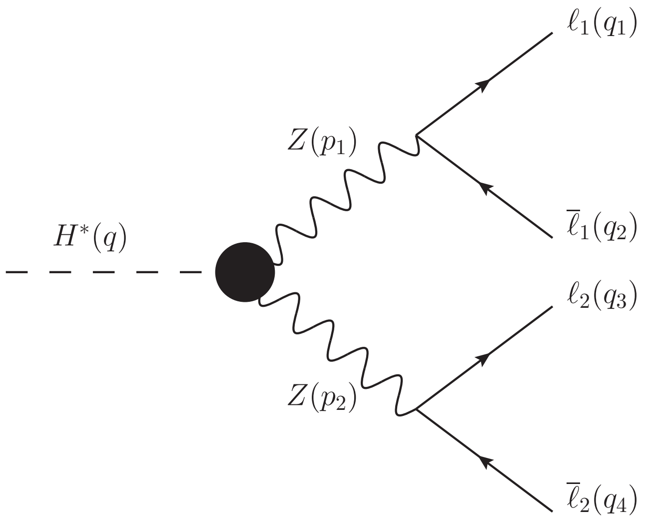


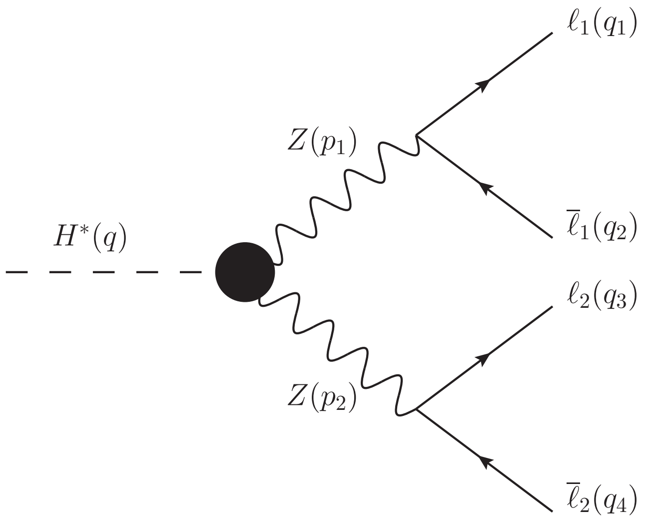

- Small effects of $h_3^H$ in the process $gg \to H^* \to ZZ \to 4l$

¿Polarized process $gg \to H^* \to Z_\lambda Z_\lambda \to 4l$ ? $\lambda = R, L$ and $0$

- Left-Right asymmetry:

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

# $HZZ$ vertex function

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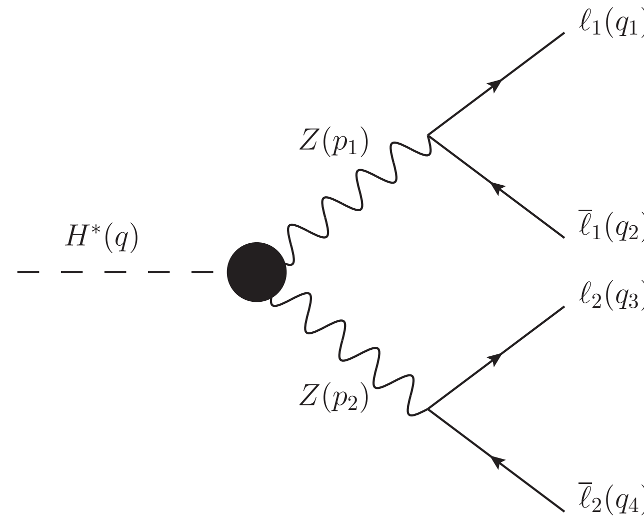
- Left-Right asymmetry:

$$\mathscr{A}_{LR}^{H} \sim \mathrm{Re}\left[h_1^H\right]\mathrm{Im}\left[h_3^H\right] - \mathrm{Re}\left[h_3^H\right]\mathrm{Im}\left[h_1^H\right]$$

# $HZZ$ vertex function

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- Left-Right asymmetry:

**CP-violation**

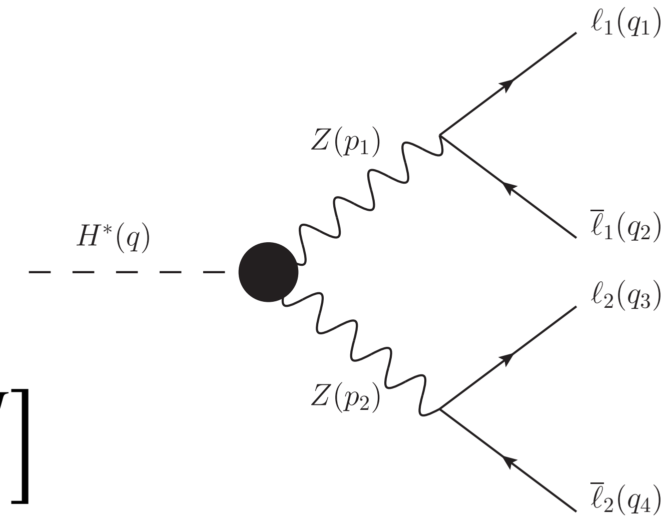
$$\mathscr{A}_{LR}^H \sim \mathrm{Re}\left[h_1^H\right]\mathrm{Im}\left[h_3^H\right] - \mathrm{Re}\left[h_3^H\right]\mathrm{Im}\left[h_1^H\right]$$

$h_1^H$ complex in the SM

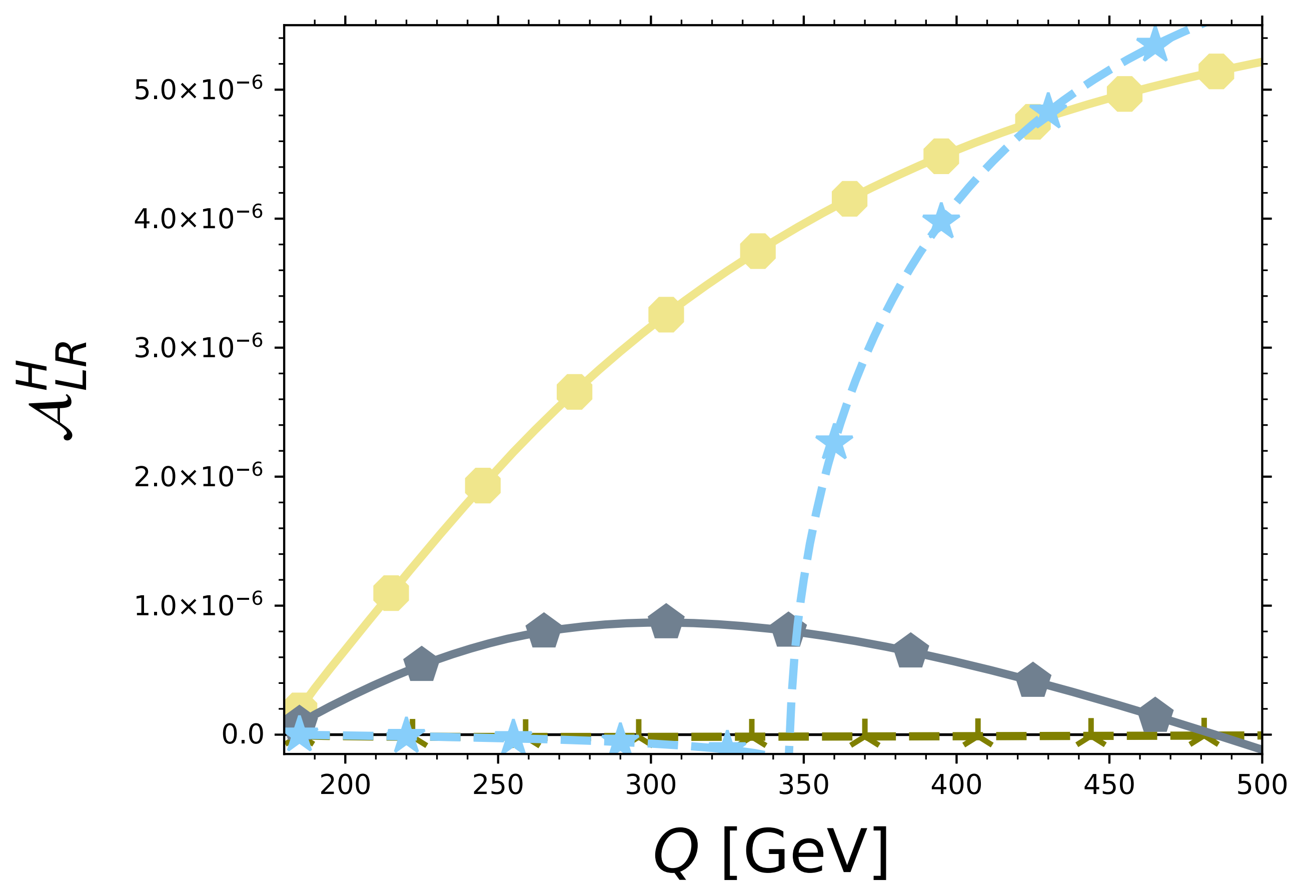
**Imaginary parts**

Similar asymmetries are posible in the $Z^* \to Z_\lambda H$ and the $HWW$ vertex

# $HZZ$ vertex function




$$\mathscr{A}^H_{LR} \sim \mathrm{Re}\left[h^H_1\right]\mathrm{Im}\left[h^H_3\right] - \mathrm{Re}\left[h^H_3\right]\mathrm{Im}\left[h^H_1\right]$$




**The observation of the $\mathscr{A}^H_{LR}$ asymmetry would imply a new source of CP violation**

# Summary

- Effects of new physics are still possible in Higgs couplings.

- CP-violation can explain the reported excess in the $H \to Z\gamma$ decay.

- New sources of CP-violation in the $HZZ$ and $HWW$.

# ¡Gracias!